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DESIGN AND VERIFICATION GUIDELINES FOR VIBROACOUSTIC AND TRANSIENT ENVIRONMENTS

Component Analysis Branch
Systems Dynamics Laboratory
Science and Engineering

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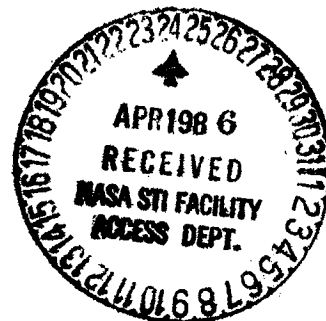
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16. ABSTRACT Design and verification guidelines for vibroacoustic and transient environments contain many basic methods that are common throughout the aerospace industry. However, there are some significant differences in methodology between NASA/MSFC and others - both government agencies and contractors. The purpose of this document is to provide the general guidelines used by the Component Analysis Branch, ED23, at MSFC, for the application of the vibroacoustic and transient technology to all launch vehicle and payload components and experiments managed by NASA/MSFC. This document is intended as a tool to be utilized by the MSFC program management and their contractors as a guide for the design and verification of flight hardware.					
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TECHNICAL MEMORANDUM

DESIGN AND VERIFICATION GUIDELINES FOR VIBROACOUSTIC AND TRANSIENT ENVIRONMENTS

I. INTRODUCTION

A. Purpose

MSFC experience has indicated a need for uniform vibroacoustic and transient criteria for the design and verification of space vehicle components and payloads. Accordingly this document has been assembled to serve this purpose. The document provides general guidelines, as specified by the Component Analysis Branch, MSFC/ED23, for the application of the vibroacoustic and transient technology 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 as a guide for the design and verification of flight hardware. 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.

B. Scope

This document presents in total the development and application of the vibroacoustic and transient design and verification criteria for MSFC-managed launch vehicle and payload hardware. Included herein are the following:

- 1) Environment definition
- 2) Design and verification criteria
- 3) Design loads methodology
- 4) Verification methods
- 5) Transportation and handling criteria.

C. MSFC Approach/Experience Base

The MSFC approach presented in this report is based on 25 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 SRB, ET, and SSME elements of the Space Shuttle. The payload programs include the Skylab; HEAO A, B, and C; Spacelab; 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 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.

D. Program Considerations and Policy

The program manager determines whether the vibroacoustic verification will be conducted with prototype or protoflight hardware. The verification program for launch vehicle hardware is always prototype, whereas for payloads it can be either prototype or protoflight depending on the number of reuses, criticality, and funding. MSFC places strong emphasis on laboratory vibration testing at the component level as the primary method of verification.

In general, the component vibroacoustic and transient design and verification criteria will be developed by MSFC/ED23 (Component Analysis Branch). When the contractor formulates the criteria, they will use MSFC/ED23 methodology. A detailed discussion concerning this methodology is included in the Design Criteria and Verification sections of this document.

MSFC/ED23 will actively participate in all phases of MSFC-managed programs to insure that adequate vibroacoustic and transient design and verification have been utilized. This will include participation at the following formal reviews.

- 1) Preliminary Requirements Review
- 2) Preliminary Design Review
- 3) Critical Design Review
- 4) Flight Readiness Review.

The vibroacoustic and transient design and verification guidelines presented in this document are intended to serve as an aid to MSFC management and their contractors. Where these guidelines conflict with information presented in a specific program document the latter will take precedent.

II. ENVIRONMENT DEFINITION

The unique reusable capability for today's launch vehicles and payloads results in more stringent vibroacoustic and transient design requirements on systems and components than are needed for expendable space vehicles. The added reentry environments and fatigue 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.

A. Acoustic Environment

The definition of the acoustic environment for this text 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 lift off and the aerodynamically generated acoustics during the transonic periods of ascent and reentry flight.

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 percent 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 lift off 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 III, paragraph A.

2. Aerodynamically Generated Acoustics

Aerodynamically 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 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 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.

