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REVISION B  
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**George C. Marshall Space Flight Center**  
Marshall Space Flight Center, Alabama 35812

**ER41**

**MSFC TECHNICAL STANDARD**

**DEVELOPMENT OF  
VIBROACOUSTIC AND SHOCK  
DESIGN AND TEST CRITERIA  
STANDARD**

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<b>MSFC Technical Standard ER41</b>		
<b>DEVELOPMENT OF VIBROACOUSTIC AND SHOCK DESIGN AND TEST CRITERIA</b>	<b>Document No.: MSFC-STD-3676</b>	<b>Revision: Revision B</b>
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## FOREWORD

This Standard describes the methodology used by the Marshall Space Flight Center to calculate random vibration, acoustic, and shock design and test criteria and subsequent design loads. In addition, the rationale for using these methods for launch vehicle components and payloads is described. Also included are guidelines and requirements for selection of appropriate criteria for qualification and acceptance testing and guidelines and requirements for their application in testing spaceflight hardware.

The major requirements detailed in this standard are:

- Section 6. Random vibration, acoustic and shock qualification test criteria shall be based on the P97.5/50 statistical basis. No margin is required above the maximum predicted environment.
- Section 6. Acceptance testing shall be conducted 6 dB below the qualification test levels.
- Section 6. Qualification test duration shall encompass flight environments as well as the fatigue induced by multiple acceptance tests.
- Requirements to be implemented during vibroacoustic and shock qualification and acceptance testing are described in section 7.
- Test tolerances are defined in section 7.

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## **1. SCOPE**

### 1.1 Scope

This document presents the methodology for the development and application of the vibroacoustic and transient design and verification criteria for Marshall Space Flight Center (MSFC) managed launch vehicle and payload hardware. The following are included:

- a. Environment definition
- b. Design and verification criteria
- c. Vibration and shock qualification test requirements and procedures
- d. Design loads methodology

### 1.2 Authority

This standard is to be used to aid in the development of random vibration, acoustic, and shock design and test criteria. It meets the intent of higher level NASA standards such as NASA-STD-7001 and NASA-STD-7003.

### 1.3 Responsibility

The Marshall Space Flight Center is responsible for implementation of this standard. Contractors fulfilling contracts that levy this standard shall adhere to the requirements included herein. Any deviation to the requirements in this standard shall require approval by the OPR.

## **2. APPLICABLE DOCUMENTS**

### 2.1 Government Documents

#### NASA

NASA-STD-7003                      Pyroshock Test Criteria

NASA-STD-7001, Rev A      Payload Vibroacoustic Test Criteria

### 2.2 Reference Documents.

Documents listed below are provided as background or supplemental information for the users of this standard. The listing in this section does not levy any new or relieve any specific requirements that are imposed by this standard or by other contractual documents.

#### 2.2.1 Government Documents

#### NASA

NASA TM-86538      Design and Verification Guidelines for Vibroacoustic and Transient Environments

NASA-HDBK-7005      Dynamic Environmental Criteria

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- NASA TN D-1836     Techniques for Predicting Localized Vibratory Environments of Rocket Vehicles
- NASA TN D-2158     Statistical Techniques for Describing Localized Vibratory Environments of Rocket Vehicles
- NASA TN D-7159     Development and Application of Vibroacoustic Structural Data Banks in Predicting Vibration Design and Test Criteria for Rocket Vehicle Structures
- NASA SP-8050        Structural Vibration Prediction
- NASA/TM-2009-215902     Using the Saturn V and Titan III Vibroacoustic Databanks for Random Vibration Criteria Development

#### 2.2.2 Non-government Documents

- NASA-CR-116437     “Aerospace Systems Pyrotechnic Shock Data - Ground Test and Flight, Volumes 1 through 6”, Martin Marietta Corp., March 7, 1970, Contract No: NAS5-15208.
- Gaberson, Howard A.: “Shock Severity Estimation”, Sound & Vibration, January 2012.
- Moening, Charles J.: “Views of the World of Pyrotechnic Shock”, Proceedings of the 56<sup>th</sup> Shock and Vibration Symposium, August 1986.
- Luhrs, Henry: “Designing Electronics for Pyrotechnic Shock”, Proceedings of the 56<sup>th</sup> Shock and Vibration Symposium, August 1986.

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### **3. ACRONYMS AND DEFINITIONS**

#### 3.1 Acronyms used in this standard

The acronyms used in this standard are defined as follows:

cg	Center of Gravity
CDR	Critical Damping Ratios
D.A.	Double Amplitude
dB	decibels
DLF	Damping Loss Factor
ET	External Tank
FEM	Finite Element Model
FPL	Fluctuating Pressure Level
$g_p$	g's peak
MDOF	Multi degree of freedom
MPC	Multi point constraint
MPE	Maximum Predicted Environment
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
OPR	Office of Primary Responsibility
PL	Probability Level
PSD	Power Spectral Density
rms	root-mean-square
SDTA	Structural Dynamic Test Article
SEA	Statistical Energy Analysis
SPL	Sound Pressure Level
SRB	Solid Rocket Booster
SSME	Space Shuttle Main Engine

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#### **4. INTRODUCTION**

MSFC experience has indicated a need for uniform vibroacoustic and transient criteria for the design and verification of space vehicle components and payloads. This document provides general guidelines and specific requirements for the application of the vibroacoustic and transient environments and criteria to all launch vehicle and payload components and experiments managed by MSFC. It is intended to be used by MSFC program management and their contractors for the design and verification of flight hardware. It does not supersede higher-level NASA requirements. The earlier in the program these requirements are recognized by the program office and their respective contractors, the more cost effective the implementation will be, and the less chance that critical design areas will be overlooked. In assembling this document, a concerted effort was made in identifying the requirements in sufficient detail so that it can be utilized effectively by management as well as technical personnel. Much of the information contained in this standard was previously documented in NASA TM-86538, which described in detail the methodology used successfully by MSFC for developing component test criteria and design loads. This standard applies the following: all mandatory actions (i.e., requirements) are denoted by statements containing the term “shall”.

##### **4.1 MSFC Approach/Experience Base**

The MSFC approach presented in this standard is based on more than 40 years of experience in developing large launch vehicles and payloads, many of which were man-rated. The launch vehicle programs include the Redstone; Jupiter; Saturn I, IB, and V; and the Solid Rocket Booster (SRB), External Tank (ET), and Space Shuttle Main Engine (SSME) elements of the Space Shuttle. The payload programs include the Skylab, Spacelab, Hubble Space Telescope and numerous Space Shuttle payloads. MSFC has been extremely successful in the vibroacoustic design and verification of the flight hardware for these programs. Vibration and acoustic data acquired from these programs during static firings, ground-based acoustic tests, and flights have been evaluated and folded into a computerized structural data bank. This data bank serves as the empirical base for the formulation of the vibroacoustic design and verification criteria for all MSFC managed launch vehicle and payload programs. The data bank also provides a basis for evaluation of predictions from analytical tools.

All analyses are simulations which are not complete (limited), which attempt to predict trends of what will happen. The same is true of test. All these partial attempts to model or test reality are melded together. How these many pieces are put together determines the validity of the design.

This principle must be fully understood so that everything is constantly challenged for applicability. The major problem we deal with is how this less-than-reality information is meshed together to get verified, reliable systems. Obviously, this can only be done in some probabilistic sense. In addition to the use of robust statistical approaches, how the limitations of model, tests, etc. are dealt with determines the design outcome. There are many ways of approaching the question; however, the fundamental approach appears to be a building block approach using a combination of analysis and test. Fundamental to this approach are the following steps: (1) formulate model, (2) perform pretest

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analysis and sensitivity studies to guide test, etc., (3) perform test with proper instrumentation, (4) correlate predictions and test, and (5) update model to produce verified model.

One of the most important general principles in the development of vibroacoustic design and test criteria is to make simplified hand analyses to understand the phenomenon and guide all more in-depth computer evaluations. A fundamental part of this approach is the determination of the extreme or limiting cases. By establishing the physical understanding of a problem and its bounds, greater insight and more efficiency are established.

MSFC has also developed a capability for using vibroacoustic models. The focus of this development has been critical evaluation and verification of analytical response results by comparison to flight and ground test measurements. Exploring the strengths and identifying the limitations of each analytical approach is important. See APPENDIX A for more information about vibroacoustic modeling.

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## **5. ENVIRONMENT DEFINITION**

The critical nature of today's launch vehicles and payloads results in stringent vibroacoustic and transient design requirements on systems and components. The stringent cost controls and critical schedules are an additional consideration. Precise definition of the vibroacoustic and transient environments is an essential design requirement. This section briefly discusses the sources of these environments and methods of predicting their magnitudes.

### **5.1 Acoustic and Aerodynamically Induced Fluctuating Pressure Environments**

The acoustic environment is the maximum fluctuating pressure acting on the surface of the launch vehicle or payload structure. The two primary sources for the acoustic environment are the engine generated noise during static firing and liftoff and the aerodynamically generated fluctuating pressure levels (FPL) during the transonic and maximum dynamic pressure periods of ascent and reentry flight.

#### **5.1.1 Engine Generated Acoustics**

The primary source of the acoustic field is the fluctuating turbulence in the mixing region of the rocket exhaust flow. Engine generated noise is a function of the exhaust flow parameters, launch stand configuration, and to a lesser extent atmospheric conditions. Preliminary estimates of the engine generated acoustics at a specified location on the vehicle can be determined by scaling measured acoustic data from previous launch vehicle programs, taking into account the above-mentioned flow, configuration, and atmospheric parameters. A better definition of the liftoff acoustic environment can be determined from hot fire testing of dynamically scaled models of the launch vehicle and stand. During the Space Shuttle development program, a 6.4% model of the launch vehicle, propulsion system, launch stand, and exhaust duct system with water suppression was used to refine the analytical/scaling estimates of the liftoff acoustic environment. Of course, final verification of the environment is provided by full-scale static firings or launches.

The maximum acoustic environment impinging on the surface of the launch vehicle from the rocket exhaust occurs during static firing or liftoff when the vehicle is in close proximity to the ground plane and the deflected exhaust flow. As the rocket lifts off, the exhaust stream trails the vehicle and the acoustic environment diminishes to a negligible level. The length of time the acoustic environment has to be considered for design and verification is discussed in section 6.5.

