METHOD 514.6

VIBRATION

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METHOD 514.6

VIBRATION

NOTE: **Tailoring is essential**. Select methods, procedures, and parameter levels based on the tailoring process described in Part One, paragraph 4, and Part One, Annex C. Apply the general guidelines for laboratory test methods described in Part One, paragraph 5 of this standard. **For vibration schedule development,** see NATO Standardization Agreement (STANAG) 4370, Allied Environmental Conditions and Test Procedures (AECTP) 200 (paragraph 6.1, reference kk), International Test Operations Procedure (ITOP) 1-1-050 (paragraph 6.1, reference e), and Method 516.6, Annex A.

The vibration profiles provided in Annexes B-E of this Method are default curves that are generally developed as a composite of multiple locations acquired from multiple vehicles of a similar construct. For technical guidance / contact information regarding the existence and availability of either item-specific or location-specific vibration profiles that may reside in various archives, see Part One, page iii, for Service points-of-contact.

Organization. The main body of this method is arranged similarly to the other methods of MIL-STD-810G. A considerable body of supplementary information is included in the Annexes. With the exception of Table 514.6-I, all tables and figures for the entire method are in Annexes B - E. Reference citations to external documents are at the end of the main body (paragraph 6). The annexes are as follows:

ANNEX A – ENGINEERING INFORMATION

ANNEX B – MANUFACTURE / MAINTENANCE - TAILORING GUIDANCE FOR VIBRATION EXPOSURE DEFINITION

ANNEX C – TRANSPORTATION - TAILORING GUIDANCE FOR VIBRATION EXPOSURE DEFINITION

ANNEX D – OPERATIONAL - TAILORING GUIDANCE FOR VIBRATION EXPOSURE DEFINITION

ANNEX E – SUPPLEMENTAL - TAILORING GUIDANCE FOR VIBRATION EXPOSURE DEFINITION

1. SCOPE.

1.1 Purpose.

Vibration tests are performed to:

a. Develop materiel to function in and withstand the vibration exposures of a life cycle including synergistic effects of other environmental factors, materiel duty cycle, and maintenance. This method is limited to consideration of one mechanical degree-of-freedom at a time. Refer to Method 527 for further guidance on multiple exciter testing. Combine the guidance of this method with the guidance of Part One and other methods herein to account for environmental synergism.

b. Verify that materiel will function in and withstand the vibration exposures of a life cycle.

1.2 Application.

a. General. Use this method for all types of materiel except as noted in MIL-STD-810G, Part One, paragraph 1.3, and as stated in paragraph 1.3 below. For combined environment tests, conduct the test in accordance with the applicable test documentation. However, use this method for determination of vibration test levels, durations, data reduction, and test procedure details.

b. Purpose of test. The test procedures and guidance herein are adaptable to various test purposes including development, reliability, qualification, etc. See Annex A for definitions and guidance.

c. Vibration life cycle. Table 514.6-I provides an overview of various life cycle situations during which some form of vibration may be encountered, along with the anticipated platform involved. Annex A provides definitions and engineering guidance useful in interpreting and applying this method. Annexes B - E provide guidance for estimating vibration levels and durations and for selection of test procedures. International Test Operations Procedure (ITOP) 1-2-601 (paragraph 6.1, reference d), https://itops.dtc.army.mil/default.aspx , includes an assortment of specific ground vehicle and helicopter vibration data.

d. Manufacturing. The manufacture and acceptance testing of materiel involves vibration exposures. These exposures are not directly addressed herein. It is assumed that the manufacturing and acceptance process completed on the materiel that undergo environmental testing are the same as the process used to produce deliverable materiel. Thus, the environmental test materiel will have accumulated the same damage prior to test as delivered materiel accumulates prior to delivery. The environmental test then verifies the field life of delivered materiel. When a change is made to the manufacturing process that involves increased vibration exposure, evaluate this increased vibration exposure to ensure the field life of subsequent materiel is not shortened. An example might be pre-production materiel completely assembled in one building, whereas production units are partially assembled at one site and then transported to another site for final assembly. Changes in the manufacturing vibration environment should be evaluated with regard to the need for design and (re)qualification. (See Annex B)

e. Environmental Stress Screening (ESS). Many materiel items are subjected to ESS, burn-in, or other production acceptance test procedures prior to delivery to the government, and sometimes during maintenance. As in basic production processes, it is assumed that both the test units and the field units receive the same vibration exposures, so that environmental test results are valid for the field units. Where units do not necessarily receive the same exposures, such as multiple passes through ESS, apply the maximum allowable exposures to the items used for environmental test as pre-conditioning for the environmental tests. (See Annex A, paragraph 2.1.6, and Annex B, paragraph 2.3.)

Table 514.6-I. Vibration environment categories.

Life Phase	Platform	Category	Materiel Description	Annex	Test [1/]
Manufacture / Maintenance	Plant Facility / Maintenance Facility	1. Manufacture / Maintenance processes	Materiel / Assembly / Part	**B**	[2/]
		2. Shipping, handling			[2/]
		3. ESS			[3/]
Transportation	Trucks and Trailers	4. Secured Cargo	Materiel as secured cargo [4/]	**C**	I
		5. Loose Cargo	Materiel as loose cargo [4/]		II
		6. Large Assembly Transport	Large assemblies, shelters, van and trailer units [4/]		III
	Aircraft	7. Jet	Materiel as cargo		I
		8. Propeller			
		9. Helicopter			
	Watercraft[5/]	10. Marine Vehicles			
	Railroad	11. Train			
Operational	Aircraft	12. Jet	Installed Materiel	**D**	I
		13. Propeller			
		14. Helicopter			
	Aircraft Stores	15. Jet	Assembled stores		IV
		16. Jet	Installed in stores		I
		17. Propeller	Assembled / Installed in stores		IV/I
		18. Helicopter			
	Missiles	19. Tactical Missiles	Assembled / installed in missiles (free flight)		
	Ground	20. Ground Vehicles	Installed Materiel in wheeled / tracked / trailer		I/III
	Watercraft[5/]	21. Marine Vehicles	Installed Materiel		I
	Engines	22. Turbine Engines	Materiel Installed on Engines		
	Personnel	23. Personnel	Materiel carried by/on personnel		[2/]
Supplemental	All	24. Minimum Integrity	Installed on Isolators / Life cycle not defined	**E**	I
	All Vehicles	25. External Cantilevered	Antennae, airfoils, masts, etc.		[2/]

[1/] Test procedure – see paragraph 4.
[2/] See Annexes B, C, D, & E, and the paragraphs related to categories identified in the "Category" column.
[3/] Use applicable ESS procedure.
[4/] See paragraph 2.3.2 above.
[5/] For Navy vessels see Method 528.

1.3 Limitations.

a. Safety testing. This method may be used to apply specific safety test requirements as coordinated with the responsible safety organization. However, vibration levels or durations for specific safety related issues are not provided or discussed.

b. Platform/materiel interaction. In this method, vibration requirements are generally expressed as inputs to materiel that is considered to be a rigid body with respect to the vibration exciter (platform, shaker, etc.). While this is often not true, it is an acceptable simplification for smaller materiel items. For large materiel items, it is necessary to recognize that the materiel and the exciter vibrate as a single flexible system. There is no simple rule to determine the validity of this assumption (see Annex A, paragraph 2.4). Further, proper treatment of a given materiel item may vary with platform. An example might be a galley designed for an aircraft. For the operational environment (installation on an operating aircraft), consider the galley structure as aircraft secondary structure, and design and test accordingly. Design subassemblies within the galley (e.g., coffee maker) for vibration levels based on guidance of Annex D, and tested in accordance with Procedure I. When packaged for shipment, the packaging, galley, and subassemblies are considered a single materiel item, and tested accordingly. Another example is a shelter transported to the field as a pre-assembled office, laboratory, etc. Consider the shelter as large materiel and develop accordingly. A suitable test would be the large assembly transport test of paragraph 4.4.3. Where impedance mismatch between platform/materiel and laboratory vibration exciter/test item are significantly different, force control or acceleration limiting control strategies may be required to avoid unrealistically severe vibration response (see paragraph 4.2). Control limits should be based upon field and laboratory measurements. For sensitive materiel for which over-conservative testing philosophy must not be applied, force or acceleration limiting control is an option. In certain cases in which the field measured response is well defined on a small component, the duration of the vibration is short, and then execution of the laboratory test under open loop waveform control based upon the field measured data is an option.

c. Environmental Stress Screening (ESS). This method does not contain guidance for selection of ESS exposures. Some discussion is in Annex A, paragraph 2.1.6, and Annex B, paragraph 2.3.

2. TAILORING GUIDANCE

2.1 Selecting the Method.

Essentially all materiel will experience vibration, whether during manufacture, transportation, maintenance, or operational use. The procedures of this method address most of the life cycle situations during which vibration is likely to be experienced. Select the procedure or procedures most appropriate for the materiel to be tested and the environment to be simulated. See Table 514.6-I for a general listing of vibration exposures and test procedures as related to environmental life cycle elements. See Annexes B-E for guidance on determining vibration levels and durations.

a. Conservatism in selection of levels. In the past, vibration test criteria often contained added margin to account for variables that cannot be included in criteria derivation. These include (among many others) undefined worst case situations, synergism with other environmental factors (temperature, acceleration, etc.), and three-axis orthogonal versus three dimensional vibration. Due to strong pressure toward minimum cost and weight, this margin is often not included. When margin is not included, be aware that any improvements in weight or cost are purchased with added risk to materiel life and function.

b. Conservatism with measured data. The guidance in this document encourages the use of materiel-specific measured data as the basis for vibration criteria. Due to limitations in numbers of transducers, accessibility of measurement points, linearity of data at extreme conditions, and other causes, measurements do not include all extreme conditions. Further, there are test limitations such as single axis versus multi-axis, and practical fixtures versus platform support. Apply margin to measured data in deriving test criteria to account for these variables. When sufficient measured data are available, use statistical methods as shown in NATO STANAG 4370 (paragraph 6.1, reference ii), AECTP 200 (paragraph 6.1, reference kk), and ITOP 1-1-050 (paragraph 6.1, reference e).

c. Conservatism with predicted data. Annexes B - E of this method provide information that can be used to generate alternate criteria for those cases where measured data are unavailable. These data are based on envelopes of wide ranges of cases and are conservative for any one case. Additional margin is not recommended.

2.1.1 Effects of environment.

Vibration results in dynamic deflections of and within materiel. These dynamic deflections and associated velocities and accelerations may cause or contribute to structural fatigue and mechanical wear of structures, assemblies, and parts. In addition, dynamic deflections may result in impacting of elements and/or disruption of function. Some typical symptoms of vibration-induced problems follow. This list is not intended to be all-inclusive:

a. Chafed wiring.
b. Loose fasteners/components.
c. Intermittent electrical contacts.
d. Electrical shorts.
e. Deformed seals.
f. Failed components.
g. Optical or mechanical misalignment.
h. Cracked and/or broken structures.
i. Migration of particles and failed components.
j. Particles and failed components lodged in circuitry or mechanisms.
k. Excessive electrical noise.
l. Fretting corrosion in bearings.

2.1.2 Sequence.

Tailor the test sequence as a function of the life cycle environments of the specific Program (See Part One, paragraph 5.5).

a. General. The accumulated effects of vibration-induced stress may affect materiel performance under other environmental conditions such as temperature, altitude, humidity, leakage, or electromagnetic interference (EMI/EMC). When evaluating the cumulative environmental effects of vibration and other environments, expose a single test item to all environmental conditions, with vibration testing generally performed first. If another environment (e.g., temperature cycling) is projected to produce damage that would make the materiel more susceptible to vibration, perform tests for that environment before vibration tests. For example, thermal cycles might initiate a fatigue crack that would grow under vibration or vice versa.

b. Unique to this method. Generally, expose the test item to the sequence of individual vibration tests that follow the sequence of the life cycle. For most tests, this can be varied if necessary to accommodate test facility schedules, or for other practical reasons. Complete all manufacture associated preconditioning (including ESS) before any of the vibration tests. Complete any maintenance associated preconditioning (including ESS) prior to tests representing mission environments. Perform tests representing critical end-of-mission environments last.

2.2 Selecting Procedures.

Identify the environments of the materiel life cycle during the tailoring process as described in Part One, paragraph 4. Table 514.6-I provides a list of vibration environments by category versus test procedure. Descriptions of each category listed in this table are included in Annexes B - E, along with information for tailoring the test procedures of paragraph 4 below, and alternate test criteria for use when measured data are not available. In general, test materiel for each category to which it will be exposed during an environmental life cycle. Tailor test procedures to best accomplish the test purpose (see Annex A, paragraph 2.1), and to be as realistic as possible (Annexes B-E, paragraphs 1.2).

2.2.1 Procedure selection considerations.

Depending on relative severity, it may be acceptable to delete vibration tests representing particular life cycle elements for a materiel test program. Base such decisions on consideration of both vibration amplitude and fatigue damage potential across the frequency range of importance. Make analytical estimates of fatigue damage potential on the basis of simple, well-understood models of the materiel.