3. Payload Compartment Acoustics

The acoustic environment internal to the payload compartment is the direct result of the external acoustic field impinging on the payload bay walls whether it be the engine generated noise or the aerodynamic fluctuating pressure environment.

The payload compartment internal acoustic environment is a function of the external acoustics, noise reduction or attenuation through the cargo bay walls, volume of the unfilled compartment, and the acoustic absorption of the cargo bay walls and external surfaces of the payload. The payload compartment internal acoustics impinge directly on the payload large area-to-weight structure producing the primary source of random vibration for payload components. Preliminary predictions of the payload compartment acoustic environment are based on noise reduction data banks from previous programs and analytical estimates of the payload and inner cargo bay wall acoustic absorption. These predictions are generally verified by full-scale reverberation field testing during the development phase of the program.

B. 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.

1. Acoustically Induced Random Vibration

Acoustically induced random vibration is the result of the engine or aerodynamically generated acoustics (as described in Section II, paragraph A) 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 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 acting on a particular structural configuration. These data banks were developed from the large amount of vibration and acoustic measurements taken during static firings and flights of previous launch vehicles (Saturn, Titan, Skylab, Space Shuttle, etc.) and from the Mobile Acoustic Research Laboratory (MARL) testing program. The MARL is a 40-ft platform on wheels. Various large flight and development structures, such as instrument units, skirts, and interstages, were installed on the MARL and located in the acoustic near- and mid-fields and subjected to static firings of the various Saturn stages and engines at MSFC and NSTL. The MARL test structures were instrumented and vibration and acoustic data were recorded during the static firings.

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 levels for varying weight ranges are then determined from conventional mass attenuation techniques.

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 C.G. simulations of the components.

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 solids and the physical engine for the liquids. Beyond these boundaries, the random vibration attenuates rapidly.

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 Space Shuttle Main Engine (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.

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 III, paragraph B.

C. 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 time duration (generally less than 5 sec) with a time varying amplitude. The transient environments can be classified as either low frequency (0 to 50 Hz) or high frequency (50 to 10,000 Hz).

1. Low 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, 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 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.

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, 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. 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 in. from device) with attenuation curves for attenuating the shock at other locations. Initial predictions of the shock environment are based on scaling measured data from similar pyrotechnic devices used on previous programs. Final verification can be accomplished by activating the device with a full scale structural test article.

III. DESIGN AND VERIFICATION CRITERIA

Section II described the development of the vibroacoustic and transient environment. 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 is used for design and verification of space vehicle components and experiments it includes the time the environment is present.

A. 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 time associated with the criteria is 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 times a fatigue scatter factor of 4). A tabular format is used to specify the criteria spectrum based on one-third octave bands covering a frequency range of 5 to 10,000 Hz. The specified criteria and verification durations must be conformed to unless it is established that the item is not susceptible to acoustic noise.

1. Engine-Generated Acoustic Criteria

The engine-generated acoustic criteria is defined as the maximum environment described in Section II-A-1 for a particular location on the space vehicle. The space vehicle is divided into criteria zones. These criteria zones 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 paragraph A of this section.

2. 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 represents 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 paragraph A.

3. Payload Compartment Acoustic Criteria

The acoustic design and verification criteria for payloads and payload components represents an envelope of the maximum internal acoustic environments that occur during lift-off and ascent flight. The criteria durations for design and verification are determined as described in paragraph A. Sometimes the lift-off and ascent criteria are combined by enveloping to provide a single criteria spectrum for simplicity. This is the case for the Space Shuttle cargo bay. The prototype test duration for space shuttle payload components/experiments is 60 sec plus 30 sec per mission. At MSFC components and experiments which are susceptible to damage from acoustic excitation must be qualified to the acoustic criteria. This generally includes large area to weight structures, components having resonances 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 simulations be subjected to the acoustic criteria early in the development in order to verify the random vibration criteria before the component qualification program.

B. Random Vibration Criteria

The random vibration design and test criteria are the envelope of the maximum random vibration environment discussed in Section II-B 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. 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.

1. 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 environment. The development of these random vibration

environments were discussed in Section II-B. 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 ringframes, 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.

2. 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 paragraph A.