#### **5.1.2 Aerodynamically Generated Fluctuating Pressures**

Aerodynamic fluctuating pressures occur as the launch vehicle accelerates during ascent and reentry due to boundary layer turbulence. These pressures, called aerodynamic noise, are applied over the vehicle surface and are generally a maximum during the transonic and maximum dynamic pressure period. Because of the difficulty of predicting boundary layer noise by analytical methods, data measured with high frequency pressure gages during wind tunnel tests of scale model vehicles are generally used. These wind tunnel tests cover the anticipated range of angle of attack and roll, and encompass Mach number ranges typically from 0.6 to 3.5. Early wind tunnel tests of a

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geometrically scaled simple model are used for the preliminary estimates of the aerodynamic noise. As the vehicle design matures, a complex model incorporating all protuberances is tested to refine the environment definition.

### 5.1.3 Internal Compartment Acoustics

The acoustic environment internal to the vehicle compartments is the direct result of the external acoustic field impinging on the compartment walls whether it is the engine generated noise or the aerodynamic fluctuating pressure environment. The compartment internal acoustic environment is a function of the external acoustics, noise reduction or attenuation through the compartment walls, volume of the unfilled compartment, and the acoustic absorption of the compartment walls and external surfaces of the components or payload. The compartment internal acoustics impinge directly on the large area-to-weight structure producing the primary source of random vibration for internal components or payloads. Preliminary predictions of the compartment acoustic environment are based on noise reduction data banks from previous programs and analytical estimates of the compartment wall acoustic absorption. Vibroacoustic models (APPENDIX A) are also used to make similar preliminary predictions of internal cavity acoustic environments. These predictions are generally verified by full-scale reverberation field testing during the development phase of the program.

## 5.2 Random Vibration Environment

The random vibration environment is the maximum level expected for a given vehicle location and flight regime. The two primary sources of random vibration are acoustically and mechanically induced.

### 5.2.1 Acoustically Induced Random Vibration

Acoustically induced random vibration is the result of the engine or aerodynamically generated acoustics (as described in section 5.1) impinging on the large area-to-weight structure causing it and the components/experiments attached to it to vibrate

The acoustically induced random vibration is usually determined from vibroacoustic structural data banks. A vibroacoustic structural data bank is a statistical compilation of vibration and acoustic data which are categorized according to definite structural configurations, such as skin stringer, ring frame, and honeycomb. Simply stated, a vibroacoustic data bank indicates the vibration level for a given sound pressure level (SPL) acting on a particular structural configuration. These data banks were developed from the large amount of vibration and acoustic measurements taken during ground-based acoustic tests, static firings, and flights of previous launch vehicles (Saturn, Titan, Skylab, Space Shuttle, etc.).

In utilizing these data banks for determining the vibration environment for a new vehicle structure, the data bank that is closest to the new vehicle structural configuration is selected. The proper mass (surface density) and sound pressure level adjustments are made to determine the vibration environment for the unloaded new vehicle or payload structure. Component random vibration

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levels for varying weight ranges are then determined from conventional mass attenuation techniques. See NASA TN D-1836 and TN D-2158 for more information.

Vibroacoustic models (APPENDIX A) may also be used to estimate the random vibration response of structures resulting from acoustic or aerodynamically induced FPL environments acting over the surface of a vehicle external panel. Finite Element Models (FEMs) are best suited for response predictions in the low to mid frequency range. Statistical Energy Analysis (SEA) models are well suited for vibration estimates in the high frequency range. Estimates based on vibroacoustic FEMs provide an advantage for estimating the response from different mass loaded conditions of a new vehicle design.

Verification of the acoustically induced random vibration early in the program can be accomplished by exposing a full-scale structural dynamic test article (SDTA) to the appropriate acoustic environments in a large reverberation room. The resulting vibration levels can then be measured directly at the component/mounting structure interface. Of course, the components will be included in the SDTA or mass, moment of inertia, and center of gravity (cg) simulations of the components.

In cases where the input acoustic environment explicitly includes uncertainty levels, the development process for acoustically-induced random vibration criteria may consider incorporating the acoustic environment uncertainty along with other sources of input uncertainties and conservatism in the criteria development process with the appropriate NASA technical approval.

#### 5.2.1.1 Aerodynamic Fluctuating Pressure Induced Random Vibration

Aerodynamic fluctuating pressure levels can be quite severe in amplitude, however, their effect on random vibration environments are usually less severe than more correlated acoustic environments occurring during liftoff. The aforementioned data banks take this lack of correlation into account since the actual vibration measured for a given acoustic environment is utilized. Newer techniques using vibroacoustic models may need to take advantage of measured spatial correlation parameters, which may include parameters for attached or separated turbulent boundary layer, flow structures that are modulated by shocks, or pressure cross spectra unique to the vehicle design and trajectory.

The area around protuberances is particularly troublesome because the effects of the high protuberance acoustic levels that do not extend very far from the local area and the amount of energy to drive the structural response is limited. For these reasons protuberance acoustic environments are not typically used to derive random vibration environments when scaling is used but are used to predict acoustic fluctuating pressure loads as described in section 8.1.

#### 5.2.2 Mechanically Induced Random Vibration

Mechanically induced random vibration is the vibratory excitation resulting from the combustion processes during rocket engine burn and the rotating turbomachinery in the case of liquid burning engines. Mechanically induced random vibration is generally confined to the source which is the motor case for the solid rocket motors and the physical engine for the liquid engines. Beyond these boundaries, the random vibration attenuates rapidly.

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The random vibration resulting from engine burn is generally scaled from measured vibration data from previous engine programs. The random vibration is directly proportional to the engine thrust and exhaust gas velocity and inversely proportional to the engine weight. Engine weight refers to the weight of that portion of the engine for which the random vibration is being formulated, such as combustion chamber, turbopumps, thrust chamber, etc., and in the case of solid rockets the surface density of the motor case. In the case of the SSME the preliminary random vibration environments were scaled from the J-2S engine. This was a good engine to scale from since the J-2S, like the SSME, is a large oxygen/hydrogen burning engine.

Vibroacoustic models may also be used to estimate the random vibration response. Estimates based on vibroacoustic Finite Element Models (FEMs) provide an advantage for estimating vibration response from mechanically induced structure-borne sources for a new vehicle design.

Verification of the mechanically induced random vibration is accomplished during the engine static firing program. Measured vibration data are taken at all the component locations on at least three static firings on each of two engines. These data are statistically analyzed and enveloped to establish the engine random vibration environment.

The duration of the random vibration environment has to be considered for design and verification as discussed in section 6.

### 5.3 Transient Environments

Launch vehicles/spacecraft are subjected to significant transient environments during the period from liftoff to landing. These transients are generally characterized by a short duration (generally less than 5 seconds) with a time-varying amplitude. The transient environments can be classified as either low frequency (0 to 50 Hz), mid frequency (50-5,000 Hz) or high frequency (50 to 10,000 Hz).

#### 5.3.1 Low and Mid Frequency Transients

The low frequency transients (0 to 50 Hz) are the result of the launch vehicle/spacecraft responding at their fundamental modes of vibration during events such as engine ignition, launch release, engine overpressure, staging, wind buffeting, on-orbit docking, landing, parachute deployment, and water impact. The low frequency vehicle transients are developed from coupled loads analyses using worst case forcing functions. The low frequency vehicle transients are specified as acceleration time histories and/or shock spectra. In the case of parachute deployment and water impact, the transient environments are verified with development tests. Final verification of the low frequency transients is accomplished by scaling the flight data to the worst case forcing functions. Since these are low frequency transients not all hardware will require test verification, depending on their size and potential response to the environment.

Mid frequency transients fall into the frequency range of 50 to 5,000 Hz and are a result of excitations that cause the vehicle secondary structures, such as ring frames or panels, to respond at their fundamental frequencies. Sources of these environments include transportation, handling, and

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water impact. Water impact can produce shock response levels in the hundreds of g's and is usually qualified by testing on a shaker using a shock response spectrum.

### 5.3.2 High Frequency Transients

High frequency transients (50 to 10,000 Hz) result from the activation of ordnance devices which are being used extensively in the aerospace industry. They include linear shaped charges, frangible joints, explosive bolts, explosive nuts, squibs, pin pullers, and bolt cutters. They are being used to perform such functions as stage separation, shroud/nosecone separation, vehicle holddown release, payload deployment, and hatch separation to name a few. The transient environment caused by these devices covers a broad frequency range. These high frequency transients can cause damage and failure to equipment as well as structure (see "Shock Severity Estimation", "Views of the World of Pyrotechnic Shock", and "Designing Electronics for Pyrotechnic Shock" for more information). The state of the art of this technology for predicting the high frequency transients is limited to scaling the measured test data. For a given development test program, the acceleration time histories of a number of locations are measured and recorded during the event. Since the signature of the transient acceleration time histories are quite complex, due to the nature of the shock, the frequency content is not readily detectable. To obtain the frequency information, a spectral analysis is performed to produce a shock response spectrum which is the basic method for specifying ordnance shock environments. A shock response spectrum is a plot of the maximum acceleration response of a series of single degree of freedom systems (50 to 10,000 Hz) resulting from the application of the acceleration time history to its base.

The magnitude of the shock spectrum is a function of the size of the explosive charge used, the thickness of the material cut, and the distance from the source of the explosion. Generally, the shock spectrum environment is specified at the source (0 to 12 inches from device) with attenuation curves for attenuating the shock through various structures and joints at other locations. Initial predictions of the shock environment are based on scaling measured data from similar pyrotechnic devices used on previous programs, such as those contained in NASA CR-116437, "Aerospace Systems Pyrotechnic Shock Data - Ground Test and Flight". Final verification can be accomplished by activating the device with a full-scale structural test article.

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## **6. DESIGN AND VERIFICATION CRITERIA**

This section discusses the vibroacoustic and transient criteria which are derived from the environments. In general, the amplitude of the criteria is the same as the environment since it also represents the maximum environment. However, for simplicity the criteria may represent an envelope of the maximum environment for several flight regimes. Also, since the criteria are used for design and verification of space vehicle components and experiments they include the time the environment is present.

The requirement for testing components to these criteria for qualification is determined by the individual projects that use the hardware, in consultation with the hardware designers, dynamics engineers, and the Safety, Reliability, and Quality organization. Some qualification tests may be waived if it can be shown that the hardware is qualified by analysis or similarity. The need for acceptance testing is established by the project manager based on quality requirements since that test is to verify manufacturing workmanship. As stated below, the qualification test shall encompass the acceptance tests in both amplitude and duration.