In evaluation of the relative severity of environments, include the differences in transportation configuration (packaging, shoring, folding, etc.) and application configuration (mounted to platform, all parts deployed for service, etc.). In addition, transportation environments are usually defined as inputs to the packaging, whereas application environments are expressed as inputs to the materiel mounting structure or as response of the materiel to the environment.

a. Transportation vibration more severe than application environment. Transportation vibration levels are often more severe than application vibration levels for ground-based and some shipboard materiel. In this case, both transportation and platform vibration tests are usually needed because the transportation test is performed with the test item non-operating, and the platform test is performed with the test item operating.

b. Application vibration more severe than transportation vibration. If the application vibration levels are more severe than the transportation levels, it may be feasible to delete transportation testing. It may also be feasible to change the application test spectrum shape or duration to include transportation requirements in a single test. In aircraft applications, a minimum integrity test (see Annex E, paragraph 2.1) is sometimes substituted for transportation and maintenance vibration requirements.

2.2.2 Difference among procedures.

a. Procedure I - General Vibration. Use Procedure I for materiel to be transported as secured cargo or deployed for use on a vehicle. This procedure applies to ground vehicles as well as fixed and rotary wing aircraft. For this procedure, the test item is secured to a vibration exciter, and vibration is applied to the test item as an input at the fixture/test item interface. Steady state or transient vibration may be applied as appropriate.

b. Procedure II - Loose Cargo Transportation. Use this procedure for materiel to be carried in/on trucks, trailers, or tracked vehicles and not secured to (tied down in) the carrying vehicle. The test severity is not tailorable, and represents loose cargo transport in military vehicles traversing rough terrain.

c. Procedure III - Large Assembly Transportation. This procedure is intended to replicate the vibration and shock environment incurred by large assemblies of materiel installed or transported by wheeled or tracked vehicles. It is applicable to large assemblies or groupings forming a high proportion of vehicle mass, and to materiel forming an integral part of the vehicle. In this procedure, use the specified vehicle type to provide the mechanical excitation to the test materiel. The vehicle is driven over surfaces representative of service conditions, resulting in realistic simulation of both the vibration environment and the dynamic response of the test materiel to the environment. Generally, measured vibration data are not used to define this test. However, measured data are often acquired during this test to verify that vibration and shock criteria for materiel subassemblies are realistic.

d. Procedure IV - Assembled Aircraft Store Captive Carriage and Free Flight. Apply Procedure IV to fixed wing aircraft carriage and free flight portions of the environmental life cycles of all aircraft stores, and to the free flight phases of ground or sea-launched missiles. Use Procedure I, II, or III for other portions of the store's life cycle as applicable. Steady state or transient vibration may be applied as appropriate. Do not apply Procedure I to fixed wing aircraft carriage or free flight phases.

2.3 Determine Test Levels and Conditions.

Select excitation form (steady state or transient), excitation levels, control strategies, durations and laboratory conditions to simulate the vibration exposures of the environmental life cycle as accurately as possible. Whenever possible, acquire measured data as a basis for these parameters. Annexes B - E include descriptions of various phases typical of an environmental life cycle, along with discussions of important parameters and guidance for developing test parameters. Annex A has further guidance in interpretation of technical detail.

2.3.1 Climatic conditions.

Many laboratory vibration tests are conducted under standard ambient test conditions as discussed in Part One, paragraph 5. However, when the life cycle events being simulated occur in environmental conditions significantly different than standard conditions, consider applying those environmental factors during vibration testing. Individual climatic test methods of this standard include guidance for determining levels of other environmental loads. Methods 520.3, "Temperature, Humidity, Vibration, Altitude," and 523.3, "Vibro-Acoustic/Temperature," contain specific guidance for combined environments testing. For temperature-conditioned environmental tests, (high temperature tests of explosive or energetic materials in particular), consider the materiel degradation due to extreme climatic exposure to ensure the total test program climatic exposure does not exceed the life of the materiel. (See Part One, paragraph 5.19.)

2.3.2 Test item configuration.

Configure the test item for each test as it will be in the corresponding life cycle phase. In cases representing transportation, include all packing, shoring, padding, or other configuration modifications of the particular shipment mode. The transportation configuration may be different for different modes of transportation.

a. Loose cargo. The method contained herein is a general representation based on experience as well as measurement, and is not tailorable (see Annex C, paragraph 2.2 for details). The most realistic alternative for truck, trailer, or other ground transportation is to use Procedure II that requires the transportation vehicle and a full cargo load. In this test, the cargo has freedom to bounce, scuff and collide with other cargo and with the sides of the vehicle. The loose cargo environment includes conditions experienced by cargo transported in a vehicle traversing irregular surfaces. This test replicates the repetitive random shock environment incurred by cargo transported under these conditions.

b. Secured cargo. Procedure I assumes no relative motion between the vehicle cargo deck or cargo compartment and the cargo. This applies directly to materiel that is tied down or otherwise restrained such that no relative motion is allowed considering vibration, shock, and acceleration loads. When restraints are not used or are such as to allow limited relative motions, provide allowance in the test setup and in the vibration excitation system to account for this motion. Procedure III is an alternative for ground transportation.

c. Stacked cargo. Stacking or bundling of sets or groups of materiel items may affect the vibration transmitted to individual items. Ensure the test item configuration includes appropriate numbers and groupings of materiel items.

2.3.3 Multiple Exciter Consideration

Method 527 addresses scenarios in which the test item size requires use of more than one exciter or test fidelity requires more than one mechanical degree-of-freedom. In general, if a test facility has the capability to address more than one mechanical degree-of-freedom, and if such testing cam be conducted in a time and cost effective manner, multiple axis testing should be considered as a test option. If the default curves provided within various categories of Method 514 are used as reference curves in a multiple-axis test, it should be recognized that Cross Spectral Density (CSD) terms will be undefined.

2.4 Test Item Operation.

Whenever practical, ensure test items are active and operational during vibration tests. Monitor and record achieved performance. Obtain as much data as possible that defines the sensitivity of the materiel to vibration. Where tests are conducted to determine operational capability while exposed to the environment, operate the test item. In other cases, operate the item where practical. Operation during transportation will not be possible in almost all cases. Also, there are cases where the operational configuration varies with mission phase, or where operation at high levels of vibration may not be required and may be likely to result in damage.

3. INFORMATION REQUIRED.

The following information is required to conduct and document vibration tests adequately. Tailor the lists to the specific circumstances, adding or deleting items as necessary. Although generally not required in the past, perform fixture and materiel modal surveys when practical. These data are useful in evaluating test results, and in evaluating the suitability of materiel against changing requirements or for new applications. These data can be particularly valuable in future programs where the major emphasis will be to use existing materiel in new applications. (When modal survey is ruled out for programmatic reasons, a simple resonance search can sometimes provide useful information.)

3.1 Pretest.

The following information is required to conduct vibration tests adequately.

a. General. See Part One, paragraphs, 5.7 and 5.9, and Part One, Annex A, Task 405 of this standard.

b. Specific to this method.

(1) Test fixture requirements.
(2) Test fixture modal survey requirements / procedure.
(3) Test item/fixture modal survey requirements / procedure.
(4) Vibration exciter control strategy.
(5) Test tolerances.
(6) Requirements for combined environments (i.e. temperature and humidity).
(7) Test schedule(s) and duration of exposure(s).
(8) Axes of exposure.
(9) Measurement instrumentation configuration.
(10) Test shutdown procedures for test equipment or test item problems, failures, etc. (See paragraph 4.3.)
(11) Test interruption recovery procedure. (See paragraph 4.3.)
(12) Test completion criteria.
(13) Assure that test requirements (force, acceleration, velocity, displacement) can be met. Seek approval for variation if required. Document any variation.
(14) Allowable adjustments to test item & fixture (if any); these must be documented in test plan and the test report.

c. Tailoring, Necessary variations in the basic test parameters/testing materials to accommodate LCEP requirements and/or facility limitations.

d. Specific to Procedure.

(1) Procedure II - Loose cargo vibration. Define the orientation of test item(s) in relation to the axis of throw of the test table, as well as the number of possible test item orientations and the test time per orientation.
(2) Procedure III - Large assembly transport. Define the test vehicle(s), loading(s), surface(s), distance(s), and speed(s).

NOTE: Modal surveys of both test fixtures and test items can be extremely valuable. Large test items on large complex fixtures are almost certain to have fixture resonances within the test range. These resonances result in large overtests or undertests at specific frequencies and locations within a test item. Where fixture and test item resonances couple, the result can be catastrophic. Similar problems often occur with small test items, even when the shaker/fixture system is well designed because it is very difficult and often impractical to achieve a lowest fixture resonant frequency above 2000 Hz. In cases where the fixture/item resonance coupling cannot be eliminated, consider special vibration control techniques such as acceleration or force limit control.

3.2 During Test.

Document the following information during conduct of the test:

a. Collect the information listed in Part One, paragraph 5.10, and in Part One, Annex A, Tasks 405 and 406 of this standard. Document any adjustments to the test item and fixture identified by the test plan, including planned stopping points. (See also paragraph 4.3.)

b. Document the vibration exciter control strategy used, e.g., single point response, multipoint response, force limit, waveform, etc.

c. Refer to the test-specific plan to address any additional data that may be required during the test phase.

3.3 Post-Test.

The following post test data shall be included in the test report.

a. General. See Part One, paragraph 5.13, and Part One, Annex A, Task 406 of this standard.

b. Specific to this method.

(1) Summary and chronology of test events, test interruptions, and test failures.

(2) Discussion and interpretation of test events.

(3) Functional verification data.

(4) Test item modal analysis data.

(5) All vibration measurement data.

(6) Documentation of any test requirement variation (paragraph 3.1 b (14))

(7) Any changes from the original test plan.

(8) Record of combined environment parameters (i.e. temperature and humidity).

4. TEST PROCESS.

Tailor the following paragraphs as appropriate for the individual program.

4.1 Test Facility.

Use a test facility, including all auxiliary equipment, capable of providing the specified vibration environments and the control strategies and tolerances discussed in paragraph 4.2. In addition, use measurement transducers, data recording and data reduction equipment capable of measuring, recording, analyzing, and displaying data sufficient to document the test and to acquire any additional data required. Unless otherwise specified, perform the specified vibration tests and take measurements at standard ambient conditions as specified in Part One, paragraph 5.1.

4.1.1 Procedure I - General vibration.

This procedure uses standard laboratory vibration exciters (shakers), slip tables, and fixtures. Choose the specific exciters to be used based on:

a. the size and mass of test items and fixtures;

b. the frequency range required;

c. the force, acceleration, velocity, and displacement required.

4.1.2 Procedure II - Loose cargo transportation.

Simulation of this environment requires use of a package tester (Annex C, Figure 514.6C-4) that imparts a 25.4 mm (1.0 inch) peak-to-peak, circular synchronous motion to the table at a frequency of 5 Hz. This motion takes place in a vertical plane. The figure shows the required fixturing. This fixturing does not secure the test item(s) to the bed of the package tester. Ensure the package tester is large enough for the specific test item(s) (dimensions and weight).

4.1.3 Procedure III - Large assembly transport.

The test facility for this method is a test surface(s) and vehicle(s) representative of transportation and/or service phases of the environmental life cycle. The test item is loaded on the vehicle and restrained or mounted to represent the life cycle event. The vehicle is then driven over the test surface in a manner that reproduces the transportation or service conditions. The test surfaces may include designed test tracks (e.g., test surfaces at the US Army Aberdeen Test Center (paragraph 6.1, reference b), typical highways, or specific highways between given points (e.g., a specified route between a manufacturing facility and a military depot)). Potentially, such testing can include all environmental factors (vibration, shock, temperature, humidity, pressure, etc.) related to wheeled vehicle transport.

4.1.4 Procedure IV - Assembled aircraft store captive carriage and free flight.

This procedure uses standard laboratory vibration exciters (shakers) driving the test item directly or through a local fixture. The test item is supported by a test frame independent of the vibration exciters (see paragraph 4.4.4). Select the specific exciters based on size and mass of test items and fixtures, frequency range, and low frequency stroke length (displacement) required.

4.2 Controls.

The accuracy in providing and measuring vibration environments is highly dependent on fixtures and mountings for the test item, the measurement system and the exciter control strategy. Ensure all instrumentation considerations are in accordance with the best practices available (see paragraph 6.1, reference c). Careful design of the test set up, fixtures, transducer mountings and wiring, along with good quality control will be necessary to meet the tolerances of paragraph 4.2.2 below.

4.2.1 Control strategy.

Select a control strategy that will provide the required vibration at the required location(s) in or on the test item. Base this selection on the characteristics of the vibration to be generated and platform/materiel interaction (see paragraph 1.3b above and Annex A, paragraph 2.4). Generally, a single strategy is appropriate. There are cases where multiple strategies are used simultaneously.

4.2.1.1 Acceleration input control strategy.
Input control is the traditional approach to vibration testing. Control accelerometers are mounted on the fixture at the test item mounting points. Exciter motion is controlled with feedback from the control accelerometer(s) to provide defined vibration levels at the fixture/test item interface. Where appropriate, the control signal can be the average (weighted average or maxima) of the signals from more than one test item/fixture accelerometer. This represents the platform input to the materiel, and assumes that the materiel does not influence platform vibration.

4.2.1.2 Force control strategy.
Dynamic force gages are mounted between the exciter/fixture and the test item. Exciter motion is controlled with feedback from the force gages to replicate field measured interface forces. This strategy is used where the field (platform/materiel) dynamic interaction is significantly different from the laboratory (exciter/test item) dynamic interaction. This form of control inputs the correct field-measured forces at the interface of the laboratory vibration exciter and test item. This strategy is used to prevent overtest or undertest of materiel mounts at the lowest structural resonances that may otherwise occur with other forms of control.