3. Payload Compartment Random Vibration Criteria

The payload component and experiment random vibration criteria are the result of the payload compartment acoustics described in paragraph A-3 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 paragraph A-3.

C. Transient Criteria

The transient design and test criteria are based on an envelope of the transient environment discussed in paragraph II-C. There are no arbitrary factors of safety applied to the transient environment.

1. Low Frequency Transient Criteria

The development and discussion of the low frequency transient environment is covered in paragraph II-C-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.

2. High Frequency Transient Criteria

The high frequency transient environments resulting from the activation of ordnance are discussed in detail in Section II-C-2. The high frequency transient criteria are based on an envelope of these environments with no added factors of safety. Verification of the component installations to the high frequency transients (50 to 10,000 Hz) is accomplished in the laboratory. The high frequency criteria are presented as shock spectra. A tabular format is used to specify these criteria in G-pk 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 percent damping.

IV. 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 (5 to 10,000 Hz) acoustic pressure environment resulting from the engine-generated noise during static firing and lift-off and the inflight 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 frequency (0 to 50 Hz) vehicle transients resulting from engine ignition, launch release, staging, parachute deployment, and landing. 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.

A. Acoustic Loads

A primary design consideration for light gage skin panels and other large area-to-weight structures is the acoustic environment described in Section II. 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

$$S_x(w) = |H(w)|^2 S_p(w)$$

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

$$R_x(\tau) = \frac{1}{2\pi} \int_0^{\infty} |H(w)|^2 S_P(w) e^{i w \tau} dw$$

The mean square is

$$\bar{x}^2 = R_x(0) = \frac{1}{2\pi} \int_0^{\infty} |H(w)|^2 S_P(w) dw$$

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

$$\bar{X}_P^2 = \frac{\pi}{2} Q f_n S_P$$

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

Although this relationship assumes a linear single-degree-of-freedom system with infinitely wide 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.
- 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 of 99 percent. 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."

$$D_m = \sum \frac{n_x}{N_x} = 1.0 \text{ at failure}$$

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.

B. Random Vibration Loads

Designing experiments and components to the random vibration environment described in Section II 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 paragraph A. An estimate of the component response requires knowledge of the components fundamental frequency in each of the three orthogonal axes, damping, and the random vibration input power spectrum. Miles relationship is then:

$$\bar{X}_g^2 = \frac{\pi}{2} Q f_n S_g$$

where

\bar{X}_g^2 = mean square response (Grms²)

Q = dynamic amplification factor at f_n (dimensionless)

f_n = component fundamental frequency (Hz)

S_g = input power spectrum Grms²/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 (\bar{X}_g^2), fundamental frequency (f_n), 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 paragraph A.

C. Transient Loads

The experiment/component quasi-static load factors resulting from the low frequency vehicle transient environments discussed in Section II 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 for engine ignition, launch release, staging, parachute deployment, and landing. 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.

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.

D. 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 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 paragraphs A and B. Therefore, determining combined loads from a large set of time varying and statistical data is usually based upon judgement.

The MSFC recommended method for combining the quasi-static 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.

<u>Axis</u>	<u>Quasi-Static Load (Limit)</u>	<u>Random Load (Limit)</u>
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

<u>Load Set</u>	<u>V_1 Axis</u>	<u>V_2 Axis</u>	<u>V_3 Axis</u>
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	$\pm S_1$	$\pm S_2$	$\pm (S_3 + R_3)$

V. DESIGN VERIFICATION

Ensuring that space vehicle components and experiments are adequately designed to withstand the vibroacoustic and transient criteria described in Section III 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. 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 as to their applicability.

A. Laboratory Verification

Components requiring laboratory verification for the vibroacoustic and transient environment are generally complex functional components consisting of parts intricately combined and impossible to analyze structurally, such as electronic and electromechanical components. Laboratory tests designed to simulate the vibroacoustic and transient criteria include acoustic, random vibration, sinusoidal vibration, and shock. These tests will be discussed in detail in paragraphs 2, 3, and 4.