### **6.1 Maximum Predicted Environment**

The predictions of flight environments may be based upon computed, assumed, or measured dynamic loads that do not reflect the potential flight-to-flight variations that will occur in service use. Hence, it is necessary to add a factor to the predicted vibration levels to arrive at a "maximum predicted environment" (MPE) that will account for point-to-point (spatial) and flight-to-flight variations in service, and thus assure the predictions are conservative relative to the potential flight environment. The level of the maximum expected environment shall be that not exceeded on at least 97.5% of operational missions, estimated with 50% confidence level (P97.5/50 level). Techniques documented in NASA-HDBK-7005, "Dynamic Environmental Criteria" or NASA-STD-7001, "Payload Vibroacoustic Test Criteria" may be used to calculate MPE.

### **6.2 Qualification and Acceptance Test Margin**

Qualification testing is conducted to verify that hardware and systems design, materials, and manufacturing processes have produced equipment that conforms to development specification requirements. Qualification testing shall be conducted at levels derived at the MPE level with tolerances as specified in sections 6.3 and 7.6.

### **6.3 Acceptance Tests**

Acceptance tests are conducted on qualification and flight hardware as required to demonstrate the acceptability of each deliverable item to meet performance specification and demonstrate error-free workmanship in manufacturing. The tests demonstrate conformance to specification requirements and provide quality-control assurance against workmanship or material deficiencies. Acceptance testing is intended to stress screen items to precipitate failures due to latent defects in parts, materials, and workmanship. However, the testing must not create conditions that exceed appropriate design safety margins or cause unrealistic modes of failure. To achieve these goals,

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acceptance testing shall be conducted 6 dB below the corresponding qualification test. If multiple criteria are specified then the acceptance criteria shall be based on the qualification criteria with the highest root-mean-square (rms) level in each axis. If the component designer requires acceptance testing at higher levels to achieve a test goal, the levels can be adjusted but the qualification test levels and duration shall be adjusted so that the acceptance test levels are encompassed.

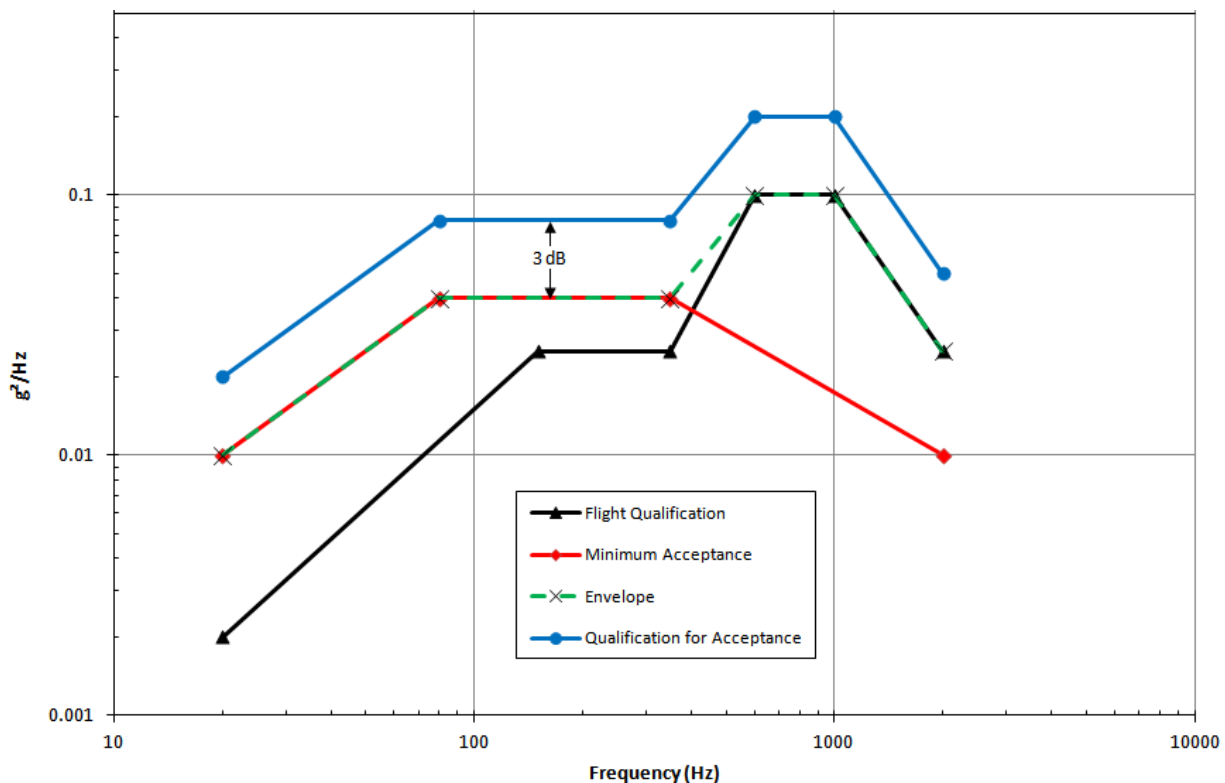
Acceptance tests are generally conducted for a duration of 1 minute per axis unless otherwise specified. The test time may be extended if needed to conduct functional tests. Qualification test duration shall encompass the fatigue induced by multiple acceptance tests. Acoustic acceptance tests are generally not conducted on spaceflight hardware, however, if required they shall be conducted 6 dB below the acoustic qualification test.

In some cases there may be reduced margin between acceptance and qualification tests because a minimum acceptance test was imposed which requires qualification above a component's capability. Tolerances for acceptance tests can be "flipped" so that there is still margin between the upper tolerance of the acceptance test and the lower tolerance of the qualification test. In this case the tolerance for the qualification test would be +3 dB, -1.5 dB and +1.5 dB, -3 dB for the acceptance test. Since the flight qualification criteria no longer cover the minimum acceptance test, a qualification for acceptance test shall be conducted. This test will serve to qualify for the higher acceptance test levels and shall be conducted in addition to the flight qualification for a duration that includes all acceptance tests planned during the components lifetime. If the "flipped" tolerances are used as defined above then the minimum margin between the acceptance test and qualification for acceptance test would be 3 dB, as illustrated in FIGURE 1 below.

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**FIGURE 1. Relationship between acceptance and qualification tests when minimum test is applied**

### 6.3.1 Hardware Selection Criteria for Acceptance Tests

To aid in determining suitability for vibration acceptance tests the following criteria can be considered.

- Items that cannot be effectively inspected during manufacture, or whose assembly involves processes and techniques not easily or effectively quality controlled; all electrical, electronic, and electromechanical components should be considered for environmental acceptance testing.
- Items shall be tested which have delicate mechanical mechanisms requiring precise adjustments.
- Mechanical items with close tolerance mechanical mating and/or interfacing mechanisms that are not easily or effectively quality controlled using standard inspection procedures.
- Items that have marginal or questionable environmental sensitivity shall be tested. TABLE I lists the types of faults expected to be found by acceptance vibration tests.

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- e. Items for which additional confidence is desired through the elimination of infant mortality failures shall be tested.

**TABLE I. Types of faults expected to be exposed by acceptance vibration testing**

Fault	Fault mode	
	Mechanical	Electrical/ mechanical
Loose electrical connections		X
Loose nuts, bolts, etc.	X	
Low-frequency relay contact chatter		X
Low-frequency switch contact chatter		X
Physical contaminants (loose foreign matter)	X	
Cold solder joints and solder voids		X
Incomplete weld joints		X
Close tolerance mechanisms		X
Improperly crimped connections		X
Wire defects such as strands cut away with insulation removal.		X
Insufficient clearance resulting in impact of component parts.	X	
Shrinkage of potting resulting in loose assembly within housing.	X	
Potting too soft, allowing excessive movement of components and wiring.	X	
Wire fatigue failure due to routing	X	
Loose or missing mounting hardware	X	
Excessive valve leakage or abnormal closure	X	
Defective piece parts	X	X

#### 6.4 Rationale and Consideration of Other NASA Standards

With the exception of Space Shuttle range safety components, all MSFC managed hardware (launch vehicle and payloads) were qualified with no added margin above the P97.5/50 MPE. While somewhat less conservative than other military and NASA standards, this policy has been very successful with no known flight failures due to random vibration or shock. The fact that MSFC establishes early on in a project that testing to these environments is expected contributes substantially to that success. Other factors include:

- a. Criteria are derived by enveloping narrow bandwidth (4-5 Hz) data whereas other standards

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allow use of wider band data, such as 1/6 octave band data. As shown in FIGURE 2 below the difference between a 95% PL based on constant percentage bandwidth data is in the range of 3-6 dB.

- b. Vibration criteria are broadband envelopes of fluctuating power spectra. The difference between the straight-line envelope of the data and the data is typically 6 dB based on the rms values.
- c. Zonal vibration criteria are higher than criteria for a specific component. The criteria for a specific weight range are based on the lightest weight component in the range.
- d. Component tests are inherently conservative. The applicable vibration test durations are applied in each of three orthogonal axes for durations that are at least four times longer than flight. Components are tested on a rigid fixture versus the more flexible vehicle structure and the impedance mismatch causes component responses to be much higher on the shaker.
- e. MSFC has extensive experience with launch vehicle design and qualification and has an excellent database as a basis for qualification criteria. These databases are documented in NASA TN D-7159 and NASA/TM-2009-215902. In addition, a wealth of Space Shuttle data is available and has been used extensively to augment these databases and to derive environments based on Shuttle heritage hardware.

Based on the above rationale the methodology documented in this standard can be considered at least as conservative as other standards that allow use of wider bandwidth data and apply fixed margins of 3-6 dB above the MPE for qualification.