4.2.1.3 Acceleration limit strategy.
Input vibration criteria are defined as in paragraph 4.2.1.1. In addition, vibration response limits at specific points on the materiel are defined (typically based on field measurements). Monitoring accelerometers are located at these points. The test item is excited as in paragraph 4.2.1.1 using test item mounting point accelerometer signals to control the exciters. The input criteria are experimentally modified as needed to limit responses at the monitoring accelerometers to the predefined limits. Changes to the specified input criteria are limited in frequency bandwidth and in level to the minimum needed to achieve the required limits.

4.2.1.4 Acceleration response control strategy.
Vibration criteria are specified for specific points on, or within the test item. Control accelerometers are mounted at the vibration exciter/fixture interface. Monitoring accelerometers are mounted at the specified points within the item. An arbitrary low level vibration, controlled with feedback from the control accelerometers, is input to the test item. The input vibration is experimentally adjusted until the specified levels are achieved at the monitoring accelerometers. This strategy is commonly used with assembled aircraft stores where store response to the dynamic environment is measured or estimated. It is also applicable for other materiel when field measured response data are available.

4.2.1.5 Waveform control strategy.
This strategy is discussed in Methods 525 and 527.

4.2.2 Tolerances.
Use the following tolerances unless otherwise specified. In cases where these tolerances cannot be met, achievable tolerances should be established and agreed to by the cognizant engineering authority and the customer prior to initiation of test. Protect measurement transducer(s) to prevent contact with surfaces other than the mounting surface(s).

4.2.2.1 Acceleration spectral density.
Carefully examine field measured response probability density information for non-Gaussian behavior. In particular, determine the relationship between the measured field response data and the laboratory replicated data relative to 3σ peak limiting that may be introduced in the laboratory test.

a. Vibration environment. The following discussion relates the measured vibration level to the specification level and, like the control system, does not consider any measurement uncertainty. The test tolerance should be kept to the minimum level possible considering the test item, fixturing and spectral shape. Test tolerances of less than ±3 dB are usually readily attainable with small, compact test items (such as small and medium sized rectangular electronic packages), well-designed fixtures, and modern control equipment. When test items are large or heavy, when fixture resonances cannot be eliminated, or when steep slopes (> 20 dB/octave) occur in the spectrum, these tolerances may have to be increased. When increases are required, exercise care to ensure the selected tolerances are the minimum attainable, and that attainable tolerances are compatible with test objectives. In any case, tolerances should not exceed ±3 dB below 500 Hz, and ±6 dB above 500 Hz. These tolerances should be limited to a maximum of 5 percent of the test frequency range. Otherwise, change the tests, fixtures, or facilities so test objectives can be met. The rms level of the vibration test should not deviate more than ±10 percent from the required level.

b. Vibration measurement. Use a vibration measurement system that can provide acceleration spectral density measurements within ±0.5 dB of the vibration level at the transducer mounting surface (or transducer target mounting surface) over the required frequency range. Do not use a measurement bandwidth that exceeds 2.5 Hz at 25 Hz or below, or 5 Hz at frequencies above 25 Hz. Use a frequency resolution appropriate for the application (i.e., generally in wheeled vehicles a resolution of 1 Hz is sufficient).

c. Statistical degrees of freedom. If possible, ensure the number of statistical degrees of freedom is not less than 120. Swept narrow-band random on random vibration tests may require lesser degrees of freedom due to sweep time constraints.

d. Root mean square (RMS) "g." Do not use RMS g as the sole parameter defining or controlling vibration tests because it contains no spectral information. RMS levels are useful in monitoring vibration tests since RMS can be monitored continuously, whereas measured spectra are available on a delayed, periodic basis. Also, RMS values are sometimes useful in detecting errors in test spectra definition. Do not use random vibration RMS g as a comparison with sinusoidal peak g. These values are unrelated.

4.2.2.2 Peak sinusoidal acceleration.

a. Vibration environment. Ensure the peak sinusoidal acceleration at a control transducer does not deviate from that specified by more than ±10 percent over the specified frequency range.

b. Vibration measurement. Ensure the vibration measurement system provides peak sinusoidal acceleration measurements within ±5 percent of the vibration level at the transducer mounting surface (or transducer target mounting surface) over the required frequency range.

c. RMS g. The RMS g of a sinusoid equals 0.707 times peak g. It is not related to RMS g of a random (g^2/Hz) spectrum; do not use this to compare sine criteria (g) to random criteria (g^2/Hz).

4.2.2.3 Frequency measurement.

Ensure the vibration measurement system provides frequency measurements within ±1.25 percent at the transducer mounting surface (or transducer target mounting surface) over the required frequency range.

4.2.2.4 Cross axis accelerations.

In a single axis vibration test, cross axis vibration acceleration in two axes mutually orthogonal and orthogonal to the drive axis should be less than or equal to 0.45 times the acceleration (0.2 times the spectral density) levels required for the cross axis of concern. If measured cross axis vibration accelerations exceed these values, the source of the vibration should be identified and addressed. The following common sources of cross axis vibration should be considered.

a. Test fixture resonance. Prior to test, a test fixture survey should be conducted to ensure that the structural characteristics of the test fixture do not introduce uncontrollable resonances into the test setup. The survey may be experimental or analytical. If problematic resonances are identified, modifications should be made to the test fixture to shift the resonance beyond the frequency range of the test or to dampen the resonance in order to minimize the effect on the test.

b. Test article resonance. Cross axis resonances of the test article may be characteristic of the test article structure and not necessarily a product of test fixture or restraint. As long as the test article is restrained in a manner consistent with the environment being tested and the test fixture is not introducing unrealistic resonance, the following options should be considered in limiting the cross axis vibration:

(1) Response Limit - A limit spectrum may be applied to the cross axis response of the test article in order to effectively notch the control spectrum in the drive axis. This limit spectrum should be defined in terms of the test profile for the cross axis of concern. For example, if the lateral response to vertical axis test is excessive, the lateral response should be limited to some factor of the corresponding lateral

profile. In a random vibration test, the cross axis resonances are often narrow frequency bands, the notching may be within acceptable tolerances.

(2) Multi-axis Test - If the test article structure is such that the cross axis vibration response to a single axis vibration test is beyond acceptable levels, it may be necessary to conduct the test as a multi-axis in order to simultaneously control multiple axes of vibration to the required test profiles. Method 527 discusses the technical details associated with multi-axis vibration testing.

4.3 Test interruption.

Test interruptions can result from multiple situations. The following paragraphs discuss common causes for test interruptions and recommended paths forward for each. Recommend test recording equipment remain active during any test interruption if the excitation equipment is in a powered state.

4.3.1 Interruption due to laboratory equipment malfunction.

a. General. See Part One, paragraph 5.11, of this standard.

b. Specific to this method. When interruptions are due to failure of the laboratory equipment, analyze the failure to determine root cause. It is also strongly advised that both control and response data be evaluated to ensure that no undesired transients were imparted to the test item during the test equipment failure. If the test item was not subjected to an over-test condition as a result of the equipment failure, repair the test equipment or move to alternate test equipment and resume testing from the point of interruption. If the test item was subjected to an over-test condition as a result of the equipment failure, the test engineer or program engineer responsible for the test article should be notified immediately. A risk assessment based on factors such as level and duration of the over-test event, spectral content of the event, cost and availability of test resources, and analysis of test specific issues should be conducted to establish the path forward. See Annex A, paragraph 2.1 for descriptions of common test types and a general discussion of test objectives.

4.3.2 Interruption due to test item operation failure.

Failure of the test item(s) to function as required during operational checks presents a situation with several possible options. Failure of subsystems often has varying degrees of importance in evaluation of the test item. Selection of option a through c below will be test specific.

a. The preferable option is to replace the test item with a “new” one and restart the entire test.

b. An alternative is to replace / repair the failed or non-functioning component or assembly with one that functions as intended, and restart the entire test. A risk analysis should be conducted prior to proceeding since this option places an over-test condition on the entire test item except for the replaced component. If the non-functioning component or subsystem is a line replaceable unit (LRU) whose life-cycle is less than that of the system test being conducted, proceed as would be done in the field by substituting the LRU, and continue from the point of interruption.

c. For many system level tests involving either very expensive or unique test items, it may not be possible to acquire additional hardware for re-test based on a single subsystem failure. For such cases, a risk assessment should be performed by the organization responsible for the system under test to determine if replacement of the failed subsystem and resumption of the test is an acceptable option. If such approval is provided, the failed component should be re-tested at the subcomponent level.

> **NOTE**: When evaluating failure interruption, consider prior testing on the same test item and consequences of such.

4.3.3 Interruption due to a scheduled event.

There are often situations in which scheduled test interruptions will take place. For example, in a tactical transportation scenario, the payload may be re-secured to the transport vehicle periodically (i.e., tie-down straps may be re-secured at the beginning of each day). Endurance testing often represents a lifetime of exposure; therefore it is not realistic to expect the payload to go through the entire test sequence without re-securing the tie-downs as is done in a tactical deployment. Many other such interruptions, to include scheduled maintenance events, are often required over the life-cycle of materiel. Given the cumulative nature of fatigue imparted by dynamic testing, it is acceptable to have test interruptions that are correlated to realistic life-cycle events. All scheduled interruptions should be documented in the test plan and test report.

4.3.4 Interruption due to exceeding test tolerances

Exceeding the test tolerances defined in paragraph 4.2.2, or a noticeable change in dynamic response may result in a manual operator initiated test interruption or an automatic interruption when the tolerances are integrated into the control strategy. In such cases, the test item, fixturing, and instrumentation should be checked to isolate the cause.

a. If the interruption resulted from a fixturing or instrumentation issue, correct the problem and resume the test

b. If the interruption resulted from a structural or mechanical degradation of the test item, the problem will generally result in a test failure and requirement to re-test unless the problem is allowed to be corrected during testing. If the test item does not operate satisfactorily, see paragraph 5 for failure analysis, and follow the guidance in paragraph 4.3.2 for test item failure.

4.4 Test Setup.

See Part One, paragraph 5.8. For standardization purposes, major axes are defined as vertical (perpendicular to level ground); longitudinal (parallel to vehicle fore and aft movement), and transverse (perpendicular to longitudinal movement).

4.4.1 Procedure I - General vibration.

Configure the test item appropriately for the life cycle phase to be simulated.

a. Transportation. Configure the test item for shipment including protective cases, devices, and/or packing. Mount the test item to the test fixture(s) by means of restraints and/or tie downs dynamically representative of life cycle transportation events.

b. Operational service. Configure the test item for service use. Secure the test item to the test fixture(s) at the mounting point(s) and use the same type of mounting hardware as used during life cycle operational service. Provide all mechanical, electrical, hydraulic, pneumatic or other connections to the materiel that will be used in operational service. Ensure these connections dynamically simulate the service connections and that they are fully functional unless otherwise specified.

c. Control accelerometer location. Location of the control accelerometer(s) can significantly affect test outcome. Control accelerometer(s) should be placed on or near the test item at the locations used to derive the test specification. Locations should be described in the test plan and in the specification derivation report. Examples are presented in Annex C.

4.4.2 Procedure II - Loose cargo transportation.

The loose cargo test can be considered as being of two types, which differ from one another only in the installation conditions of the materiel. Two different setups of fencing are required depending on the type of test item. The two types are those that are more likely to slide on the test surface or “rectangular cross section items” (typically packaged items), and those most likely to roll on the surface or “circular cross section items.” See paragraph 4.5.3 for details of the test procedure. Fencing information is presented in Annex C, paragraph 2.2. Because part of the damage incurred during testing of these items is due to the items impacting each other, the number of test items should be greater than three.

4.4.3 Procedure III - Large assembly transport.

Install the test item in/on the vehicle in its intended transport or service configuration. If the test assembly is to be contained within a shelter, or if other units are attached to the materiel assembly in its in-service configuration, also install these items in their design configuration.

a. Test surfaces. When setting up the test, consider the test surfaces available at the particular test location (see paragraph 6.1, reference b). Also, ensure the selection of test surfaces, test distances, and test speeds are appropriate for the specified vehicles and their anticipated use.

b. Test loads. Response of the vehicle to the test terrain is a function of the total load and the distribution of the load on the vehicle. In general, a harsher ride occurs with a lighter load, while a heavier load will result in maximum levels at lower frequencies. Multiple test runs with variations in load may be required to include worst case, average, or other relevant cases.

c. Tie-down/mounting arrangements. During the test, it is important to reproduce the more adverse arrangements that could arise in normal use. For example, during transportation, relaxation of tie-down strap tension could allow the cargo to lift off the cargo bed and result in repeated shock conditions.

Excessive tightening of webbing straps could prevent movement of test items and thereby reduce or eliminate such shocks.

4.4.4 Procedure IV - Assembled aircraft store captive carriage and free flight.

a. Captive carriage test fixture. Suspend the test item from a structural support frame by means of the operational service store suspension equipment (bomb rack, launcher, pylon, etc.). Ensure the flexible modes of the support frame are as high as practical, at least twice the first flexible frequency of the store, and that they do not coincide with store modes. Include and load (torque, clamp, latch, etc.) sway braces, lugs, hooks or other locking and load carrying devices that attach the store to the suspension equipment and the suspension equipment to the carrier aircraft, as required for captive carriage in service. Ensure the layout of the structural support frame and the test area is such that there is adequate access for the vibration exciters and test materiel.