1. Types of Verification Tests

In general, there are three classifications of laboratory verification tests associated with a typical hardware development program: development, qualification, and acceptance.

a. Development Tests — Development tests are usually performed early in the design phase to obtain the appropriate design data and to confirm the feasibility of the component design concept. Other objectives of development testing include identification of failure modes, substantiation of analytical methods, demonstration of design advantages/disadvantages, confirmation of hardware modification concepts, and investigation of hardware failures. The degree of development testing depends largely on the complexity of the component design and on the quantity of qualified parts used in the design. Component designs utilizing conventional hardware will require less development testing than state-of-the-art designs. Development tests are generally not specified contractually and are not as closely monitored by the customer as are qualification and flight acceptance tests. The hardware developer will conduct development tests on engineering models to preclude having failures during the qualification program. During development testing the selection of test conditions, test configuration, holding fixtures, and instrumentation vary with the test objectives, environments, and laboratory limitations. All engineering disciplines must achieve early agreement, maintain communication, and coordinate all test activities effectively in order to have a successful development test program.

b. Qualification Tests — Qualification tests are conducted on flight-quality components, subsystems, and systems to demonstrate that structural and functional design requirements have been achieved. The appropriate vibroacoustic and transient loading conditions are simulated during these tests and the hardware performance assessed. Functional performance (electrical and or mechanical) proceed and follow

the exposure to the test conditions. Some components must function during the time the vibroacoustic and transient environments are present. These are primarily the launch vehicle components and must be operable during the laboratory simulations for acceptable performance verification. The methodology for determining the qualification test amplitudes and durations were discussed in Section III. These test durations, are applicable if the qualification test program utilizes dedicated test hardware. This is commonly referred to as a prototype test program as opposed to a protoflight test program which uses flight hardware for verification.

In a prototype test program, the component is subjected to the maximum expected flight environment for the equivalent time the maximum level is present based on cumulative damage using typical aerospace material fatigue properties (S-N curve slope of S) times a fatigue scatter factor of 4. Testing in this manner results in a high level of confidence that, if the test hardware performs acceptably, similar items manufactured with the same quality can survive the expected service environments. Prototype qualification testing is mandatory for launch vehicle components and hardware that is safety critical.

The economics of manufacturing dedicated test hardware (prototype) for payload scientific experiments has precipitated a design verification approach called protoflight. In a protoflight verification program the flight hardware are the test hardware. The flight hardware are subjected to the maximum expected flight environment for 60 sec. If successful this insures that the dynamic stresses are below the ultimate capability of the hardware. It does not, however, provide fatigue verification since the damage fraction is unknown. Protoflight testing is generally limited to payload experiments and hardware where failure does not affect safety.

c. Acceptance Testing - Acceptance tests are conducted on the flight hardware to verify that materials, manufacturing processes, and workmanship used in the flight hardware have met the design specifications. At the component level acceptance testing is conducted with random vibration at levels that are generally 6 dB down from the qualification level. If it is necessary to conduct acceptance testing at levels higher than this, then a special test is conducted on the qualification unit to qualify the hardware for the acceptance test. System level acceptance testing is generally conducted with acoustics at a level which is 6 dB below the qualification level. Acceptance tests are generally conducted for a duration of 1 min per axis unless otherwise specified.

2. Random Vibration Test Application

Hardware verification for the vibroacoustic environment is generally accomplished by laboratory vibration and/or acoustic testing at the component, subsystem or system level. MSFC is a proponent of a strong component verification program. Most hardware can be verified for the vibroacoustic environment with laboratory random vibration testing. The random vibration criteria described in Section III-B is defined at the component bracketry/primary structure interface. Therefore, in the laboratory the random vibration is controlled at the component bracketry/test fixture interface.

Testing is conducted in the three orthogonal axes of the component for the specified criteria time. In general, successful completion of the component vibration test will qualify the hardware for flight. In some cases, component and/or system level acoustic testing is also required. Acceptable test tolerances for the random vibration testing are as follows:

Composite Root Mean Square Acceleration	± 10 percent
Acceleration Spectral Density (tolerances pertain to bandwidths of 25 Hz or less)	+ 100 percent - 30 percent
Frequency	± 5 percent
Test Duration	+ 10 percent - 0 percent

3. Acoustic Test Application

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 resonant above 2000 Hz. Vibration isolators attenuate the high frequency mechanical vibration below the level resulting from direct acoustic impingement. Also, many electronic black boxes have microstructural elements that are resonant above 2000 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.