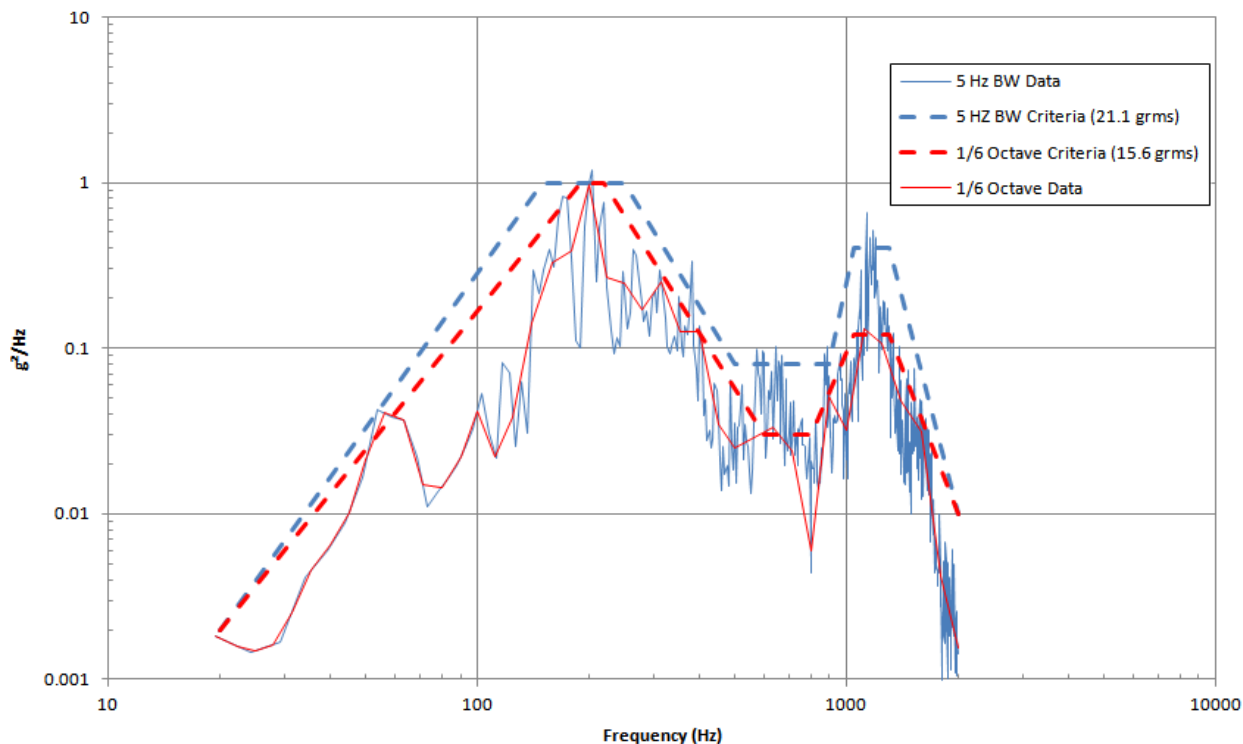
In the past, pyrotechnic shock criteria were generally based on either data measured on similar vehicles or on the extensive database contained in NASA CR-116437, "Aerospace Systems Pyrotechnic Shock Data-Ground Test and Flight" produced under a contract administered by the Goddard Space Flight Center. No arbitrary margin was added to the predictions based on these methods because the MPE levels were so high that adding additional margin would have risked successful fulfillment of the schedules and budgets. Testing to the extremely high shock levels presented a challenge to the engineers even without the margin.

It is recommended that the developer of shock criteria consult other standards such as NASA-STD-7003 when calculating criteria for new launch vehicles or payloads, particularly if shock sources are used that are not referenced in the shock database. In those cases judicious use of margin is recommended.

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**FIGURE 2. Comparison of criteria drawn on 5 Hz versus 1/6 octave bandwidth data**

## 6.5 Acoustic Criteria

The acoustic design and verification criteria are the maximum acoustic environment occurring on the external surface, in an equipment compartment, or in the payload bay of a space vehicle, during one or more flight regimes as discussed above. The test duration associated with the criteria shall be at least the equivalent time the environment is present at the maximum level based on cumulative damage using typical aerospace material fatigue properties (S-N curve slope of 5 multiplied by a fatigue scatter factor of 4). NASA/TM-2009-215902 covers the methodology used to calculate equivalent times in more detail. A tabular format is used to specify the criteria spectrum based on 1/3 octave bands covering a frequency range of 5 to 10,000 Hz. The specified criteria and verification durations shall be conformed to unless it is established that the item is not susceptible to acoustic noise.

### 6.5.1 Acoustically Insensitive Components

Basically, components with insensitive properties are those having small surface areas, high mass to volume ratios and high internal damping that are directly exposed to external or internal vehicle acoustics. Examples are as follows:

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- a. High density modules, particularly the solid or encapsulated type.
- b. Modules or packages with solid-state elements mounted on small constrained or damped printed circuit boards or matrices.
- c. Massive valves, hydraulic servo controls, auxiliary power unit pumps, etc.
- d. Equipment surrounded by heavy metallic casting, particularly those that are potted or encased within the casting by attenuating media.

### 6.5.2 Acoustically Sensitive Components

Components with sensitive properties are those normally classified as being microphonic and those having large, compliant areas of exposure, low mass to area ratios, and low internal damping that are directly exposed to external or internal vehicle acoustics. Examples are as follows:

- a. Equipment containing microphonic elements with high frequency resonances such as electron tubes, wave-guides, klystrons, magnetrons, piezoelectric components, and relays attached to thin plate surfaces.
- b. Equipment containing or consisting of exposed diaphragmatic elements such as pressure sensitive transducers, valves, switches, relays, and flat spiral antenna units.
- c. Glass panes or panels that could shatter as a result of exposure to acoustic waves.
- d. Equipment mounted on isolators that could be susceptible to direct acoustic impingement on the box surface, causing more vibration than it would experience from a vibration test with isolators.

### 6.5.3 Engine Generated Acoustic Criteria

The engine generated acoustic criteria are defined as the maximum environment described in section 5.1.1 for a particular location on the space vehicle. The space vehicle is divided into criteria zones, which are based on a combination of minimum variation in environmental amplitude and similar structural dynamic characteristics. The acoustic criteria durations are determined as discussed in section 6.5 above.

### 6.5.4 Aerodynamically Generated Acoustic Criteria

The aerodynamically fluctuating pressure environment which occurs during ascent and reentry is specified as a design and verification criteria that also represent the maximum expected environment within each zone as described above. For the aerodynamic acoustic criteria there are special zones to account for all protuberances. Here again, the criteria durations are as discussed in section 6.5.

### 6.5.5 Payload Compartment Acoustic Criteria

The acoustic design and verification criteria for payloads and payload components represent an envelope of the maximum internal acoustic environments that occur during liftoff and ascent flight.

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The criteria durations for design and verification are determined as described in section 6.5. Sometimes the liftoff and ascent criteria are combined by enveloping to provide a single criteria spectrum for simplicity; this was the case for the Space Shuttle cargo bay. Components and experiments which are susceptible to damage from acoustic excitation should be qualified to the acoustic criteria. This generally includes large area-to-weight structures, components that are highly resonant above 2000 Hz, and components that have been mounted with vibration isolators. Also, it is MSFC policy to recommend an all-up acoustic test on the assembled flight payload. It is also a recommendation that a structural dynamic test article with mass, moment of inertia, and center-of-gravity component simulators be subjected to the acoustic criteria early in the development in order to verify the random vibration criteria before the component qualification program.

## 6.6 Random Vibration Criteria

The random vibration design and test criteria are the envelope of the maximum random vibration environment discussed in section 5.2 for a particular zone or component location and flight condition. No arbitrary factors or margins of safety are applied to the maximum environmental level in developing the criteria as explained in section 6.2. It is quite common for the envelope to clip peaks in the spectrum, as demonstrated in FIGURE 1. Peaks can be clipped by 3 dB if the half-power bandwidth of the peak is less than 10% of the center frequency. A tabular format is utilized to specify the criteria in terms of power spectral density ( $g^2/Hz$ ) covering a frequency range of from 20 to 2000 Hz.

### 6.6.1 Power Spectral Density (PSD) Calculation

To be consistent with PSD data produced in the past the following technique should be used to calculate PSDs from flight and static test data. Overlapping and windowing is left up to the discretion of the analyst although overlapping is usually not necessary unless the data is extremely nonstationary. This envelope should be the basis for calculation of the MPE.

1. Determine areas where the data are reasonably stationary.
2. Calculate multiple PSDs over a reasonably stationary time using sequential periods totaling one second. Use an approximately 5 Hz bandwidth.
3. Calculate the average of the PSDs within the one second period.
4. Over the period of interest calculate the envelope of the one second averages.

The use of a maxi-max technique for the entire flight time is discouraged for vibroacoustic data because it tends to result in unreasonably conservative test criteria. A more reasonable technique is to establish separate criteria for different flight regimes as discussed previously in section 5.

### 6.6.2 Acoustically Induced Random Vibration Criteria

The acoustically induced random vibration criteria are the envelope of the maximum vibration environment resulting from the engine generated and aerodynamic fluctuating pressure

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environment. The development of these random vibration environments were discussed in section 5.2. In presenting the criteria, the space vehicle and payload are divided into major structural zones, such as aft skirt, forward skirt, nose cone, payload rack, etc. Each of these major zones is further divided into subzones based on local structural configuration, such as ring-frames, stringers, coldplates, etc. The subzones are further broken down based on component weight ranges and component population. In special cases random vibration criteria are formulated for specific components.

### 6.6.3 Mechanically Induced Random Vibration Criteria

The mechanically induced random vibration criteria are the envelope of the maximum vibration environment produced by the combustion processes during liquid engine/solid motor burn and the rotating turbomachinery for the case of liquid engines. A zonal technique similar to the one for acoustically induced random vibration is used in presenting the verification criteria. Since the mechanically induced random vibration are the result of the combustion processes during engine burn and the rotating turbomachinery, the environment is present as long as the engine is burning. The mechanically induced random vibration criteria duration is based on the equivalent time the environment is present at the maximum level using cumulative damage and material fatigue properties as described in section 6.5.

### 6.6.4 Payload Compartment Random Vibration Criteria

The payload component and experiment random vibration criteria are the result of the payload compartment acoustics described in section 6.5.5 impinging on the large area-to-weight structure causing it and the components attached to it to vibrate. These criteria are generally derived and presented in terms of zones and subzones based on the local structural configuration, component population, and weight range. The test duration is the same as for the payload compartment acoustic criteria discussed in section 6.5.5.

### 6.7 Transient Criteria

The transient design and test criteria are based on an envelope of the transient environment discussed in section 5.3. There are no arbitrary factors of safety applied to the transient environment. When two shock criteria are specified for a component and one shock completely envelopes others, only the maximum shock spectrum should be used for testing, however the number of shocks specified shall encompass the applicable lower level shock events.

#### 6.7.1 Low and Mid Frequency Transient Criteria

The development and discussion of the low frequency transient environment is covered in section 5.3.1. The low frequency criteria are based on an envelope of these environments for use in design and test. Verification of the experiment/component installations to the low frequency transients is generally accomplished by analysis. In some cases the verification is by laboratory test, either with a fast sinusoidal sweep or impulse testing to a shock spectrum or shock pulse of the input acceleration time history. Vehicle dynamics test criteria are intended to account for the low

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frequency acceleration environments experienced by components that are induced by the vehicle as a result of the various vehicle loading events that occur during prelaunch, liftoff, and ascent. Mid frequency criteria are usually in the form of shock spectra and shall be based on the maximum predicted environment.