(1) Configure the assembled store for captive carriage and mount it to the structural support frame. Softly suspend the structural support frame within the test chamber. Ensure that rigid body modes of the store, suspension equipment, and structural support frame combination are between 5 and 20 Hz, and lower than one half the lowest flexible mode frequency of the store. Use structural support that is sufficiently heavy and of sufficient pitch and roll inertias to approximately simulate carrier aircraft dynamic reaction mass. If the structural support is too heavy or its inertia too large, the store suspension equipment and store hardback will be over-stressed. This is because unrealistically high dynamic bending moments are needed to match acceleration spectral densities. Conversely, if the structural support is too light or its inertia too low, there will be an undertest of the suspension equipment and store hardback.

(2) Do not use the structural support to introduce vibration into the store. Hard-mounting stores to large shakers has proven to be inadequate. Recent test experience with F-15, F-16, and F/A-18 stores indicates that including a structural support/reaction mass greatly improves the match between flight measured data and laboratory vibrations, particularly at lower frequencies.

(3) In cases in which the frequency requirements in (1) and (2) cannot be met, consider force control strategy (see paragraph 4.2.1.2).

b. Free flight test fixture. Configure the assembled test store for free flight and softly suspend it within the test chamber. Ensure rigid body modes of the suspended store are between 5 and 20 Hz and lower than one half the lowest flexible mode frequency of the store.

c. Orientation. With the store suspended for test, the longitudinal axis is the axis parallel to the ground plane and passing through the longest dimension of the store. The vertical axis is mutually perpendicular to the ground plane and the longitudinal axis. The lateral axis is mutually perpendicular to longitudinal and vertical axes.

d. Vibration excitation. Store longitudinal vibration is typically less than vertical and lateral vibration. Vertical and lateral excitation of store modes usually results in sufficient longitudinal vibration. When a store is relatively slender (length greater than 4 times the height or width), drive the store in the vertical and lateral axes. In other cases, drive the store in the vertical, lateral, and longitudinal axes. If a store contains material that is not vibration tested except at assembled store level, or the store contains components that are sensitive to longitudinal vibration, include longitudinal excitation.

(1) Transmit vibration to the store by means of rods (stingers) or other suitable devices running from vibration exciters to the store. Separate drive points at each end of the store in each axis are recommended. Ideally, the store will be driven simultaneously at each end. However, it can be driven at each end separately. A single driving point in each axis aligned with the store aerodynamic center has also been successful. Use drive points on the store surfaces that are relatively hard and structurally supported by the store internal structure or by test fixture(s) (usually external rings around the local store diameter) that distribute the vibratory loads into the store primary structure.

(2) There are many signal forms available to drive the vibration exciters. Some of the most popular are uncorrelated random, sinusoidal and transient (burst random or sine) excitation. Consideration of the characteristics of the store structure, the suspension equipment, general measurement considerations, and the desired data resolution will dictate selection of the driving signals. Uncorrelated random excitation and burst random excitation should be accomplished such that the signals are driven periodically within each data acquisition block in order to improve the data quality of the derived frequency response functions (FRFs). Use of more than one vibration exciter with random excitation will assist in minimizing the influence of non-linear behavior and allows the structure to be uniformly excited and allow for better frequency response functions (FRFs). In turn, sinusoidal excitation should be used to characterize non-linearities in the system. For suspension systems involving carriage of multiple stores, the relative phase characteristics between stores should be defined and efforts made to replicate relative phasing in the laboratory setting to the maximum degree possible. It is acknowledged that there may not be sufficient excitation degrees-of-freedom to have full control authority over the phase characteristics of multiple stores. When more than one vibration exciter is used simultaneously, knowledge of multiple exciter testing techniques that include specification of the vibration exciter cross-spectral density matrices is required (reference Method 527). The auto and cross-spectral density characteristics should be made available as part of the test specification. In the absence of measured cross-spectral data, the cross-spectrum will need to be either estimated via model or assumed to be uncorrelated. Additional information regarding specification of cross-spectral parameters is addressed in paragraph 6.1, reference gg. For the case in which the cross-spectral density between drive points is assumed to be zero, recognize that due to coupling between the vibration exciters via the store/suspension structure, some level of correlation between the control points will generally exist.

e. Instrumentation. Mount transducers on the store and/or the store excitation devices to monitor compliance of vibration levels with requirements, to provide feedback signals to control the vibration exciter, and to measure materiel function. Additionally, it is usually important to overall program objectives to add transducers to measure the local vibration environment throughout the store. Note the vibration exciter control strategy used, e.g., single point response, multipoint response, force limit, waveform, etc. Also note the relationship between field measurement data and laboratory measurement data.

(1) Mount accelerometers to monitor vibration levels at the forward and aft extremes of the primary load carrying structure of the store. Do not mount these accelerometers on fairings, unsupported areas of skin panels, aerodynamic surfaces, or other relatively soft structures. In some cases (see paragraph 4.4.4c above), transducers are required in the vertical and lateral directions. In other cases, transducers are required in vertical, lateral, and longitudinal directions. Designate these transducers as the test monitor transducers.

(2) An alternate method is to monitor the test with strain gages that are calibrated to provide dynamic bending moment. This has proven successful where integrity of the store primary structure is a major concern. Flight measured dynamic bending moment data is required for this method. Also, use accelerometers positioned as discussed above to verify that general vibration levels are as required.

(3) As feedback control transducers, use either accelerometers on or near the store/vibration transmission device(s)/vibration exciter interface, force transducer(s) in series with the store/vibration transmission device(s)/vibration exciter, or dynamic bending moment strain gages. A clear understanding of the vibration exciter control strategy and its effects on the overall measurements is necessary.

4.5 Test Execution.

The following steps, alone or in combination, provide the basis for collecting necessary information concerning the durability and function of a test item in a vibration environment.

4.5.1 Preparation for test.

4.5.1.1 Preliminary steps.

Before starting a test, review pretest information in the test plan to determine test details (procedure(s), test item configuration(s), levels, durations, vibration exciter control strategy, failure criteria, item operational requirements, instrumentation requirements, facility capability, fixture(s), etc.).

a. Select appropriate vibration exciters and fixtures.

b. Select appropriate data acquisition system (e.g., instrumentation, cables, signal conditioning, recording, analysis equipment).

c. Operate vibration equipment without the test item installed to confirm proper operation.

d. Ensure the data acquisition system functions as required.

4.5.1.2 Pretest standard ambient checkout.

All items require a pretest standard ambient checkout to provide baseline data. Conduct the pretest checkout as follows:

Step 1. Examine the test item for physical defects, etc. and document the results.

Step 2. Prepare the test item for test, in its operating configuration if required, as specified in the test plan.

Step 3. Examine the test item/fixture/exciter combination for compliance with test item and test plan requirements.

Step 4. If applicable, conduct an operational checkout in accordance with the test plan and document the results for comparison with data taken during or after the test. If the test item does not operate as required, resolve the problems and repeat this step.

4.5.2 Procedure I - General vibration.

Step 1. Conduct a fixture modal survey and verify that fixture design is compliant with recommended practices, and meets any test defined requirements that may have been provided in the item-specific test plan (see paragraph 6.1, references aa, dd, and ee).

Step 2. Mount the test item to the test fixture in a manner dynamically representative of the life cycle event simulated.

Step 3. Install sufficient transducers on or near the test item/fixture/vibration exciter combination to measure vibration at the test item/fixture interface, to control the vibration exciter as required by the control strategy, and measure any other required parameters. Mount control transducer(s) as close as possible to the test item/fixture interface. Ensure that the total accuracy of the instrumentation system is sufficient to verify that vibration levels are within the tolerances of paragraph 4.2.2, and to meet additionally specified accuracy requirements.

Step 4. Conduct a test item modal survey, if required.

Step 5. Perform a visual inspection of the test setup.

Step 6. Apply low level vibration to the test item/fixture interface. If required, include other environmental stresses.

Step 7. Verify that the vibration exciter, fixture, and instrumentation system function as required.

Step 8. Apply the required vibration levels to the test item/fixture interface. Apply additional environmental stresses as required.

Step 9. Monitor vibration levels and, if applicable, test item performance continuously through the exposure. If levels shift or a failure occurs, shut down the test in accordance with the test interruption procedure (paragraph 4.3.2). Determine the reason for the shift and proceed in accordance with the test interruption recovery procedure (paragraph 4.3.2).

Step 10. When the required duration has been achieved, stop the vibration.

Step 11. If the test plan calls for additional exposures, repeat Steps 5 through 10 as required by the test plan before proceeding.

Step 12. Inspect the test item, fixture, vibration exciter, and instrumentation. If failure, wear, looseness, or other anomalies are found, proceed in accordance with the test interruption recovery procedure (paragraph 4.3.2).

Step 13. Verify that the instrumentation functions as required, and perform an operational check of the test item as required per the test plan. If the test item fails to operate as intended, follow the guidance in paragraph 4.3.2 for test item failure.

Step 14. Repeat Steps 1 through 13 for each required excitation axis.

Step 15. Remove the test item from the fixture and inspect the test item, mounting hardware, packaging, etc., for any signs of visual mechanical degradation that may have occurred during testing. See paragraph 5 for analysis of results.

4.5.3 Procedure II - Loose cargo transportation

Step 1. Place the test item(s) on the package tester within the restraining fences in accordance with paragraph 2.2 of Annex C.

Step 2. Install instrumentation to measure the rotational speed of the package tester. Ensure the total accuracy of the instrumentation system is sufficient to meet specified accuracy requirements.

Step 3. After determining the number of possible test item orientations and corresponding test time (paragraph 3.1d), operate the package tester for the prescribed orientation duration (Annex C, paragraph 2.2).

Step 4. Perform a visual inspection of the test item and an operational check. If the test item fails to operate as intended, follow the guidance in paragraph 4.3.2 for test item failure. Otherwise, proceed to Step 5.

Step 5. Reorient the test item(s) and/or the fencing/impact walls in accordance with paragraph 3.1d(1) and Annex C, paragraph 2.2b.

Step 6. Operate the package tester for the next prescribed duration.

Step 7. Perform a visual inspection of the test item and an operational check. If the test item fails to operate as intended, see paragraph 5 for analysis of results, and follow the guidance in paragraph 4.3.2 for test item failure.

Step 8. Repeat Steps 5-7 for the total number of orientations.

Step 9. Perform a final visual inspection of the test item and an operational check. See paragraph 5 for analysis of results.

4.5.4 Procedure III - Large assembly transport.

Step 1. Mount the test item(s) on/in the test vehicle as required in the test plan.

Step 2. If required, install transducers on or near the test item sufficient to measure vibration at the test item/vehicle interface, and to measure any other required parameters. Protect transducers to prevent contact with surfaces other than the mounting surface.

Step 3. Subject the vehicle containing the test item to the specified test conditions in Annex C, paragraph 2.3, or as otherwise specified in the test plan.

Step 4. Perform a visual inspection of the test item and an operational check. If the test item fails to operate as intended, follow the guidance in paragraph 4.3.2 for test item failure.

Step 5. Repeat Steps 1 through 4 for additional test runs, test loads, or test vehicles as required by the test plan.

Step 6. Perform a final visual inspection of the test item and an operational check. See paragraph 5 for analysis of results.

4.5.5 Procedure IV - Assembled aircraft store captive carriage and free flight.

Step 1. With the store suspended within the test chamber and the instrumentation functional, verify that the store suspension system functions as required by measuring the suspension frequencies.

Step 2. If required, conduct a test item modal survey.

Step 3. If required, place the test item in an operational mode and verify that it functions properly. Perform a visual inspection of the test setup.

Step 4. Apply low level vibration to the vibration exciter/store interface(s) to ensure the vibration exciter and instrumentation system function properly. For acceleration feedback control, use an initial input level 12 dB down from the required forward test monitor transducer spectrum. For force feedback control, use a flat force spectrum where the response at the test monitor accelerometer is at least 12 dB below the required test monitor value at all frequencies. For bending moment feedback control, use an initial input level that is 12 dB down from the required test monitor transducer spectrum.

Step 5. Adjust the vibration exciter(s) such that the test monitor transducers in the excitation axis meet the test requirements. For acceleration control, identify the test monitor transducer spectrum peaks that exceed the input spectrum by 6 dB or more (frequencies may differ fore and aft). For force feedback control, identify major peaks from the force measurements to check monitor accelerometer transfer functions. For both cases, equalize the input spectra until the identified peaks equal or exceed the required test levels. The resulting input spectra should be as smooth and continuous as possible while achieving the required peak responses. (It is not necessary to fill in valleys in the test monitor transducer spectra; however, it is not acceptable to notch out the input in these valleys.) For bending moment control raise and shape the input spectrum until it matches the required spectrum (peaks and valleys).