Components/experiments requiring acoustic testing, as described above, are subjected to either broadband reverberant field or progressive wave testing. The acoustical random noise source for either method will have an approximate normal amplitude distribution. The test duration will be within +10 to -0 percent of the specified time. The overall sound pressure level and the individual 1/3 octave band sound pressure levels will be within ±2 dB of the test criteria. The sound pressure level tolerance applies to the frequency range of 50 to 10,000 Hz. Below this frequency range, the capability of the testing facility will be the governing factor.

4. Transient Test Applications

The low frequency transient criteria discussed in Section III-C are generally verified by analyses. When the verification is by test it is accomplished with either an impulse or sinusoidal sweep test. When the testing is by impulse, then two shocks per axis are required (one in each direction) for each mission. 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. When the verification is mechanical, then two shocks per axis (one in each direction) per mission are required. When ordnance is used, then one shock per mission is the requirement. Acceptable tolerances for the transient test criteria are as follows:

Sinusoidal Peak Acceleration	+ 20 percent - 10 percent
Sinusoidal Control Signal Maximum Harmonic Distortion	± 10 percent
Frequency	± 5 percent
Shock Spectrum Amplitude (when analyzed with a 1/3 octave shock spectrum analyzed and 5 percent damping)	+ 40 percent - 20 percent
Shock Pulse Duration	± 10 percent

B. Analytical Verification

The preceding paragraphs discussed laboratory verification for the vibroacoustic and transient environments. They discussed how each of the dynamic environments could be reproduced for this purpose. Although laboratory testing is necessary, it generally cannot be used to confirm the structural integrity of a component installation for the total environment. This has to be done analytically so that the loads resulting from all applicable environments can be combined and included in the structural analyses. The dynamic loads resulting from the vibroacoustic and transient environments and their combination are determined using the methodology described in Section IV.

C. Verification by Similarity

One of the most cost effective ways of verification is by similarity. This can be accomplished by using hardware that was qualified for a previous program. However, the environments and their durations from the previous program must be equal to or exceed the new program requirements. In those areas where the old requirements are lower, exceedance studies can be used to verify the hardware.

VI. TRANSPORTATION AND HANDLING CRITERIA AND PROCEDURES

The shock and vibration environment encountered by space vehicle components and experiments during handling and shipment can be severe enough to cause damage if the equipment items are not properly protected or qualified for the environment. Packaging and design engineers must have detailed information concerning the environment to determine if an item requires protection. If protection is required, the information is used for designing protective packaging or isolation systems. The MSFC approach to the transportation and handling criteria is that, in general, they should be used in verifying component shipping containers. These criteria should not influence component design, but should provide information for shipping container design to ensure that the vibratory and shock amplitude transmitted to the component do not exceed the flight design and verification criteria. In those cases where it is obvious that the component can survive the transportation and handling criteria without protection, the designer may elect to qualify the hardware to the specified criteria rather than provide protection.

A. Transportation Criteria

The transportation vibration criteria are specified in terms of G-pk as a function of frequency. The transportation shock criteria are specified as shock response spectra.

1. Vibration Criteria

The transportation vibration criteria are presented in paragraphs (a) through (d) for the various modes of transportation. When testing is performed, the vibration test frequencies are swept logarithmically from 5 Hz to the maximum frequency and back to 5 Hz at 1 octave per minute in each axis. The components should be instrumented to determine major resonances. A 15 min sinusoidal dwell is required at each major component resonance at the criteria amplitude specified for the sweep test. Criteria below 5 Hz are for design considerations only and no test is required. The criteria are tabulated below.