### 6.7.2 High Frequency Transient Criteria

The high frequency transient environments resulting from the activation of ordnance are discussed in detail in section 5.3.2. The high frequency transient criteria shall be based on an envelope of these environments or the calculated MPE with no added factors of safety. When establishing test criteria consideration should be given to the recommendations in NASA-STD-7003. The high frequency criteria are presented as shock spectra. A tabular format is used to specify these criteria in g's peak ( $g_p$ ) amplitude as a function of frequency from 50 to 10,000 Hz. The criteria are based on scaling measured data that was analyzed using a 1/3 octave shock spectrum analyzed using 5% damping.

There is widespread agreement within the industry (Gaberson, Moening, and Luhrs) that high frequency (primarily pyrotechnic) transients with pseudo velocities below 50 inches per second are benign and do not cause failures for most aerospace hardware. It is acceptable to report that zones where the shock criteria fall below this level (or approximately 1,000  $g_p$  at 5,000 -10,000 Hz) as "N/A" and no test is required. If hardware is suspected to be vulnerable to damage from shock levels below this threshold then test criteria shall be provided.

Verification of the component installations to the high frequency transients (50 to 10,000 Hz) is accomplished in the laboratory. Analysis to establish margins of safety for these environments is not necessary and may result in overly conservative design loads.

### 6.7.3 Low and Mid Frequency Transients

The low frequency transients (0 to 50 Hz) are the result of the launch vehicle/spacecraft responding at their fundamental modes of vibration during events such as engine ignition, launch release, engine overpressure, staging, wind buffeting, on-orbit docking, landing, parachute deployment, and water impact. The low frequency vehicle transients are developed from coupled loads analyses using worst case forcing functions. The low frequency vehicle transients are specified as acceleration time histories and/or shock spectra. In the case of parachute deployment and water impact, the transient environments are verified with development tests. Final verification of the low frequency transients is accomplished by scaling the flight data to the worst case forcing functions. Since these are low frequency transients not all hardware will require test verification, depending on their size and potential response to the environment.

Mid frequency transients fall into the frequency range of 50 to 5,000 Hz and are a result of excitations that cause the vehicle secondary structures, such as ring frames or panels, to respond at their fundamental frequencies. Sources of these environments include transportation, handling, and water impact. Water impact can produce shock response levels in the hundreds of g's and is usually qualified by testing on a shaker using a shock response spectrum.

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#### 6.7.4 High Frequency Transients.

High frequency transients (50 to 10,000 Hz) result from the activation of ordnance devices which are being used extensively in the aerospace industry. They include linear shaped charges, frangible joints, explosive bolts, explosive nuts, squibs, pin pullers, and bolt cutters. They are being used to perform such functions as stage separation, shroud/nosecone separation, vehicle holddown release, payload deployment, and hatch separation to name a few. The transient environment caused by these devices covers a broad frequency range. These high frequency transients can cause damage and failure to equipment as well as structure (see “Shock Severity Estimation”, “Views of the World of Pyrotechnic Shock”, and “Designing Electronics for Pyrotechnic Shock” for more information). The state of the art of this technology for predicting the high frequency transients is limited to scaling the measured test data. For a given development test program, the acceleration time histories of a number of locations are measured and recorded during the event. Since the signature of the transient acceleration time histories are quite complex, due to the nature of the shock, the frequency content is not readily detectable. To obtain the frequency information, a spectral analysis is performed to produce a shock response spectrum which is the basic method for specifying ordnance shock environments. A shock response spectrum is a plot of the maximum acceleration response of a series of single degree of freedom systems (50 to 10,000 Hz) resulting from the application of the acceleration time history to its base.

The magnitude of the shock spectrum is a function of the size of the explosive charge used, the thickness of the material cut, and the distance from the source of the explosion. Generally, the shock spectrum environment is specified at the source (0 to 12 inches from device) with attenuation curves for attenuating the shock through various structures and joints at other locations. Initial predictions of the shock environment are based on scaling measured data from similar pyrotechnic devices used on previous programs, such as those contained in NASA CR-116437, “Aerospace Systems Pyrotechnic Shock Data - Ground Test and Flight”. Final verification can be accomplished by activating the device with a full-scale structural test article.

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## **7. VIBRATION AND SHOCK QUALIFICATION TEST REQUIREMENTS AND PROCEDURES**

Ensuring that space vehicle components and experiments are adequately designed to withstand the vibroacoustic and transient criteria described in section 6 requires the selection of appropriate verification methods. Characteristics of both the hardware and the environments affect the verification method. The primary methods of verification are laboratory, analytical, and verification by similarity. When the verification is accomplished in the laboratory, it may be prototype or protoflight, depending on program objectives. Protoflight hardware is that which will be qualified and flown, without a dedicated qualification test article. Also, it is necessary to distinguish between design development, qualification, and acceptance testing, and when and where each is used. Analytical verification and verification by similarity need to be discussed between the analysis, design, and projects elements as to their applicability.

Components requiring laboratory verification for the vibroacoustic and transient environment are generally complex functional components consisting of parts intricately combined and difficult or impossible to analyze structurally, such as electronic and electromechanical components. Laboratory tests designed to simulate the vibroacoustic and transient criteria include random vibration, sinusoidal vibration, and shock. These tests will be discussed in detail in sections 7.2, 7.3, and 7.4.

All instruments and test equipment used in conducting the tests in this document should be calibrated per MPR 8730.5 or the appropriate contract requirement and calibration shall be maintained until test conclusion. Calibration information shall be included in the test report per paragraph 7.9.

The requirements in this section apply only to flight and qualification hardware qualification and acceptance tests. All other test programs may use these requirements as guidelines.

### **7.1 General Vibration and Shock Testing Requirements**

#### **7.1.1 Specimen**

The specimens shall be production components in accordance with current manufacturing drawings. Supporting brackets and component attachment hardware (lines, valves, etc.) up to the first attachment point, shall be included in all tests to achieve dynamic similarity to actual installation. Hardware so included in the test setup is considered part of the test specimen. If the actual attached hardware is not available for the test then reasonable facsimiles that simulate the dynamic stiffness and damping of the actual hardware shall be included.

The cognizant quality organization shall verify test article pedigree and test configuration for qualification and acceptance tests performed under the criteria contained within this standard.

#### **7.1.2 Fixture**

The fixture shall support the specimen in the manner simulating actual installation. The fixture

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shall be designed to minimize fixture response at resonances within the test frequency range. The fixture design and specimen installation should be reviewed by responsible dynamics and test engineers prior to testing.

### 7.1.3 Test Specimen and Fixture Resonance Survey

Random and/or sinusoidal fixture resonance surveys shall be conducted on all test fixtures prior to utilizing the fixtures for any tests. A sinusoidal resonance survey test is recommended. These tests will also be used to determine the proper location of control accelerometers and to determine the response characteristics of the fixture to the applied vibration. The basic requirements for such surveys are:

- a. Fixture surveys shall be conducted utilizing a dummy test specimen which simulates the dimensions, mounting provisions, mass, and center of gravity of the actual test hardware, or by utilizing the actual certification test specimen. When the latter approach is utilized, random test levels shall be at least 6 dB below the qualification test levels. Sinusoidal sweep levels and rates shall not exceed the following:

5 – 62 Hz @ 0.005 inch Double Amplitude (D.A.) displacement  
62 – 2000 Hz @ 1.0 g<sub>p</sub>  
Sweep Rate = 1 octave/minute from 5 Hz to 2000 Hz to 5 Hz

- b. Fixture surveys shall be performed in all three axes.
- c. A sufficient number of accelerometers, or multiple tests, shall be utilized so that information is obtained at each significant specimen mounting point in all three orthogonal axes. Test data obtained during the fixture survey shall be retained throughout the program in the form of g vs. frequency or transmissibility plots for sinusoidal vibration and g<sup>2</sup>/Hz vs. frequency plots for random vibration. Such data shall be made available to the Office of Primary Responsibility (OPR), per the appropriate contract deliverable.
- d. Resonance surveys should also be conducted on the test specimen. An accelerometer should be mounted at the component's center of gravity or as near as possible. Sweep at 1 octave/minute from 5 Hz to 2000 Hz at 0.5 g<sub>p</sub>. If it is determined that the 0.5 g<sub>p</sub> input level will result in component damage, then lower the input to 0.25 g<sub>p</sub>.

### 7.1.4 Test Amplitude

All component test amplitudes shall be applied as inputs to the component bracket at the interface of the bracket and the test fixture. The inputs shall be applied along each of three mutually perpendicular axes as referenced to the interface of the component and the vehicle primary structure. The test procedure shall clearly indicate by sketch and/or photograph the orientation of these axes relative to the component.

Control and response accelerometers should be mounted to the fixture and test specimen by either

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studs or non-elastic cement such as dental cement, Eastman 910 cement, etc.

#### 7.1.5 Test Sequence

The preferred qualification testing order for the components is:

1. Acceptance Vibration Test (when specified)
2. Qualification/Acceptance Random Vibration Test (when specified)
3. Ascent (Boost) Random Vibration Test (when specified, instead of liftoff and boost). Ascent tests are a combination of the liftoff and boost environments.
4. Liftoff Random Vibration Test
5. Boost Random Vibration Test
6. Reentry Random Vibration Test (when specified)
7. Vehicle Dynamics Test (when specified)
8. Shock Test(s) (when specified)
  - a. Ordnance
  - b. Water Impact
  - c. Parachute Deployment
9. Acoustic Test (when specified)
  - a. Liftoff
  - b. In-Flight Fluctuating Pressure (Boost)
  - c. Reentry
10. Transportation and Handling Tests (when specified)

The resonance surveys described in section 7.1.3 above (fixture and test article) shall be performed before any other vibration tests are conducted. Acceptance testing, when required, should be completed in all three axes prior to any other qualification testing. All random vibration, vehicle dynamics, and shock testing should be completed in one axis before proceeding to the next. When shock testing is performed on separate test equipment, all vibration testing should be completed prior to shock testing. The test sequence above may be performed out of order with the approval of the OPR.

#### 7.1.6 Functional Performance

Specimens that function in the dynamic environment shall perform to their functional specifications prior to, during, and after each qualification test as defined in the component specification. All normal, alternate, redundant, and emergency operational modes shall be functioned where possible.