Step 6. When the input vibration is adjusted such that the required input response (R_1) is achieved, measure the off-axis response(s) (R_2, R_3). Verify that off-axis response levels are within requirements using the following equations. If the result obtained from the equation is greater than the value established for the equation, reduce the input vibration level until the achieved input and off-axis response levels are less than or equal to the appropriate constant. Apply these equations at each peak separately. Use the first equation for testing that requires vibration application in two separate mutually perpendicular axes, and use the second equation for testing that requires vibration application in three separate mutually perpendicular axes. Refer to paragraph 4.2.2.4 for additional guidance.

$$(R_1/A_1 + R_2/A_2) \leq 2$$

or

$$(R_1/A_1 + R_2/A_2 + R_3/A_3) \leq 3$$

Where

R_i = Response level in g^2/Hz or $(N\text{-}m)^2$/Hz or $(in\text{-}lb)^2$/Hz for i = 1 - 3, and
A_i = Test requirement level in g^2/Hz or $(N\text{-}m)^2$/Hz or $(in\text{-}lb)^2$/Hz for i = 1 - 3

For example:
For testing that requires vibration application in three, separate, mutually-perpendicular axes, and the vibration is being applied in the vertical axis, use the equation below as follows:

$$(R_1/A_1 + R_2/A_2 + R_3/A_3) \leq 3$$

Where:

R_1 = Vertical axis responselevel
A_1 = Vertical axis requirement level
R_2 = Horizontal axis response level
A_2 = Horizontal axis requirement level
R_3 = Longitudinal axis response level
A_3 = Longitudinal axis requirement level.

For vibration being applied in either the horizontal and longitudinal axis, repeat the above process.

$$3 = (R_1/A_1 + R_2/A_2 + R_3/A_3)$$

Where:

R_1 = Horizontal axis test requirement level
A_1 = Horizontal axis response level
R_2 = Vertical axis test requirement level
A_2 = Vertical axis response level
R_3 = Longitudinal axis test requirement level
A_3 = Longitudinal axis response level

For vibration being applied in the longitudinal axis, use the equation below as follows:

$$3 = (R_1/A_1 + R_2/A_2 + R_3/A_3)$$

Where:

R_1 = Longitudinal axis test requirement level
A_1 = Longitudinal axis response level
R_2 = Vertical axis test requirement level
A_2 = Vertical axis response level
R_3 = Horizontal axis test requirement level
A_3 = Horizontal axis response level.

Step 7. Verify that vibration levels are as specified. If the exposure duration is 1/2 hour or less, accomplish this step immediately after full levels are first applied, and immediately before scheduled shut down. Otherwise, accomplish this step immediately after full levels are first applied, every half-hour thereafter, and immediately before scheduled shut down.

Step 8. Monitor the vibration levels and test item performance continuously through the exposure. If levels shift, performance deviates beyond allowable limits, or failure occurs, shut down the test in accordance with the test shut down procedure (paragraph 3.1b(10)). Determine the reason for the anomaly and proceed in accordance with the test interruption recovery procedure (paragraph 4.3).

Step 9. When the required duration has been achieved, stop the vibration.

Step 10. If the test plan calls for additional exposures, repeat Steps 3 through 9 as required by the test plan before proceeding.

Step 11. Inspect the test item, fixture, vibration exciter, and instrumentation. If failure, wear, looseness or other anomalies are found, proceed in accordance with the test interruption recovery procedure (paragraph 4.3).

Step 12. Verify that the instrumentation functions as required and perform an operational check of the test item for comparison with data collected in paragraph 4.5.1.2. If the test item fails to operate as intended, follow the guidance in paragraph 4.3.2 for test item failure.

Step 13. Repeat Steps 1 through 12 for each required excitation axis.

Step 14. Remove the test item from the fixture and inspect the test item, mounting hardware, packaging, etc., for any signs of visual mechanical degradation that may have occurred during testing. See paragraph 5 for analysis of results.

5. ANALYSIS OF RESULTS.

In addition to the guidance provided in Part One, paragraph 5.14, the following is provided to assist in the evaluation of the test results.

5.1 Physics of Failure.

Analyses of vibration related failures must relate the failure mechanism to the dynamics of the failed item and to the dynamic environment. It is insufficient to determine that something broke due to high cycle fatigue or wear. It is necessary to relate the failure to the dynamic response of the materiel to the dynamic environment. Thus, include in failure analyses a determination of resonant mode shapes, frequencies, damping values and dynamic strain distributions, in addition to the usual material properties, crack initiation locations, etc. (See Annex A, paragraph 2.5, and paragraph 6.1, references mm and nn).

5.2 Qualification Tests.

When a test is intended to show formal compliance with contract requirements, recommend the following definitions:

a. Failure definition. "Materiel is deemed to have failed if it suffers permanent deformation or fracture; if any fixed part or assembly loosens; if any moving or movable part of an assembly becomes free or sluggish in operation; if any movable part or control shifts in setting, position or adjustment, and if test item performance does not meet specification requirements while exposed to functional levels and following endurance tests." Ensure this statement is accompanied by references to appropriate specifications, drawings, and inspection methods.

b. Test completion. "A vibration qualification test is complete when all elements of the test item have successfully passed a complete test. When a failure occurs, stop the test, analyze the failure, and repair the test item. Continue the test until all fixes have been exposed to a complete test. Each individual element is considered qualified when it has successfully passed a complete test (see paragraph 4.3). Qualified elements that fail during extended tests are not considered failures, and can be repaired to allow test completion."

5.3 Other Tests.

For tests other than qualification tests, prepare success and/or failure criteria and test completion criteria that reflect the purpose of the tests.

6. REFERENCE/RELATED DOCUMENTS

6.1 Referenced Documents.

a. Methodology Investigation, Final Report of the TECOM Package Tester Characterization, DTIC AD No. B217688, September 1996.

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METHOD 514.6 ANNEX A
Engineering Information

NOTE: Unless specifically noted, all document references refer to paragraph 6.1 in the front part of this method.

1. SCOPE.

1.1 Purpose.
This Annex provides information intended to be useful in interpreting the main body and Annex A of Method 514.6.

1.2 Application.
The following discussions concern basic engineering information. They are intended as a quick introduction to the subject matter and are offered without detailed explanations, mathematics, or references. If further information or understanding is required, the technical literature and engineering textbooks should be consulted. Paragraph 6.1, reference aa is recommended as a starting point.

1.3 Limitations.
See paragraph 1.3 in the front part of this method.

2. ENGINEERING INFORMATION.

2.1 Vibration Test Types.
The following presents discussions of general types of vibration tests. Other test types, definitions, and names will be found in practice. All of these test types may not be applied to a given materiel item. A typical materiel development might include development testing and durability testing, while another might include qualification and reliability testing. Environmental worthiness testing is included when needed. Environmental Stress Screening (ESS) is a part of most current DOD acquisitions. All of the tests, including ESS, consume vibratory fatigue life. In many cases, a qualification test, a durability test, or a reliability test consumes so much of the fatigue life of the test article that it is not suitable for field deployment. However, there are instances in which the same tests are conducted to only a portion of the fatigue life in the conduct of a system level version of an ESS test. Similarly, development tests and worthiness tests may or may not consume a complete life depending on the specific test goals. It is important to ensure ESS consumes only an appropriate, hopefully negligible, portion of total life, and that this portion is accounted for in the total life cycle of vibration exposures. In all cases, it is vital to tailor test methodology and requirements to achieve the desired results.

2.1.1 Development test.
Development testing is used to determine characteristics of materiel, to uncover design and construction deficiencies, and to evaluate corrective actions. Begin as early as practical in the development, and continue as the design matures. The ultimate purpose is to assure developed materiel is compatible with the environmental life cycle, and that formal testing does not result in failure. The tests have a variety of specific objectives. Therefore, allow considerable freedom in selecting test vibration levels, excitation, frequency ranges, and durations. Typical programs might include modal analysis to verify analytical mode shapes and frequencies, and sine dwell, swept sine, transient, or random excitation transient vibration to evaluate function, fatigue life, or wear life. The test types, levels, and frequencies are selected to accomplish specific test objectives. Levels may be lower than life cycle environments to avoid damage to a prototype, higher to verify structural integrity, or raised in steps to evaluate performance variations and fragility.

2.1.2 Qualification test.
Qualification testing is conducted to determine compliance of a materiel with specific environmental requirements. Such tests are commonly a contractual requirement and will include specific test specifications. Qualification tests should be conducted using an excitation that has the same basic characteristics as the anticipated service environment. For most items, this consists of a functional test and an endurance test (sometimes combined). The functional test represents the worst case vibration (or envelope of worst case conditions) of the environmental life cycle. The endurance test is a fatigue test representing an entire life cycle. Often, vibration can be combined with other environmental stresses.

2.1.2.1 Functional test.
Functional testing is conducted to verify that the materiel functions as required while exposed to worst case operational vibration. Fully verify function at the beginning, middle and end of each test segment. Monitor basic

function at all times during each test run. Functional test levels are normally maximum service levels. When separate functional and endurance tests are required, split the functional test duration, with one half accomplished before the endurance test, and one half after the endurance test (in each axis). The duration of each half should be sufficient to fully verify materiel function. This arrangement has proven to be a good way of adequately verifying that materiel survives endurance testing in all respects. In some cases, materiel that must survive severe worst case environments may not be required to function or function at specification levels during worst case conditions. Typically "operating" and "non-operating" envelopes are established. Tailor functional tests to accommodate non-operating portions by modifying required functional monitoring requirements as appropriate.

2.1.2.2 Endurance test.
Endurance testing is conducted to reveal time-dependent failures. In many cases the test is accelerated in order to produce the same damage as the entire duration of the required service life. Generally, it is not required to have an item powered-up during the endurance phase of test. Refer to paragraph 2.1.2.1 for functional testing. Use the simplified fatigue relationship in paragraph 2.2 below to scale the less severe vibration levels to the maximum service levels that occur during the service life. This, in turn, will define the test time at maximum service levels (functional levels) that is equivalent to a vibration lifetime (levels vary throughout each mission). Use the equivalent time as the functional test duration, thereby combining functional and endurance tests. There may be cases when this test duration is too long to be compatible with program restraints. In these cases, use as long of a test duration as is practical and use the fatigue relationship to define the test level. While this approach does not completely eliminate nonlinearity questions, it does limit levels to more realistic maximums. Generally, the test item will not be in a powered-up state during the endurance (“non-operating”) phase of testing; particularly in a situation in which the test levels have been exaggerated beyond maximum measured values in order to significantly compress the test duration.

2.1.3 Durability test.
Durability testing is a real-time (non-exaggerated) simulation of the environmental life cycle to a high degree of accuracy. A durability analysis precedes the test and is used to determine which environmental factors (vibration, temperature, altitude, humidity, etc.) must be included in the test to achieve realistic results. Although the test is intended to be a real time simulation of the life cycle, it may be shortened by truncation if feasible. Truncation is the elimination of time segments that are shown by the durability analysis to be benign with regard to materiel function and life. Durability analyses should use fatigue and fracture data applicable to each material, rather than the simplified expressions of paragraph 2.2 below.

a. Worst case levels. Mission portions of the environmental life cycle are represented in the durability test by mission profiles. Mission profiles are statistical definitions of environmental stress and materiel duty cycle versus time. Mission profiles often do not include worst case environmental stresses because they are encountered too rarely to be significant statistically. However, it is important to verify that materiel will survive and function as needed during extreme conditions. Therefore, insert maximum environmental levels into the durability test, in a realistic manner. For example, in the case of a fighter airplane, the maximum levels would be inserted during an appropriate combat mission segment rather than a more benign segment such as cruise.

b. Success criteria. Pass/fail criteria for durability tests are established for the particular effort. Criteria could include no failures, a maximum number of failures, a maximum amount of maintenance to fix failures, or some combination of these.

2.1.4 Reliability test.
Reliability testing is accomplished to obtain statistical definitions of materiel failure rates. These tests may be development tests or qualification tests. The accuracy of the resulting data is improved by improving realism of the environmental simulation. Test requirements are developed by engineers responsible for materiel reliability. Specific definitions for reliability test as discussed in paragraph 6.1, reference aa are provided below.

2.1.4.1 Statistical Reliability test.
A statistical reliability test is a test performed on a large sample of production items for a long duration to establish or verify an assigned reliability objective for the equipment operating in its anticipated service environment, where the reliability objective is usually stated in terms of a mean-time-to-failure (MTTF), or if all failures are assumed to be statistically independent, a mean-time-between-failures (MTBF) or failure rate (the reciprocal of MTBF). To provide an accurate indication of reliability, such tests must simulate the equipment shock and vibration environments with great accuracy. In some cases, rather than applying stationary vibration at the measured or

predicted maximum levels of the environment, even the non-stationary characteristics of the vibration are reproduced, often in combination with shocks and other environments anticipated during the service life (see Annex A of Method 516.6). The determination of reliability is accomplished by evaluating the times to individual failures, if any, by conventional statistical techniques.

2.1.4.2 Reliability Growth test.
A reliability growth test is a test performed on one or a few prototype items at extreme test levels to quickly cause failures and, thus, identify weaknesses in materiel design. In many cases, the test level is increased in a stepwise manner to clearly identify the magnitude of the load needed to cause a specific type of failure. Design changes are then made and the failure rate of the materiel is monitored by either statistical reliability tests in the laboratory or valuations of failure data from service experience to verify that the design changes produced an improvement in reliability. Unlike statistical reliability tests, reliability growth tests do not simulate the magnitudes of the service environments, although some effort is often made to simulate the general characteristics of the environments; for example, random vibration would be used to test materiel exposed to a random vibration service environment.