(a) Aircraft

- (1) Jet (5-200-5 Hz @ 1 oct/min)
 - 5 - 10 Hz @ 0.022 in. D.A. Disp.
 - 10 - 35 Hz @ 0.11 g's peak
 - 35 - 200 Hz @ 0.0017 in. D.A. Disp.
 - 200 - 2000 Hz @ 3.5 G's peak
- (2) Propeller (5-700-5 Hz @ 1 oct/min)
 - 2 - 4 Hz @ 0.42 in. D.A. Disp.*
 - 4 - 5 Hz @ 0.35 g's peak*
 - 5 - 12 Hz @ 0.35 g's peak
 - 12 - 55 Hz @ 0.046 in. D.A. Disp.
 - 55 - 300 Hz @ 7.0 g's peak
 - 300 - 700 Hz @ 3.5 g's peak
- (3) Helicopter (5-600-5 Hz @ 1/oct/min)
 - 5 - 12 Hz @ 0.22 in. D.A. Disp.
 - 12 - 40 Hz @ 1.6 g's peak
 - 40 - 55 Hz @ 0.019 in. D.A. Disp.
 - 55 - 120 Hz @ 3.0 g's peak
 - 120 - 170 Hz @ 0.0040 in. D.A. Disp.
 - 170 - 220 Hz @ 6.0 g's peak
 - 220 - 260 Hz @ 0.0024 in. D.A. Disp.
 - 260 - 600 Hz @ 8.0 g's peak

(b) Trucks

- (1) Smooth Paved Roads (5-300-5 Hz @ 1 oct/min)
 - 1 - 4 Hz @ 0.43 in. D.A. Disp.*
 - 4 - 5 Hz @ 0.35 g's peak*
 - 5 - 150 Hz @ 0.35 g's peak
 - 150 - 300 Hz @ 0.06 g's peak

* Design criteria only, no test required.

- (2) All Road Conditions (5-1000-5 Hz @ 1 oct/min)
- 1 - 7 Hz @ 1.7 g's peak*
 - 7 - 15 Hz @ 1.7 g's peak
 - 15 - 1000 Hz @ 1.7 g's peak

(c) Trains

- Normal Railroad Operations (5-2000-5 Hz @ 1 oct/min)
- 2 - 3 Hz @ 2.6 in. D.A. Disp.*
 - 3 - 6 Hz @ 1.2 g's peak*
 - 6 - 130 Hz @ 1.2 g's peak
 - 130 - 185 Hz @ 0.0014 in. D.A. Disp.
 - 185 - 2000 Hz @ 2.5 g's peak

(d) Ships

- Normal Maneuvers (5-300-5 Hz @ 1 oct/min)
- 0.1 - 0.3 Hz @ 0.35 g's peak*
 - 0.3 - 1.5 Hz @ 0.35 g's peak*
 - 1.5 - 4 Hz @ 0.10 g's peak*
 - 4 - 5 Hz @ 0.12 in. D.A. Disp.
 - 5 - 11 Hz @ 0.12 in. D.A. Disp.
 - 11 - 300 Hz @ 0.75 g's peak

* Design criteria only, no test required.

2. Shock Criteria

When shock testing is required because of rail shipment, the tests should be conducted by applying five shocks in each of three mutually perpendicular axes (15 shocks total). Any shock pulse that results in a reponse spectrum ($Q = 10$) as severe as that presented below will be acceptable.

Railroad Car Humping Conditions (5 shocks per axis)

- 20 - 160 Hz @ +6 dB/oct
- 160 - 340 Hz @ 500 G's peak
- 340 - 400 Hz @ -6 dB/oct

B. Handling Criteria and Procedures

Handling criteria are required to account for typical conditions that occur during loading or unloading operations. Tests for these conditions consist of numerous container drops from various orientations of the container. Where equipment design allows, equipment will be subjected to a transit drop test as described below. If normal equipment design does not allow this type testing, the procedures and required protection in handling are to be submitted to the appropriate MSFC program manager for approval.

1. Test Conditions

The transit drop test should be used for equipment in its transit or combination case as prepared for field use to determine if the equipment is capable of withstanding the shocks normally induced by loading and unloading of equipment.