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## 7.2 Random Vibration Tests

The control accelerometer(s) shall be mounted on the test fixture at the point where the test specimen or specimen-supporting bracket attaches to the test fixture, unless otherwise indicated by the test fixture resonance survey. Where only one control accelerometer is used, its location shall be one which most nearly represents the average condition of all the specimen mounting points. In instances where the test specimen and/or fixture is very large and/or complex, it is recommended that the control signal input use the average of multiple control accelerometers. The number, orientation, and tentative locations of control accelerometers shall be shown by sketches and/or photographs in the component test procedure.

In addition to in-axis control accelerometers the cross-axes shall also be monitored, typically by installing tri-axial accelerometers either on the same mounting block as the in-axis accelerometer or in very close proximity. The cross-axis inputs should be compared to their respective input criteria to ensure that those criteria are not exceeded. This review should occur before the full level test so that the test article won't be damaged by excessive cross-axis excitation.

The test specimen should be instrumented with response accelerometer(s) both externally and, where technically feasible, internally. These accelerometers should be located to determine the response characteristics (frequency and amplitude) of hardware elements believed to be vibration-sensitive. The number, orientation, and tentative locations of response accelerometers, if any, shall be shown by sketches and/or photographs in the component test procedure.

When necessary to prevent unrealistic input forces or unit responses, the spectrum at the vehicle input may be limited or notched as described in paragraph 7.2.1. Notch depth during qualification tests should be limited so that the resulting levels do not go below the component's acceptance test criteria.

The vibration test tolerances in section 7.6 are abort limits. Unless otherwise approved by the OPR, when a test tolerance is exceeded the test shall be immediately aborted and the OPR notified before proceeding. Any exceedances shall be documented.

Band splitting to achieve high vibration levels for qualification and acceptance testing is not recommended; however, it may be necessary in some circumstances. The following steps should be completed before considering this test method.

1. Remove all unnecessary conservatism in the test criteria. Check to make sure that narrowband peaks have the appropriate clipping.
2. Make sure that axis specific criteria have been provided. Enveloping all axes introduces unnecessary conservatism.
3. Evaluate the test fixture to ensure that all unnecessary weight has been removed.
4. Identify the first few resonances in the test article by running a low-level random vibration or sine-sweep test. Use the resonance information to determine where the frequency breaks

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should be so that the splits occur between resonances.

5. Notify and get approval from the OPR before proceeding to a test with band splitting.

### 7.2.1 Force or Response Limiting and Notching

Vibration testing inevitably involves unnatural constraints on the state of vibration experienced in flight, particularly for large components or payloads. Most testing, for example, strives to achieve equal input motions at all attachment points for one direction of input. Another is the use of envelope spectra of flight data, bridging over spectral dips. Such constraints can lead to an excessively conservative test. Force or response limiting refers to the practice of notching (reduction of level in frequency bands) of the input acceleration spectrum to a test item to reduce either the applied force spectrum or to reduce the magnitude of the spectrum of test item response at critical locations. In both cases the reduction is in frequency bands which contain major resonant behavior of the test item. A justifiable basis for such limiting is necessary in order to avoid excessive reduction of inputs that will result in inadequate acceptance or qualification.

Force limiting requires that three-axis force transducers be positioned at each attachment point during the test and that an upper-bound net force spectrum be developed and imposed for each direction of translation, and perhaps also net moments about rotational axes. The concept is that the input motion is reduced because a relatively high mechanical impedance of the test item inhibits the motion of the supporting structure that would occur in the absence of the test item being in place, as well as the fact that test specifications are based on enveloping nulls in environmental spectra which may be due to such impedance interaction. The establishment of the limiting force spectra requires a mathematical model of the interaction and predicted or test derived impedance data. This is an evolving art and must be cautiously practiced.

Response limiting requires that positions of large response on the test item be instrumented during test and that a response limit at those positions be imposed during the test. In this way analytical or test information for the response positions can be used to limit input to the test item.

### 7.2.2 Random Vibration Test Procedure

1. Perform pre-test inspection and functional tests of test specimen as required.
2. Mount fixture and test specimen on the vibration table in the first axis, and install accelerometers.
3. Perform vibration table equalization by either of the following methods, following the best practices of the test facility:
  - a. Obtain initial equalization using actual test specimens and reduced vibration inputs. Final equalization will then be obtained by applying short duration excitation to the specimen at the specified test amplitudes. Equalization during qualification testing shall be held to the minimum required to perform a rigorous test. Full-level equalization runs which are proven to be within tolerance, or out of tolerance on the positive side, shall be

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considered part of the specified test time for that axis. Equalization runs which are out of tolerance on the negative side shall not be considered part of the specified test time.

- b. Subject a mass-simulated dummy component to the specified test inputs. After equalization, replace the dummy component with the actual component, and verify equalization by applying short duration excitation at the specified test amplitudes. Test setup and equalization times should be minimized. Neither of these time durations shall be considered part of the specified test duration.
4. Perform the ascent or liftoff vibration test, with the component in an operational mode if required by section 7.1.6 above. Record all control accelerometer inputs and response accelerometer outputs.
5. Repeat steps 3 and 4 for boost (if applicable) and reentry (if applicable) in the same axis, with the component in an operational mode if required by section 7.1.6 above.
6. Perform vehicle dynamics test as described in section 7.3 below.
7. Perform any shock tests in this axis capable of being produced by the vibration table.
8. Repeat steps 3 through 7 with the test specimen mounted in each of the remaining two axes.
9. Inspect the test specimen and perform post-vibration functional tests as required.

### 7.3 Transient (Shock) Tests

The low frequency transient criteria discussed in section 6.7 are generally verified by analyses. When the verification is by test it is accomplished with either an impulse or sinusoidal sweep test. When sinusoidal sweep testing is used for verification, testing is conducted in the three orthogonal axes of the component at a sweep rate that results in twice the number of mission cycles.

Verification of the high frequency transient criteria, resulting from the activation of ordnance, is always accomplished in the laboratory. The high frequency test criteria are specified as shock spectra (50 to 10,000 Hz). Testing can be accomplished by mechanical simulations or with ordnance.

#### 7.3.1 Vehicle Dynamics Test Procedure.

This procedure applies to vehicle dynamics testing using sine-sweeps. If a shock spectrum is used then use procedures in section 7.3.2.

Test amplitudes are provided in the applicable specifications. The specified frequency spectrum shall be swept logarithmically at the rate and for the duration stated in the component specification.

If sweep rates and durations are not specified then sweep logarithmically at a rate of three octaves per minute. For a single mission, sweep from the low frequency to the high frequency one time in each of the vehicle axes.

If the resonance survey described in section 7.1.3 above shows that all component resonances are

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above 100 Hz in each axis, then this test does not have to be conducted. However, if the function of the component will be affected because of this low frequency environment, then the test shall be conducted with the component operating. Isolated components shall also be tested to this environment, when specified, unless the isolated component frequencies are above 100 Hz.

### 7.3.2 Shock Test Requirements

Shock pulses or spectra are stated for each specification. Any pulse that results in a spectrum within the test tolerances at every frequency of the specified shock spectrum is acceptable. Either mechanical or ordnance shock testing is acceptable. During half-sine pulse shock testing, the test specimen shall be subjected to the specified number of shocks per mission in each axis (equivalent to one in each direction) for a total of six shocks for each shock event. When testing is conducted on a vibration shaker using a shock spectrum, the test article shall be rotated so that shocks are repeated in each axis, for a total of three shocks per shock event. During ordnance shock testing, the specimen shall be subjected to the specified number of shocks per mission, which shall satisfy the applicable specifications in at least one axis. The test fixture used for mounting the test specimen shall be structurally capable of transmitting the required shock levels to the test specimen attach points. Data provided to show compliance shall include shock response spectra (Q=10) and time histories of each accelerometer output. Pseudo velocity spectra should also be provided if possible.

### 7.3.3 Test Instrumentation

High frequency, high-intensity accelerometers shall be used to measure the input shock pulse and the component response. These accelerometers shall be used in a system having a flat frequency response from 50 Hz to 15 KHz within  $\pm 1$  decibels (dB). Equipment required for recording the shock data for analyses shall have a flat frequency response to 15 KHz. The data collection equipment shall use anti-alias filtering and details of the filtering shall be documented in the test report. Compliance with the test specification shall be determined by the absolute maxi-max response (an envelope of the positive and negative shock spectra), as determined by shock spectrum analysis. This analysis shall be conducted at 1/3 octave center frequencies using 5% damping.

### 7.3.4 Shock Test Procedure

1. Perform pre-test inspection and functional tests of test specimen as required.
2. Mount the test fixture to the shock machine in the first axis. Utilize a dummy mass simulating the component weight to calibrate the vibration exciter or shock machine for conformance with the specified shock spectrum. The center of gravity and the mounting provisions of the dummy mass shall approximate those of the actual test specimen. Accelerometers used to monitor the input shock to the dummy (or test specimen) shall be mounted on the test fixture as close as possible to a test specimen mounting point without touching the specimen.
3. Replace the dummy mass with the test specimen. Apply the specified number of shocks.

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Record the input and any response shock pulses and perform a shock spectrum analysis to ensure that the input pulse conforms to the required shock spectrum.

4. For ordnance-produced shocks, no further shock tests are required. For vibration shaker or other mechanical-based shocks, repeat steps 2 and 3 with the test specimen mounted in each of the remaining two axes. Sine shock tests shall orient the specimen to be tested facing the positive and negative directions of each axis as well.
5. Inspect the test specimen and perform post-shock functional tests as required.

#### 7.4 Acoustic Test Requirements and Procedures.

##### 7.4.1 General Requirements

Aerospace hardware requiring acoustic testing for vibroacoustic verification are large area-to-weight structures, such as skin panels, that respond significantly to the direct impingement of the acoustic environment. Components requiring both vibration and acoustic testing are components that are mounted with vibration isolators and components consisting of piece parts that are highly resonant above 2,000 Hz. Vibration isolators attenuate the high frequency mechanical vibration below the level resulting from direct acoustic impingement. Also, many electronic black boxes have micro structural elements that are resonant above 2,000 Hz which is generally the limitation of most large electrodynamic shakers. Acoustic testing can be conducted in the frequency range from 5 to 10,000 Hz.

All structures and components requiring acoustic testing shall be subjected to either broadband reverberant field or progressive wave testing. The acoustical random noise source for either type shall have an approximate normal amplitude distribution. Reverberant field testing is preferred for both structures and components. However, structural panels as well as components may be tested using progressive wave facilities where this type of test is justified.