2.1.5 Worthiness test.
When unqualified materiel is to be evaluated in the field, verification that the materiel will function satisfactorily is normally required for safety and/or test efficiency reasons. This is accomplished by environmental worthiness test. The worthiness test is identical to a qualification test except that it covers only the life cycle of the field evaluation. Levels are usually typical operating levels unless safety is involved; then maximum operating levels are necessary. Durations are either equivalent to a complete system/subsystem test, long enough to check materiel function, or an arbitrary short time (5 or 10 minutes). For safety driven worthiness test, the test item is considered to be consumed by the test (the test item may not be used in the field). An identical item of hardware is used in the field evaluation. When safety is not an issue, an item may be subjected to a minimum time functional test and then used in the field evaluation. When it is required to evaluate the cumulative environmental effects of vibration and environments such as temperature, altitude, humidity, leakage, or EMI/EMC, a single test item should be exposed to all environmental conditions. For air worthiness testing, a three step approach may be required. For example, this could include conducting and initial laboratory vibration test, followed by experimental flight testing to acquire the actual exposure levels, and ending with a qualification test based on the measured field data.

2.1.6 Environmental Stress Screening (ESS).
ESS is not an environmental simulation test representative of a life cycle event and is not a substitute for a qualification test. It is a production or maintenance acceptance inspection technique designed to quickly induce failures due to latent defects that would otherwise occur later during service. However, it is an environmental life cycle event and should be included as preconditioning or as part of the test as appropriate. Materiel may be subject to multiple ESS cycles, and maintenance ESS vibration exposures may differ from production acceptance exposures. ESS should be included in development tests only as appropriate to the test goals. The vibration environment is sometimes applied using relatively inexpensive, mechanically or pneumatically driven vibration testing machines (often referred to as impact or repetitive shock machines) that allow little or no control over the spectrum of the excitation. Hence, the screening test environment generally does not represent an accurate simulation of the service environment for the materiel.

2.2 Test Time Compression and the Fatigue Relationship.
The major cause of items failing to perform their intended function is material fatigue and wear accumulated over a time period as a result of vibration-induced stress. It is preferable for materiel to be tested in real-time so the effects of in-service conditions are simulated most effectively. However, in most instances real-time testing cannot be justified based on cost and/or schedule constraints and, therefore, it is customary to compress the service life environment into an equivalent laboratory test. For vibration environments that vary in severity during the materiel's service life, the duration of the environment can often be reduced for testing by scaling the less severe segments of the vibration environment to the maximum levels of the environment by use of an acceptable algorithm. In many cases, scaling less severe segments to the maximum levels may still yield a test duration that is still too long to be practical. In such cases, the same algorithm may be used to further reduce test duration by increasing test amplitude. Provided that fatigue is a significant potential failure criterion for the materiel under test, this practice is acceptable within strict limits, notably that test amplitudes are not over exaggerated (or accelerated) simply to achieve short test durations. Such excessive amplitudes may lead to wholly unrepresentative failures, and cause suppliers to design materiel to withstand arbitrary tests rather than the in-service conditions.

The most commonly used method for calculating a reduction in test duration is the Miner-Palmgren hypothesis that uses a fatigue-based power law relationship to relate exposure time and amplitude. The mathematical expression and variable descriptions for this technique are illustrated below in Equations (1) and (4).

$$\frac{t_2}{t_1} = \left[\frac{S_1}{S_2}\right]^m \qquad \text{Equation (1)}$$

where

t_1 = equivalent test time

t_2 = in-service time for specified condition

S_1 = severity (rms) at test condition

S_2 = severity (rms) at in-service condition

[The ratio S_1/S_2 is commonly known as the exaggeration factor.]

m = a value based on (but not equal to) the slope of the S-N curve for the appropriate material where S represents the stress amplitude and N represents the mean number of constant amplitude load applications expected to cause failure.

Fatigue damage can be calculated using either a stress life or strain life process. For the strain life technique, the number of cycles to failure, N_f , is computed from:

$$\varepsilon_a = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \qquad \text{Equation (2)}$$

where

ε_a = test or environment strain amplitude

σ'_f = fatigue strength coefficient (material property)

E = modulus of elasticity (material property)

N_f = number of cycles to failure

b = fatigue strength exponent (material property)

ε'_f = fatigue ductility coefficient (material property)

c = fatigue ductility exponent (material property)

The fatigue strength portion of the equation represents the elastic portion of the S-N curve and the fatigue ductility portion of the equation represents the plastic portion. The stress life technique uses only the linear (elastic) portion of the curve (below yield) and is written as:

$$S_a = \sigma'_f\left(2N_f\right)^b \qquad \text{Equation (3)}$$

Where

S_a = test or environment stress amplitude

Equation (3) is valid only in the finite life region with elastic nominal stresses (generally 1000 to 10,000,000 cycles to failure). Fatigue damage outside this region can be described by a power law model in the form of Equation (1) with an exponent "*m*" that is not equal to "*b*." The value of "*m*" is strongly influenced by the material S-N curve, but fatigue life is also influenced by the surface finish, the treatment, the affect of mean stress correction, the contributions of elastic and plastic strain, the waveshape of the strain time history, etc. Therefore, the value of "*m*" is generally some proportion of the slope of the S-N curve, known as the fatigue strength exponent and designated as "*b*." Typical values of "*m*" are 80 percent of "b" for random waveshapes, and 60 percent of "*b*" for sinusoidal waveshapes. Historically, a value of *m* = 7.5 has been used for random environments, but values between 5 and 8 are commonly used. A value of 6 is commonly used for sinusoidal environments. This cumulative damage assumption is based on the fatigue properties of metals. Paragraph 6.1, reference aa (chapter 35) recommends that Miner's cumulative damage theory not be used for composite materials. However, a "wearout model," defined as "the deterioration of a composite structure to the point where it can no longer fulfill its intended purpose," is shown as a power law model in the form of Equation (1) with variable exponents dependent upon the type of composite system. It is recommended that test time compression for composite structures be treated on a case-by-case basis.

Since most vibration environments are expressed in terms of the power spectral density function, Equation (1) can also be formulated as:

$$\frac{t_2}{t_1} = \left[\frac{W(f)_1}{W(f)_2}\right]^{m/2} \qquad \text{Equation (4)}$$

where:

t_1 = equivalent test time

t_2 = in-service time for specified condition

$W(f)_1$ = PSD at test condition, g^2/Hz

$W(f)_2$ = PSD at in-service condition, g^2/Hz

[The ratio $W(f)_1/W(f)_2$ is commonly known as the exaggeration factor]

m = as stated in Equation (1)

In many instances these equations appear to offer a satisfactory solution. However, caution should always be exercised in the application of the equations. Some methods of characterizing vibration severities, notably PSDs, do not necessarily reproduce under laboratory testing the same strain responses as those experienced under in-service conditions. Exaggeration factors for materials whose fatigue characteristics are unknown or for failure mechanisms other than fatigue (such as loosening of threaded connections) cannot be calculated. Real time test levels and durations should be used in these instances unless there is sufficient information about the particular application to allow for the use of a reasonable exaggeration factor. It is recommended that the exaggeration factor be kept to a minimum value consistent with the constraints of in-service time and desired test time, and should generally not exceed values of 1.4 (S_1/S_2) or 2.0 $(W(f)_1/W(f)_2)$.

Note: Using material S-N curves results in different equivalencies for different parts in a given test item. A decision will be required as to which equivalency to use to establish test criteria.

2.3 Vibration Characterization.

The majority of vibration experienced by materiel in operational service is broadband in spectral content. That is, vibration is present at all frequencies over a relatively wide frequency range at varying intensities. Vibration amplitudes may vary randomly, periodically, or as a combination of mixed random and periodic. Most vibration tests run with steady state excitation. Steady state vibration is appropriate at times in simulation of transient events. However, there are cases where transient events can only be satisfactorily represented by transient vibration excitation.

2.3.1 Random vibration.

Random vibration is expressed as auto spectral density (also referred to as power spectral density, or PSD). The auto spectral density at a given frequency is the square of the root mean square (rms) value of the acceleration, divided by the bandwidth of the measurement. Accuracy of spectral values depends on the product of the measurement bandwidth and the time over which the spectral value is computed. The normalized random error for a spectral estimate is given by $1/\sqrt{BT}$, where B is the analysis bandwidth in Hz, and T is the averaging time in seconds. In general, use the smallest practical bandwidth or minimum frequency resolution bandwidth. Most commercially available vibration control systems assume that the acceleration amplitude has a normal (Gaussian) distribution. Other amplitude distributions may be appropriate in specific cases. Ensure that test and analysis hardware and software are appropriate when non-Gaussian distributions are encountered (refer to Method 525).

a. Frequency range. Auto spectral density is defined over a relevant frequency range. This range is between the lowest and highest frequencies at which the materiel may be effectively excited by mechanical vibration. Typically, the low frequency is one half the frequency of the lowest resonance of the materiel, or the lowest frequency at which significant vibration exists in the environment. The high frequency is two times the highest materiel resonant frequency, the highest frequency at which significant vibration exists in the environment, or the highest frequency at which vibration can be effectively transmitted mechanically. Historically due to limitations in fixture transmissibility and shaker resonances, testing has been limited to a high frequency of 2000 Hz for mechanically transmitted vibration. However this limitation has changed with some facilities now performing system level tests to 3000 Hz and component level tests to 4000 Hz. When higher frequencies are needed, it may be necessary to augment the vibration with acoustic noise (see Method 523.3).

b. Rms values. The use of rms values to specify random vibration is not sufficient. The spectrum rms value is the square root of the area under the spectral density curve over the total frequency range. It contains no frequency information. Rms values are useful as a general error check, and as a measure of power needed to run a vibration shaker. Definitions of vibration should always include frequency spectra.

2.3.2 Sinusoidal vibration.

Sine vibration is expressed as acceleration and a frequency. An environment dominated by sine vibration is characterized by a fundamental frequency and harmonics (multiples) of that fundamental. Often there will be more than one fundamental frequency. Each fundamental will generate harmonics. The service vibration environment in some cases (low performance propeller aircraft and helicopters for example) contains excitation that is basically sinusoidal in nature, and with a very low broadband background. The excitation derives from engine rotational speeds, propeller and turbine blade passage frequencies, rotor blade passage, and their harmonics. Environments such as this may be best simulated by a sinusoidal test. Ensure the frequency range of the sinusoidal exposure is representative of the platform environment. In many cases the broadband random may be of sufficient amplitude that the concept of simply omitting the broadband energy and conducting a pure sine test is either questionable or not acceptable. If so, refer to paragraph 2.3.3.

2.3.3 Mixed broadband and narrowband vibration.

In some cases, the vibration environment is characterized by quasi-periodic excitation from reciprocating or rotating structures and mechanisms (e.g., rotor blades, propellers, pistons, gunfire). When this form of excitation predominates, source dwell vibration is appropriate. Source dwell is characterized by broadband random vibration, with higher level narrowband random, or sinusoidal vibration superimposed. Since data reduction techniques affect the apparent amplitudes of these different types of signals, exercise care when determining levels of random and sinusoidal vibration from measured data.

a. Narrowband random over broadband random. Ensure that the amplitudes and frequencies of the total spectrum envelope the environment. The narrowband bandwidth(s) should encompass or be cycled through frequencies representative of variations of the environment and variations of materiel resonant frequency (see paragraph 2.4.3 below).

b. Sinusoid(s) over broadband random background. Ensure the random spectrum is continuous over the frequency range, and that it envelopes all of the environment except for the amplitude(s) to be represented by the sinusoid(s). The sinusoid(s) amplitude(s) should envelope the sinusoid(s) in the environment. Cycle the sinusoid(s) frequency(s) through bands representative of frequency variations in the environment and resonant frequency variations in materiel (see paragraph 2.4.3 below).

2.3.4 Transient vibration.

Transient vibration is a time-varying "windowed" portion of a random vibration that is of comparatively short duration, e.g., 0.5 second to 7.5 seconds. Currently, such a measured environment is replicated in the laboratory on a vibration exciter under waveform control. Verification of the laboratory test is provided by (1) display of the laboratory measured amplitude time history; (2) an optimally smooth estimate of the amplitude time history time-varying root-mean-square, and (3) either an energy spectral density estimate, or a Shock Response Spectrum (SRS) estimate for comparatively short environments (transient vibration duration less than the period of the first natural mode of the test item), or a time-varying autospectral density estimate of longer duration environments, e.g., 2.5 to 7.5 seconds. In general, since the environment is being replicated in the laboratory under waveform control, if the impulse response function of the system is correctly determined and correctly applied, the replication should be nearly identical to the measured environment. The transient vibration environment is an important environment for stores resident in platform weapon bays that may be exposed to such environments many times in the life of training missions. (See paragraph 6.1. references c and bb, Method 516.6, and Method 525 for procedures relative to transient vibration.)