For equipment weighing 1000 pounds or less, the floor or barrier receiving the impact shall be of solid, 2-in. thick plywood backed by either concrete or a rigid steel frame. For equipment weighing over 1000 pounds, the floor or barrier shall be concrete or its equivalent.

2. Test Performance

(a) Subject the test item to the number and heights of drop as indicated in the following table. Prior to proceeding with any of the test methods, the test item shall be operated under standard ambient conditions and a record made of all data necessary to determine compliance with required performance. These data shall provide the criteria for checking satisfactory performance of the test item, either during or at the conclusion of the test, or both, as required.

Weight of Test Item and Case (pounds)	Largest Dimensions (inches)	Notes	Height of Drop (inches)	Number of Drops
Under 100 lb Man-Packed and Man-Portable	Under 36	A	48	Drop on each face, edge, and corner. Total of 26 drops.
	36 and over	A	30	
100 to 200 lb Inclusive	Under 36	A	30	Drop on each corner.
	36 and over	A	24	
Over 200 to 1000 lb Inclusive	Under 36	A	24	Total of 8 drops.
	36 to 60	B	36	
	Over 60	B	24	
Over 1000	No limit	C	18	4 edgewise drops 2 cornerwise drops

Note A. Drops shall be made from a quick-release hook or drop tester as made by the L.A.B. Corporation, Skaneateles, New York, or equal. The test item shall be oriented so that upon impact a line from the struck corner or edge to the center of gravity of the case and contents is perpendicular to the impact surface.

Note B. With the longest dimension parallel to the floor, the transit or combination case with the test item within shall be supported at the corner of one end by a block 5 in. high and at the other corner or edge of the same end by a block 12 in. high. The opposite end of the case shall then be raised to the specified height at the lowest unsupported corner and allowed to fall freely.

Note C. While in the normal transit position, the case and contents shall be subjected to the edgewise and cornerwise drop test as follows (if normal transit position is unknown, the case shall be oriented such that the two longest dimensions are parallel to the "floor").

Edgewise drop test: One edge of the base of the case shall be supported on a sill 5 to 6 in. high. The opposite edge shall be raised to the specified height and allowed to fall freely. The test shall be applied once to each edge of the base of the case (total of four drops).

Cornerwise drop test: One corner of the base of the case shall be supported on a block approximately 5 in. high. A block normally 12 in. high shall be placed under the other corner of the same end. The opposite end of the case shall be raised to the specified height at the lowest unsupported corner and allowed to fall freely. This test shall be applied once to each of two diagonally opposite corners of the base (total of two cornerwise drops). When the proportions of width and height of the case are such as to cause instability in the cornerwise drop test, edgewise drops shall be substituted. In such instances two more edgewise drops on each end shall be performed (four additional edgewise drops for a total of eight edgewise drops).

(b) Upon completion of the transit drop test, the test item shall be operated and the results compared to data obtained prior to testing in accordance with the following procedures. Prior to proceeding with any of the test methods, the test item shall be operated under standard ambient conditions and a record made of all data necessary to determine compliance with required performance. These data shall provide the criteria for checking satisfactory performance of the test item during testing or at the conclusion of the test or both, as required. Certification by signature and date block is required.

(c) The test item shall then be visually inspected and a record made of any damage/deterioration resulting from the test. If a test chamber is used for the test, perform a visual inspection of the test item within the chamber at test conditions when possible. Upon completion of the test, visually inspect the test item again after the test item has been returned to standard ambient conditions. Deterioration, corrosion, or change in tolerance limits or any internal or external parts which could in any manner prevent the test item from meeting operational service or maintenance requirements shall be reason to consider the test item as having failed to withstand the conditions of the test.

VII. 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 basic to the technology 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 thinks 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 25 years of success without a component vibroacoustic failure during flight using the method described herein.

As stated in the introduction, this document provides general guidelines 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 are recognized and 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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APPROVAL

DESIGN AND VERIFICATION GUIDELINES FOR VIBROACOUSTIC
AND TRANSIENT ENVIRONMENTS

Component Analysis Branch
Systems Dynamics Laboratory

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.



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