##### 7.4.2 Reverberation Chamber Facilities

The test chamber shall be of sufficient volume and dimensions to ensure that the insertion of test specimen will not affect the generation and maintenance of a broadband diffuse sound field above 50 Hz. Normally, the test specimen shall be suspended in the center of the test chamber with soft suspension cords. The suspension system shall have a fundamental frequency of less than 25 Hz.

The sound field in the proximity of each major surface of any test specimen that will be subjected to external acoustic environments may be determined by either flush mounted microphones or microphones mounted approximately 0.25 inches from the specimen surface. At least three microphones located in the field shall serve as control measurements. Locate a microphone in proximity to each major different face of the test item at a distance of 18 inches from the face, or midway between the center of the face and the chamber wall, whichever is smaller. Average the outputs from these microphones to provide a single control signal.

With the specimen in the test chamber, the liftoff sound pressure level spectrum shall be shaped

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first, at a level approximately 6 dB less than the specification. The time required to shape the spectrum shall be minimized to avoid possible fatigue of the test specimen. After completion of the spectrum shaping, the sound pressure level shall be increased to the specified value, and the test will commence. As an alternative to reducing the sound pressure level while shaping the spectrum, a dummy specimen may be positioned in the test chamber, and the spectrum shaped at the test level. Upon completion of the spectrum shaping, replace the dummy specimen with the test specimen, and commence the test at the required levels. Apply power to the component and function the test specimen if it is required to operate during this portion of flight. Repeat this procedure for the in-flight fluctuating pressure and reentry levels. After completion of acoustic testing, perform functional tests and inspect the specimen as required.

#### 7.4.3 Progressive Wave Facilities

The structural panel specimens may be tested in progressive wave facilities. The test specimen shall be centrally mounted in the wall of the progressive wave duct. The width of the wave duct shall be of sufficient distance to ensure minimum effects on the panel response characteristics.

Components may be tested in progressive wave facilities. The specimen shall be centrally located in the progressive wave duct and suspended by a system having a fundamental frequency of less than 25 Hz. The cross section of the progressive wave duct shall be of sufficient area, relative to the frontal area of the test specimen, to ensure that the insertion of the test specimen will not affect the generation and maintenance of the progressive wave. The test specimen shall have each major surface exposed to the sound field by orienting each major surface parallel to the progressive wave front. Each major surface shall be exposed to the sound field for the full test duration.

For progressive wave testing, the liftoff sound pressure level spectrum shall be shaped first, without the test specimen in place. The uniformity of the sound field shall be determined by locating at least three microphones in the proximity of the duct cross sectional plane where the test specimen will be mounted. After mounting the test specimen, the sound pressure level shall be reestablished, and the test will commence. Alternatively, for structural panel specimens, the sound pressure level may be shaped at a level 6 dB less than the specification. The time required to shape the spectrum shall be minimized to avoid inadvertent fatigue. Upon completion of the spectrum shaping, apply power to the component and function the test specimen if it is required to operate during this portion of flight. Repeat this procedure for the in-flight fluctuating pressure and reentry levels if required. After completion of acoustic testing, perform functional tests and inspect the specimen as required.

#### 7.4.4 Tolerances

Tolerances are as specified in section 7.6. The sound pressure level tolerance applies to the frequency range of 50 through 10,000 Hz. Below this frequency range, the capability of the testing facility shall be the governing factor.

#### 7.4.5 Acoustic Test Procedure

1. Perform pre-test inspection and functional tests of test specimen as required.

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2. Following section 7.4.2 or 7.4.3 above (depending on the type of test facility), prepare the test chamber and mount the test specimen inside. Install microphones and any accelerometers required.
3. Shape the sound pressure level spectrum using the methods described in section 7.4.2 or 7.4.3 above, following the best practices of the test facility. Test setup and shaping times should be minimized. Neither of these time durations shall be considered part of the specified test duration.
4. Perform the liftoff (or ascent, as required) acoustic test, with the component in an operational mode if required by section 7.4.2 above. Record all control inputs and response accelerometer outputs.
5. Repeat steps 3 and 4 for in-flight fluctuating pressure and reentry levels, with the component in an operational mode if required by section 7.4.2 above.
6. If a progressive wave facility is used, repeat steps 2 through 5 for each of the remaining major surfaces of the test component following section 7.4.3 above.
7. Inspect the test specimen and perform post-vibration functional tests as required.

#### 7.4.6 Acoustic Test Reports

Test reports shall include the following information:

1. Photographs of the test setup showing instrumentation locations, suspension system, etc.
2. Spectral plots of all microphone measurements for the test runs.
3. Spectral plots of the instrumentation transducers for the test run.
4. All functional test data taken before, during, and after the test.
5. A summary showing the total time the test item was subjected to each different sound pressure level, including all spectrum shaping times at 6 db down and at full levels.

#### 7.5 Combined Environments

Vibration, shock, and acoustic testing under various combined environments will be specified when required, by the current design activity.

#### 7.6 Test Tolerances

The test spectra shall be verified by narrow band spectral analysis. See section 6.3 for further discussion of qualification and acceptance test tolerances. Tolerances considered acceptable are as follows:

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Vibration

Composite Root Mean Square Acceleration.....	±10%
Acceleration Spectral Density.....	+3 dB, -1.5 dB
(Tolerances pertain to bandwidths of 25 Hz or less)	
Sinusoidal Peak Acceleration .....	+20%, -10%
Sinusoidal Control Signal Maximum Harmonic Distortion .....	±10%
Frequency.....	±5%
Test duration .....	+10%, -0%
Acceptance Tests .....	See section 6.3

Shock Spectrum

Spectrum Peak Acceleration.....	+6 dB, -3 dB
(When analyzed with a 1/3 octave shock spectrum analyzer and 5% damping)	

Shock Pulse

Amplitude .....	+40% -20%
Duration .....	±10%
Pulse Overshoot (Half-sine testing).....	+20%

Acoustic

Individual 1/3 Octave Bands.....	±2 dB
(50 – 10,000 Hz)	
Overall Sound Pressure Level.....	±2 dB
Test duration .....	+10%, -0%

7.7 Failure Determination

A specimen shall be considered to have failed a particular test if the specimen malfunctions during or after the test, if posttest prescribed inspection reveals structural damage, or any other failure criteria documented in the test plan/procedure. All test failures shall be reported immediately to the current design activity.

7.8 Deviations from Specifications

Deviations from these specifications may be obtained only from the OPR. All deviations shall be stated in the test report.

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## 7.9 Test Reports

A report shall be submitted to the current design activity by the testing agency describing in detail the tests performed and the results of the tests. The report shall include drawings, sketches, and photographs showing in detail all measurement locations. The report shall include all calibration and measured test levels and any other information pertinent to the acquisition, reduction, analysis, and interpretation of the test data. Equalization levels and durations shall be included. Progress reports shall be provided to the current design activity as requested.

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## 8. DESIGN LOADS METHODOLOGY

Launch vehicle/payload hardware must be designed and built to withstand the exposure to various environments during fabrication, transportation, integration, launch, reentry, and landing. These environments include static, dynamic, thermal, electrical, corrosive, etc. The principal topic herein is the MSFC approach in designing experiment/components for the dynamic environment.

There are three basic dynamic environments which generate loads on the component hardware at various time points during launch, ascent, reentry, and landing: (1) The high frequency acoustic pressure environment resulting from the engine generated noise during static firing and liftoff and the in-flight fluctuating pressure environment during the transonic and supersonic periods of ascent and reentry; (2) the high frequency (20 to 2000 Hz) random vibration environments both mechanically and acoustically induced; and (3) the low and mid frequency (0 to 50 Hz) vehicle transients described in section 5.3. The remainder of this discussion will focus on the development of the low and high frequency load factors and the combination of these load factors for design assessment.

### 8.1 Acoustic and Fluctuating Pressure Loads

A primary design consideration for light gage skin panels and other large area-to-weight structures is the acoustic environment described in section 5.1. Panel response to acoustics is dependent upon the normal modes of the panel, the acoustic pressure spectrum acting on the panel, the spatial correlation of the acoustic spectrum over the panel, and the panel damping. The response of a linear system to random excitation can be expressed as

$$S_x(\omega) = |H(\omega)|^2 S_p(\omega) \quad (1)$$

where  $S_x(\omega)$  is the power spectrum of the response,  $S_p(\omega)$  is the power spectrum of the input, and  $H(\omega)$  is the complex frequency response. The Fourier transform is

$$R_x(\tau) = \frac{1}{2\pi} \int_0^\infty |H(\omega)|^2 S_p(\omega) e^{i\omega\tau} d\omega \quad (2)$$

The mean square is

$$\bar{X}^2 = R_x(0) = \frac{1}{2\pi} \int_0^\infty |H(\omega)|^2 S_p(\omega) d\omega \quad (3)$$

The mean-square response of a single-degree-of-freedom system to "white noise" is then

$$\bar{X}_p^2 = \frac{\pi}{2} Q f_n S_p \quad (4)$$

This equation, sometimes referred to as Miles' relationship, is used to calculate equivalent static pressures and random vibration load factors (to be discussed in section 8.2).

Although this relationship assumes a linear single-degree-of-freedom system with infinitely wide

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band excitation, it provides a good approximation for the mean-square response of a lightly damped system. Equivalent static pressures for specific panels are determined from this relationship as follows:

1. The fundamental panel resonant frequency ( $f_n$ ) is determined.
2. The magnification factor  $Q$  is determined from experience with similar structures or from development test data when available. In lieu of obtaining acceptable test data, a  $Q$  of 25 (2% damping) should be used.
3. The PSD ( $S_p$ ) input at resonance is determined from the published acoustic criteria for the panel location.

The probability density function of the enveloped peaks of the response of a single-degree-of-freedom system excited by white noise has a Rayleigh distribution. The three sigma peaks for a Rayleigh distribution have a probability level (PL) of 99%. The RMS level (the square root of the mean square) from Miles' relationship is multiplied by three to determine the limit equivalent static pressure. This assumes the panel fundamental mode shape is the same as the deflected shape for a uniform pressure and the spatial correlation of the acoustic pressure field over the panel is uniform.

The mean-square stress in the panel can be determined by multiplying the mean-square response by the square of the maximum stress in the panel under a unit pressure. Given the mean square stress, the natural frequency of the panel, the exposure time of the acoustic environment, the probability distribution of the response (Rayleigh), and the panel material fatigue properties, fatigue life estimates can be made. The effect of randomly varying stresses on fatigue life is not fully understood, but a first approximation can be made by using Miner's "cumulative damage hypothesis."

$$D_m = \sum \frac{n_x}{N_x} = 1.0 \text{ at failure} \quad (5)$$

where

$D_m$  = cumulative damage

$n_x$  = applied cycles at a given stress level

$N_x$  = allowable cycles to failure at a given stress level from the appropriate material fatigue curve.