2.3.5 Random versus sinusoidal vibration equivalence.

In the past, most vibration was characterized in terms of sinusoids. Currently, most vibration is correctly understood to be random in nature and is characterized as such. This results in a demand to determine equivalence between random and sine vibration. This demand is generated by the need to use materiel that was developed to sine requirements.

a. General equivalence. Sine and random characterizations of vibration are based on distinctly different sets of mathematics. In order to compare the effects of given random and sine vibration on materiel, it is necessary to know the details of materiel dynamic response. A general definition of equivalence is not feasible.

b. Grms. Often, attempts are made to compare the peak acceleration of sine to the rms acceleration of random. The only similarity between these measures is the dimensional units that are typically acceleration in standard gravity units (g). Peak sine acceleration is the maximum acceleration at one frequency (see paragraph 2.3.2). Random rms is the square root of the area under a spectral density curve (see paragraph 2.3.1). **These are not equivalent!**

2.4 Platform/Materiel and Fixture/Test Item Interaction.

Generally, it is assumed that the vibration environment of the materiel is not affected by the materiel itself. That is, the vibration of the platform at the materiel attachment point would be the same whether or not the materiel is attached. Since the entire platform, including all materiel, vibrates as a system, this is not strictly correct. However, when the materiel does not add significantly to the mass or stiffness of the platform, the assumption is correct within reasonable accuracy. The following paragraphs discuss the limitations of this assumption. These effects also apply to sub-elements within materiel and to the interactions of materiel with vibration excitation devices (shakers, slip tables, fixtures, etc.).

2.4.1 Mechanical impedance.

a. Large mass items. At platform natural frequencies where structural response of the platform is high, the materiel will load the supporting structures. That is, the mass of the materiel is added to the mass of the structure, and it inertially resists structural motions. If the materiel mass is large compared to the platform mass, it causes the entire system to vibrate differently by lowering natural frequencies and changing mode shapes. If the materiel inertia is large compared to the stiffness of the local support structure, it causes the local support to flex, introducing new low frequency local resonances. These new local resonances may act as vibration isolators (see paragraph 2.4.2 below).

b. Items acting as structural members. When materiel is installed such that it acts as a structural member of the platform, it will affect vibrations and it will be structurally loaded. This is particularly important for relatively large materiel items, but it applies to materiel of any size. In these cases, the materiel structure adds to the stiffness of the platform and may significantly affect vibration modes and frequencies. Further, the materiel will be subjected to structural loads for which it may not have been designed. An example is a beam tied down to the cargo deck of a truck, aircraft, or ship. If the tie-downs are not designed to slip at appropriate points, the beam becomes a structural part of the deck. When the deck bends or twists, the beam is loaded and it changes the load paths of the platform structure. This may be catastrophic for the beam, the platform, or both. Be careful in the design of structural attachments to assure that the materiel does not act as a structural member.

c. Large item mass relative to supporting structures. When materiel items are small relative to the overall platform, but large relative to supporting structures, account for the change in local vibration levels, if practical. This effect is discussed in Annex D, paragraph 2.1 for materiel mounted in jet aircraft. Due to differences in environments, relative sizes, and structural methods, the factor defined in Annex C, Table 514.5C-VIII is not applicable to materiel mounted in small, unmanned aircraft.

d. Large item size/mass relative to platform. When materiel is large in size or mass relative to the platform, always consider the potential of damage to the platform as a result of materiel vibration. It is imperative to consider these effects in the design of vibration test fixtures. Otherwise, the vibration transmitted to the test item may be greatly different than intended.

2.4.2 Vibration isolation.
Vibration isolators (shock mounts), isolated shelves, and other vibration isolation devices add low-frequency resonances to the dynamic system that attenuate high-frequency vibration inputs to materiel. Vibration inputs at the isolation frequencies (materiel six degree-of-freedom rigid body modes) are amplified, resulting in substantial rigid body motions of the isolated materiel. Effective performance of these devices depends on adequate frequency separation (minimum factor of two) between materiel resonant frequencies and isolation frequencies, and on adequate sway space (clearance around isolated materiel) to avoid impacts of the isolated materiel with surrounding materiel (possibly also vibration isolated and moving) and structure.

a. Sway space. Include sway amplitude and isolation characteristics (transmissibility versus frequency) in all design analyses and measure them in all vibration tests. Isolation devices are nonlinear with amplitude. Evaluate these parameters at vibration levels ranging from minimum to maximum. These comments also apply to isolated sub-elements within materiel items.

b. Minimum ruggedness. All materiel should have a minimum level of ruggedness, even if protected by isolation in service use and shipping. Thus, when materiel development does not include all shipping and handling environments of the materiel's life cycle, include the appropriate minimum integrity exposures in materiel (Annex E, paragraph 2.1.1).

2.4.3 Materiel resonant frequency variation.
The installed resonant frequencies of materiel may vary from those of the laboratory test. One cause is the small variations between serial items from an assembly process. Tightness of joints, slight differences in dimensions of parts and subassemblies, and similar differences affect both the resonant frequencies and the damping of the various modes of the item. A second cause is the interaction between the materiel and the mounting. As installed for field use, a materiel item is tied to mounting points that have an undefined local flexibility, and that move relative to each other in six degrees of freedom as the platform structure vibrates in its modes. In a typical laboratory test, the test item is tied to a massive, very stiff fixture intended to transmit single axis vibration uniformly to each mounting point. In each case, the mounting participates in the vibration modes of the materiel item and, in each case, the influence is different. When defining test criteria, consider these influences. Both in the cases of measured data and arbitrary criteria, add an allowance to narrow band spectral elements. Plus and minus five per cent has been chosen for the propeller aircraft criteria of Annex D, paragraph 2.2. This was chosen because the enveloped C-130 and P-3 aircraft data (paragraph 6.1, references p through t) in g^2/Hz form exhibited approximately this bandwidth.

2.5 Modal Test and Analysis.
Modal test and analysis is a technique for determining the structural dynamic characteristics of materiel and test fixtures. Modal tests (paragraph 6.1, reference cc), also known as ground vibration tests (GVT) and ground vibration surveys (GVS), apply a known dynamic input to the test item, and the resulting responses are measured and stored. Modal analysis methods are applied to the measured data to extract modal parameters (resonant frequencies, mode shapes, modal damping, etc.). Modal parameters are used to confirm or generate analytical models, investigate problems, determine appropriate instrumentation locations, evaluate measured vibration data, design test fixtures, etc. Modal analysis methods range from frequency domain, single degree of freedom methods, to time domain, multi-degree of freedom methods (paragraph 6.1, references dd and ee).

2.5.1 Modal test techniques.
Modal analysis may be accomplished in various ways. The simplest method consists of excitation with a modally tuned impact hammer. This technique is commonly used as a quick check of resonant frequencies for fixtures and installed components and is also used for verification of analytical models. A more sophisticated approach would use multi-shaker wide band random excitation, simultaneous measurement of signals from an acceleraometer and force gage array, and computer computation and storage of frequency response functions (FRF). Sinusoidal and random burst techniques are also an option. Select methodology that will result in well-understood , usable data, and that will provide the level or detail needed for the specific test goals.

2.5.2 Material non-linear behavior.
Dynamic inputs should be at as realistic levels as possible, and at as many levels as practical because materiel response is generally nonlinear with amplitude.

2.6 Aerodynamic Effects.
A primary source of vibration in aircraft and aircraft stores is the aerodynamic flow over the vehicle. Oscillating pressures (turbulence) within the flow drive vibration of the airframe surfaces. These pressures and, thus, the vibration are a linear function of dynamic pressure, and a non-linear function of Mach number. When a flow becomes supersonic, it smoothes out and turbulence drops off. Then, as speed increases, further turbulence builds up again. This phenomenon is well illustrated in the vibration data contained in paragraph 6.1, reference k. The Mach corrections given in Annex D, Table 514.5D-IV are based on an average of this data. The following definitions and the values and the formulas of Annex D, Table 514.5D-V are provided for use in calculating airspeeds and dynamic pressures. The source of the formulas is paragraph 6.1, reference ff, and the source of the atmospheric values is paragraph 6.1, reference ll.

2.6.1 Dynamic pressure.
The total pressure of a gas acting on an object moving through it is made up of static pressure plus dynamic pressure (q). The proportions vary with speed of the body through the gas. Dynamic pressure is related to speed by $q = 1/2\ \rho\ V^2$ where ρ is the density of the gas, and V is the velocity of the object through the gas.

2.6.2 Airspeed.
The speed of an aircraft moving through the atmosphere is measured in terms of airspeed or Mach number. There are several forms of airspeed designation. These are discussed below. At sea level these are equal, but as altitude increases they diverge. Equations and data required for airspeed and dynamic pressure calculations are provided in Annex D, Table 514.5D-V. These are based on paragraph 6.1, references ff and ll.

a. Calibrated airspeed. Airspeed is usually specified and measured in calibrated airspeed. Calibrated airspeed is typically expressed in nautical miles per hour (knots) and designated knots calibrated air speed (Kcas). Kcas is not true airspeed. It is derived from quantities that are directly measurable in flight. Since it is not true airspeed, it cannot be used in the simple formula for q given above.

b. Indicated airspeed. Another form of airspeed measurement is indicated airspeed. Calibrated airspeed is indicated airspeed when empirical corrections are added to account for factors in the specific aircraft installation. Indicated airspeed is expressed in various units (kilometers per hour, miles per hour, and knots), but in military aircraft it is normally in knots indicated airspeed (Kias).

c. Equivalent airspeed. Equivalent airspeed is a form directly related to dynamic pressure. It is sometimes used in engineering calculations since other forces (lift, drag, and structural air-loads) acting on an airframe are also proportional to dynamic pressure. However, it is not used in airspeed measurement systems or flight handbooks. Equivalent airspeed may be expressed in various units, but it is usually seen as knots equivalent airspeed (Keas).

d. True airspeed. This is the actual airspeed. To calculate true airspeed with an aircraft air data system, local atmospheric properties must be accurately known. This was not practical until recent years and aircraft generally do not use true airspeed in handbooks or to navigate. True airspeed may be expressed in various units but it is usually seen as knots true airspeed (Ktas).

e. Mach number. Mach number is the ratio of true airspeed to the speed of sound. When Mach number is measured by an aircraft air data system, it is true Mach number.

2.6.3 Altitude.
Aircraft air data systems measure local atmospheric pressure and convert this value to pressure altitude through a standard atmosphere model that relates pressure, temperature, and density. Pressure altitude is used in the equations relating airspeeds and dynamic pressure. Care must be exercised to assure that altitudes are pressure altitudes. Often, low altitude values for modern military aircraft are given as absolute height above local terrain. These values should be changed to pressure altitude values. Guidance from engineers familiar with mission profile development is required to make this adjustment.

2.7 Similarity.
It is often desirable to use materiel in an application other than that for which it was developed. Also, changes are made to existing materiel or the environmental exposures of an application change. The question arises as to how to verify that the materiel is suitable for the application? This is usually accomplished through a process called "qualification by similarity." Unfortunately, this process has never had a generally accepted definition. In practice it sometimes devolves to a paper exercise that provides traceability but has no engineering content. The following paragraphs are an adaptation of a set of criterion that was provided to an Air Force avionics program. It is suggested as a basis for vibration similarity criteria. Tailor the criteria for materiel type, platform environments, and program restraints. Change the emphasis from circuit cards to the particular critical elements when the materiel is not an electronic box. Also, change the fatigue equation exponents as appropriate.

2.7.1 Unmodified materiel.
Qualify unmodified materiel by documented evidence that one of the following is met:

a. The materiel was successfully qualified by test to vibration criteria that equals or exceeds the vibration requirements of the application.

b. The materiel has demonstrated acceptable reliability in an application where vibration environments and exposure durations are equal to, or more stringent than the vibration requirements of the application.

c. The materiel was successfully qualified by test to vibration criteria that falls short of the application PSD requirements in very narrow bands of energy (<5 percent of the test bandwidth) by no more than 3 dB, contingent that the materiel under test has no resonant frequencies within the subject narrow band, and that the Grms falls within a minimum of 90 percent of the application and subsequently the materiel demonstrated acceptable reliability.

2.7.2 Modified materiel.
Qualify modified materiel by documented evidence that the unmodified materiel meets the vibration requirements for the application supplemented by analyses and/or test data demonstrating that the modified materiel is dynamically similar to the unmodified materiel.

2.7.3 Equal vibration environment.
Previous tests or other vibration exposures are considered to equal the application requirement when <u>ALL</u> of the following conditions are met:

a. Previous exposures were the same type of vibration as the application requirement. That is, random vibration must be compared to random criteria, and sine must be compared to sine criteria.

b. The exposure frequency range encompasses the application frequency range. Use a low frequency limit of the range that is the low frequency limit of the application requirement, or 1/2 of the lowest materiel resonant frequency, whichever is higher. The high frequency limit of the range is the high frequency limit of the application requirement.

c. The exposure level (acceleration spectral density level or peak sinusoidal acceleration as applicable) was no more than 3.0 dB below the application requirement at any frequency, and was at or above the requirement for at least 80 percent of the total bandwidth.

d. The fatigue damage potential of the exposure(s) is not less than 50 percent of the application fatigue damage potential at each frequency, and the fatigue damage potential of the exposure(s) equals or exceeds the application fatigue damage potential over 80 percent of the frequency range. State fatigue damage potentials as totaled equivalent exposure times at maximum application levels. Base summations and equivalencies on the relationships shown in para 2.2.. These relationships should be used with metal structures only.

2.7.4 Reliability data.
Use field reliability data that meets all of the following criteria:

a. The numbers of fielded materiel from which the data were taken are sufficient to statistically represent the specific materiel item.

b. The field service seen by the materiel from which the data were taken is representative of the design environmental life cycle.

c. The field reliability data satisfies maintainability, mission readiness, mission completion, and safety requirements.