## 8.2 Random Vibration Loads

Designing experiments and components to the random vibration environment described in section 5 requires analytical estimates of the component response loading to the random vibration excitation. The procedure for computing the component response loads is similar to that for determining panel response to acoustics described in section 8.1. An estimate of the component response requires knowledge of the components fundamental frequency in each of the three orthogonal axes, damping

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(a Q of 10 is often assumed for avionics components until more information is acquired), and the random vibration input power spectrum. Miles' relationship is then:

$$\bar{X}_g^2 = \frac{\pi}{2} Q f_n S_g \quad (6)$$

where

- $\bar{X}_g^2$  = mean square response ( $g_{rms}^2$ )
- Q = dynamic amplification factor at  $f_n$  (dimensionless)
- $F_n$  = component fundamental frequency (Hz)
- $S_g$  = input power spectrum ( $g_{rms}^2$ )/Hz

The RMS level (the square root of the mean square) from Miles' relationship is multiplied by three to determine the limit random load. Knowing the mean square response, fundamental frequency, time of exposure to the random vibration, and assuming a Rayleigh probability distribution for the response, the fatigue assessment can be performed using Miner's cumulative damage theorem as described in section 8.1. TABLE II below can be used to assign the number of cycles to be applied for varying multiples of standard deviation ( $\sigma$ ).

**TABLE II. Rayleigh distribution**

Level	Number of Cycles per Mission
1 x $g_{rms}$	0.39 x total cycles
2 x $g_{rms}$	0.47 x total cycles
3 x $g_{rms}$	0.14 x total cycles

### 8.3 Transient Loads

The experiment/component quasi-static load factors resulting from the low frequency vehicle transient environments discussed in section 5.3.1 are determined from coupled dynamic response analyses of the launch vehicle/payload. Structural dynamic math models of the launch vehicle/payload structure are developed, coupled, and excited with the appropriate forcing functions as described in section 5.3.1. The maximum low frequency (0 to 50 Hz) dynamic response of the launch vehicle/payload is generally obtained during the liftoff and landing transient events. Since several parameters are utilized to establish the forcing functions, coupled loads analyses are required for various combinations of these parameters in order to establish the maximum dynamic responses. However, coupled loads analyses cannot be conducted for all the possible forcing function cases, therefore, a somewhat conservative approach must be used for establishing the experiment/component quasi-static load factors.

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A minimum natural frequency requirement is generally imposed on the experiment/component installations in order to minimize excessive loads caused by dynamic coupling with the launch vehicle forcing functions.

High frequency transients are verified by laboratory tests and since displacements of the component on its mounting structure are low, design loads for these environments are not specified. Mid frequency shocks may produce significant loads on components so design loads may be specified using either the forcing function approach described above or the shock response spectrum. The sensitivity of the component structure to these shocks must be carefully considered before specifying these design loads, as they may be significant design drivers.

#### 8.4 Dynamic Load Combination

In order to perform structural analyses on the experiment/component installations, the low frequency quasi-static load factors must be combined with the high frequency vibroacoustic load factors in some manner. There is considerable variation of practice in the aerospace industry in the development and combination of loads for design and testing of space vehicle components and experiments. This variation in practice is caused by the lack of a consistent and rational approach for combining the low frequency quasi-static and transient load factors with the high frequency vibroacoustic load to establish realistic component design loads. For example, because of the various combinations of input forcing functions for liftoff transient response analyses (variations in winds, thrust rise-rates, mismatch, misalignment, etc.), a large collection of time-varying low frequency response-induced loads can be determined for any given component. In addition, the high frequency random vibration induced loads are statistical in nature as described in sections 8.1 and 8.2. Therefore, determining combined loads from a large set of time varying and statistical data is usually based upon judgment.

The MSFC recommended method for combining the quasi-static and transient loads with the vibroacoustic loads is as follows:

For each axis, the vibroacoustic limit load in that axis is added to the corresponding quasi-static load, and the resulting sum in that axis is combined with the quasi-static load in the remaining two axes simultaneously. This results in three sets of load cases to be considered for structural analysis as shown below.

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Axis	Quasi-Static and Transient Load (Limit)	Random Load (Limit)
$V_1$	$\pm S_1$	$\pm R_1$
$V_2$	$\pm S_2$	$\pm R_2$
$V_3$	$\pm S_3$	$\pm R_3$

### Combined Loads

Load in Each Axis Acting Simultaneously

Load Set	$V_1$ Axis	$V_2$ Axis	$V_3$ Axis
1	$\pm(S_1+R_1)$	$\pm S_2$	$\pm S_3$
2	$\pm S_1$	$\pm(S_2+R_2)$	$\pm S_3$
3	$\pm S_1$	$\pm S_2$	$\pm(S_3+R_3)$

## **9. SUMMARY AND CONCLUSIONS**

The design and verification guidelines for vibroacoustic and transient environments presented herein represent the approach that MSFC has been using successfully for most of its existence. Although most of the methods are inherent to the vibroacoustics community, there are some significant differences compared to other government agencies and industry. The design and verification criteria represent the maximum expected environment without adding arbitrary margins. Many government agencies and industry add margins of 3 to 6 dB on the maximum expected environment in specifying the criteria. MSFC believes this added margin is unwarranted and costly, based on their extensive vibroacoustic and transient database and the inherent conservatism associated with the verification program. In support of this policy, MSFC has more than 40 years of success without a known component vibroacoustic failure during flight using the method described herein.

As stated in the introduction, this document provides general guidelines and requirements for the application of the vibroacoustic and transient technology in the design and verification of MSFC managed flight hardware. It is intended to be used by MSFC program management and their contractors. The earlier in the program these guidelines and requirements are recognized and

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utilized by the program office and their contractors the more cost effective the implementation will be and the less chance that critical design areas will be overlooked.

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## APPENDIX A

### A.1. VIBROACOUSTIC MODELS

Finite Element (FE) structural models are recommended for addressing vibration response in the lower frequency bands where modal density is sparse and where boundary conditions play a large role. They are also well suited for assessing the addition of equipment to a vehicle primary structure zone. FE structure is very useful if:

1. The equipment cg for the added equipment is off-set from the interface attach points securing it to primary structure.
2. The interface locations that assemble the subsystem to the vehicle are somewhat compliant compared to the size of interface forces induced by inertial response of fundamental modes of the secondary component installation.

Suitability of FE structural models can be limited by several factors in the mid-to-high frequency range:

1. Inadequate Mesh Density. A useful rule of thumb is 6 elements per structural wavelength.
2. Over use of lumped mass and MPCs to represent elastic MDOF subsystems. The real design of subsystems systems represented by lump mass and MPC attachment should be independently assessed to determine at what frequency they begin to demonstrate constrained elastic modes.
  - a. Above the frequency where these modes begin to occur apparent mass would diminish the interface force reactions at interface connection points.
  - b. The FE simulated vibration response will deviate from the true response if the simulation cannot represent diminishing apparent mass at the interface.
  - c. A more suitable FE model or another approach is recommended beyond the frequency where the subsystem has been over simplified.

It is important to note that SEA structure interfacing with FE though hybrid connections is not recommended as a boundary condition for low frequency band FE structural assessments. The boundary conditions should be applied to FE structure in a more deterministic fashion.

Hybrid structural models address vibration response in the mid frequency bands. They are not appropriate for developing response estimates in the lower frequency bands where the modes per band become sparse and the boundary conditions are more important. When modes are sparse, the assumption that each and every mode stores energy in a way that can be considered equally distributed is very poor. For this reason hybrid models that couple FEA and SEA subsystems are better suited to extending the model estimates into the mid- frequency range. Hybrid structural

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models can increase efficiency of response solutions and serve to bridge the gap between the frequency bands where the FE structure model was most appropriate and the bands where SEA may provide the best approach for approximation of vibration response. Flexural damping spectra obtained from NASA-SP-8050 and recent vibroacoustic work has led to the following recommendations. These are not meant to be prescriptive, but instead to recommend what has worked well for a number of rib-stiffened metallic panel test cases. These panels have been instrumented and test measurements compared to modeling predictions. Typically a system damping schedule (spectrum) will be specified when vibroacoustics estimates are produced using frequency response analyses from models. Measured response trends show that damping is greater for more complex assemblies. For instance, the addition of bolted joints and/or cable harnesses to an assembly contributes more mechanisms for energy losses to the system. For typical launch vehicle assemblies the critical damping ratio will be greater at low frequency (perhaps 3-4 % of critical at frequencies below 300 Hz) and will roll off in the mid frequencies so that the values above 1000 Hz are very low (perhaps 0.5% of critical or lower). Damping in the lower frequencies is also higher because the modal participation results in more of the component weight forcing the joints to rub against each other, increasing the frictional losses.

The damping spectra shown in Table III are the flexural damping loss factors (DLF) and the critical damping ratios (CDR). The number of slip-stick friction sources is a parameter that can assist in estimating the amount of damping and the break points. When no bolted connections are present, lower values of damping are expected at low frequency. Engineering judgment will play a part in the selection of a damping spectrum chosen for a given application. When in-plane damping spectra are needed for SEA modeling, a spectrum that is one-third of the flexural damping loss factor is recommended.

**TABLE III. Recommended flexural damping levels for vibroacoustic models**

Frequency	Bare panel		With bolt-on equipment		With bolt-on equipment and blankets	
	CDR	DLF	CDR	DLF	CDR	DLF
0 to <300 Hz	0.01	0.02	0.04	0.08	0.057	0.113
≥300 to <1,000 Hz	0.01	0.02	0.01	0.02	0.014	0.028
≥1,000 Hz to 3,000 Hz	0.005	0.01	0.005	0.01	0.007	0.014

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The model output locations will be documented consistent to the component specification documentation. The subsystem names should have an identifier so that the environments in the specifications can easily be traced to the model. Relevant SEA subsystem response should be recovered in bands no greater than 1/3 octave band up to 2,000 Hz for vibration environments and up to 10,000 Hz for cavity sound pressure levels when SEA models are used. When hybrid FE SEA models are used, the upper frequency limit will be based on the time available and the quality and amount of good flight or ground test data already in hand.

Model outputs must be specified to indicate whether they are average response (i.e., both frequency band and spatial averages if SEA) or other type of response. If an alternative is used, the estimated frequency band where results are considered suitable must be provided. When SEA structural predictions are used, the spatial average will be converted to a maximum predicted environment before use in design and testing work.

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