2.7.5 Critical resonant response.
Evaluate the first three natural frequencies of the chassis, and the first natural frequency of each sub assembly with the following procedure:

a. Determine the required set (first set) of natural frequencies by test.

b. Compare maximum levels at which the materiel is required to operate for the original qualification and for the application environment. Define the set (second set) of frequencies at which the application environment exceeds the original levels.

c. Determine which resonances of the first set coincide with the frequencies of the second set. Show by test or analysis that the materiel will function as required when these resonances are exposed to the application environment maximum levels.

d. Use the procedure of paragraph 2.2 above to compare the fatigue damage potential of the original qualification and the application environment. Define the set (third set) of frequencies at which the application fatigue damage potential exceeds the fatigue damage potential of the original criteria.

e. Determine which resonances of the first set coincide with the frequencies of the third set. Show by test or analysis that the required materiel life will be obtained when these resonances are exposed to the application fatigue damage potential.

2.7.6 Dynamic similarity.
Consider modified materiel as dynamically similar to baseline materiel when all of the following apply (circuit card used as an example):

a. The total change in mass of the unit and of each subassembly is within ±10 percent.

b. The unit center of gravity is within ±10 percent of the original location in any direction.

c. The mounting configuration is unchanged.

d. The mounting configuration of circuit cards is unchanged.

e. The first three natural frequencies of the chassis and the first natural frequency of each subassembly are within ±5 percent of the original frequencies.

f. The first natural frequency of each circuit board is within ±10 percent of the original frequency.

g. Each modified circuit card is vibrated for one hour in the axis perpendicular to the plane of the board. Use a test exposure that is 0.04 g^2/Hz from 15 to 1000 Hz rolled off at 6 dB per octave to 2000 Hz. Maintain electrical continuity throughout the card during and after the test. (Where vibration levels and durations at board level are known, these may be substituted for the stated exposure.)

h. Changes to mounts, chassis, internal support structures, and circuit card materials are to materials with equal or greater high cycle fatigue strength.

METHOD 514.6 ANNEX B

Manufacture / Maintenance Tailoring Guidance for Vibration Exposure Definition

1. SCOPE.

1.1 Purpose.

This Annex provides guidance intended to be useful in determining the vibration levels and durations related to the manufacture and/or maintenance of materiel.

1.2 Application.

Recommended actual environments be measured, and materiel life cycle durations be used to develop materiel design and test criteria whenever possible. Existing databases can sometimes be used in lieu of measurements. A preliminary environmental life cycle based on data provided herein can be useful as a planning tool. A preliminary life cycle definition can be used to concentrate limited resources on those vibration exposures most significant to the materiel. Guidance for setting design and test exposure values is given below with descriptions of vibration environments of many typical life cycle events. Suggested alternate criteria (levels and durations) or other guidance is recommended for those cases where measured data defining the actual environments are not available.

1.3 Limitations.

See paragraph 1.3 in the front part of this method.

2. MANUFACTURE/MAINTENANCE.

The following areas are not usually considered as part of the environmental life cycle. However these activities may result in vibratory fatigue damage to the materiel. Evaluate these environments and, where significant, include them in design and as preconditioning to environmental tests.

2.1 Category 1 - Manufacturing/Maintenance Processes.

All materiel will experience some vibration during manufacture and maintenance. When different serial number items (lots) experience significant differences in vibration exposure during manufacture, select vibration test specimens, exposure levels, and exposure durations from those lots that experience the maximum vibration exposure. For maintenance, evaluate this environment and, when significant, include it in design and test exposures, along with the exposure levels and durations.

2.2 Category 2 - Shipping and Handling.

Parts, subassemblies, and materiel are subject to vibration during handling and transportation within and between manufacturing and maintenance facilities. When there are significant differences between exposures to different serial number items (lots), select vibration test articles from those lots that experience the maximum vibration exposure, and determine exposure durations from manufacturing and maintenance planning. Where transportation is by normal commercial means, use the applicable guidance of Annex C, paragraph 2. For other means of transportation, measure exposure levels.

2.3 Category 3 - Environmental Stress Screening (ESS).

Parts, subassemblies, and materiel are often subject to ESS vibration exposures during manufacturing and maintenance. While exposure levels are identical for each like item, exposure durations are not. Items can be subjected to multiple cycles of ESS prior to production acceptance. Further, exposures are often significant with respect to vibratory fatigue. Include maximum allowable exposures in design calculations and as environmental test preconditioning. Use specified exposure levels and the maximum allowable production and maintenance exposure durations for part, subassembly, and materiel ESS.

METHOD 514.6 ANNEX C

Transportation Tailoring Guidance for Vibration Exposure Definition

NOTE: Unless specifically noted, all document references refer to paragraph 6.1 of the front part of this method.

1. SCOPE.

1.1 Purpose.

This Annex provides information on transportation environments that is intended to be useful in determining the vibration levels and durations of environmental life cycle events, and in defining the tests necessary to develop materiel to operate in and survive these environments.

1.2 Application.

Recommend actual environments be measured and materiel life cycle durations be used to develop materiel design and test criteria whenever possible. Existing databases can sometimes be used in lieu of measurements. A preliminary environmental life cycle based on data provided herein can be useful as a planning tool. A preliminary life cycle definition can be used to concentrate limited resources on those vibration exposures most significant to the materiel. Guidance for setting design and test exposure values is given below with descriptions of vibration environments of many typical life cycle events. Suggested alternate criteria (levels and durations) or other guidance is recommended for those cases where measured data defining the actual environments are not available. Table 514.6-I in the front part of this method contains an outline of the following section with references to the paragraph numbers.

1.3 Limitations.

See paragraph 1.3 in the front part of this method.

2. TRANSPORTATION.

a. Test item configuration. In all transportation exposures, configure the test item (packaged or not) as appropriate for the specific transportation phase. The following criteria are defined as inputs to packaged (or transportation configured) materiel. Use test items that are real materiel in real packaging. Making a vibration measurement on a simulated (dummy) item and comparing this to other vibration exposures of the materiel life cycle is generally not adequate. See paragraph 1.3b in the front part of this method, and Annex A, paragraph 2.4.

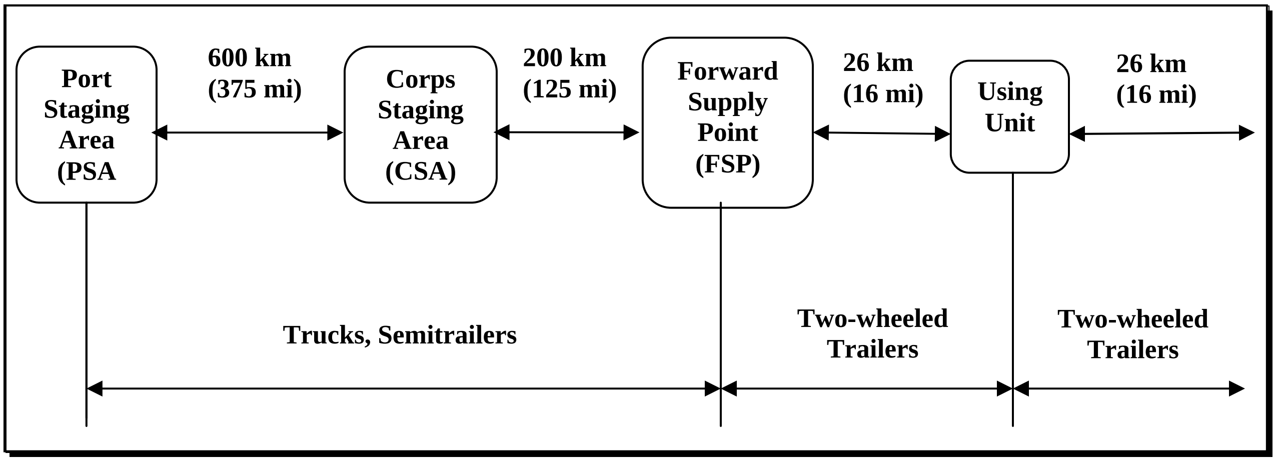
b. Configuration variation with transportation phase. Packaging is sometimes reconfigured for different transportation phases. For example, shipping containers may have low frequency shock isolation systems to protect against dropping and bumping while loading and unloading. This low frequency system may be bypassed by blocking or bracing when the container is loaded in the cargo area of the transport vehicle. The guidance provided below is for the vibration portion of the environment while being transported by various vehicles. See Method 516.6 for guidance on shock environments.

c. Shock or vibration isolation. Materiel as packaged for shipment should not have very low resonant frequencies (see Annex A, paragraph 2.4.2). Otherwise, damage due to impacting of fixed and suspended elements or over-extension of suspension elements is likely. Packaging/configuring for transport should include blocking softly suspended internal elements to prevent low frequency relative motion between suspended elements and surrounding structures. The minimum suspension frequency should be two times the frequency of any low frequency spike or hump in the input spectra. In addition, the minimum suspension frequency of materiel packaged for transport on fixed wing aircraft should be 20 Hz (see paragraphs 2.4 and 2.5 below).

d. Materiel orientation. When packaged materiel orientation is fixed relative to the transportation vehicle, vibration exposures should be related to vehicle orientation (e.g., vertical, longitudinal, transverse). When orientation within the vehicle can vary, vibration exposures should be derived from envelopes of possible orientations (e.g., longitudinal and transverse combined, vertical).

> **Note**: Paragraph 2.2 below for truck/trailer large assembly cargo can be tailored to any cargo size or tiedown configuration when high accuracy of ground vehicle transport environmental measurement or test is required.

Table 514.6C-I. Typical mission / field transportation scenario.[1, 2]



[1]See paragraph 6.1, reference oo.

[2]Track vehicles are no longer used as cargo carriers.

2.1 Category 4 - Truck/Trailer - Secured Cargo.
These transportation environments are characterized by broadband vibration resulting from the interaction of vehicle suspension and structures with road and surface discontinuities. Representative conditions experienced on moving materiel from point of manufacture to end-use are depicted inFigure 1-4a. This environment may be divided into two phases, truck transportation over US highways, and mission/field transportation. Mission/field transportation is further broken down into two-wheeled trailer and wheeled vehicles categories.

2.1.1 Truck transportation over US highways. This involves movement from the manufacturer's plant to any continental United States storage or user installation. (Data are available for US roads but not for roads in other countries.) This movement is usually accomplished by large truck and/or tractor-trailer combination. Mileage for this transportation generally ranges from 3200 to 6400 kilometers (2000 to 4000 miles) over improved or paved highways.

2.1.2 Mission/field transportation. This involves movement of materiel as cargo where the platform may be two-wheeled trailers, 2-1/2 to 10 ton trucks, and/or semi-trailers. Typical distances for this phase are 483 to 804 kilometers (300 to 500 miles). Road conditions for mission/field support differ from the common carrier in that, in addition to the paved highway, the vehicles will traverse unimproved roads and unprepared terrain (off-the-road) under combat conditions.

2.1.3 Exposure levels. Whenever possible, measure vibration on the transport vehicles using the road conditions (surfaces, speeds, and maneuvers) of the materiel's Life Cycle Environment Profile. Include realistic load configurations (approximately 75 percent of the vehicle load capacity by weight). Use these data to develop exposure levels (see examples in ITOP 1-2-601 (paragraph 6.1, reference d)). Alternatively, derive exposure levels as discussed below.

2.1.3.1 Truck transportation over US highways. Derive exposure levels from Figure 514.6C-1 and Table 514.6C-II. These figures are based on data measured at the cargo floor of seven different configurations of trucks and semitrailer combinations. Both conventional suspensions and air-cushioned suspensions are represented. The data were collected from typical interstate highways (including rough portions as part of the database).

a. **Test Schedule:** Secured Cargo - Common Carrier (See paragraph 6.1, reference pp.)

Vehicles Used for Composite: This schedule is based on data measured at the cargo floor of seven different configurations of trucks and semitrailer combinations. Both conventional suspensions and air-cushioned suspensions are represented. The data were collected from typical interstate highways with rough portions as part of the database:

Measured Locations: Measurements were made on the cargo floor of the vehicles tested.

Type of Test Load: Unknown.

Scenario to be Simulated: 1609 km (1000 miles) on interstate highways.

Assumptions (Scenario, Load, Failure Mechanism, etc.):
100 percent of scenario is on improved interstate highways
Fatigue is the failure mode

Test Time Compression: This test represents 1609 km in 60 minutes so there is time compression involved. The algorithm used to determine the exaggeration factor is unknown.

Test Time: 60 minutes per axis

Exaggeration Factor: Unknown

Method of Combination of Spectra: Unknown.

Location of Control Accelerometer(s): 2 accelerometers at opposite corners, within 30 cm (12 in.) from test item

Recommended Control Scheme: Average (Extremal control may be appropriate for some applications)

For movement direction definitions, see paragraph 4.4 in the front part of this method.

RMS Acceleration:[1] (Grms): Vertical - 1.04;
Transverse - 0.20;
Longitudinal - 0.74.

Velocity (in/sec) (peak single amplitude):[1]
Vertical – 7.61;
Transverse – 1.21;
Longitudinal – 4.59.

Displacement (in) (peak double amplitude):[1]
Vertical – 0.20
Transverse – 0.02;
Longitudinal – 0.11.

[1] Approximate values for a Gaussian random distribution which may vary based on the control system and spectral resolution, 3σ clipping not invoked for estimates.

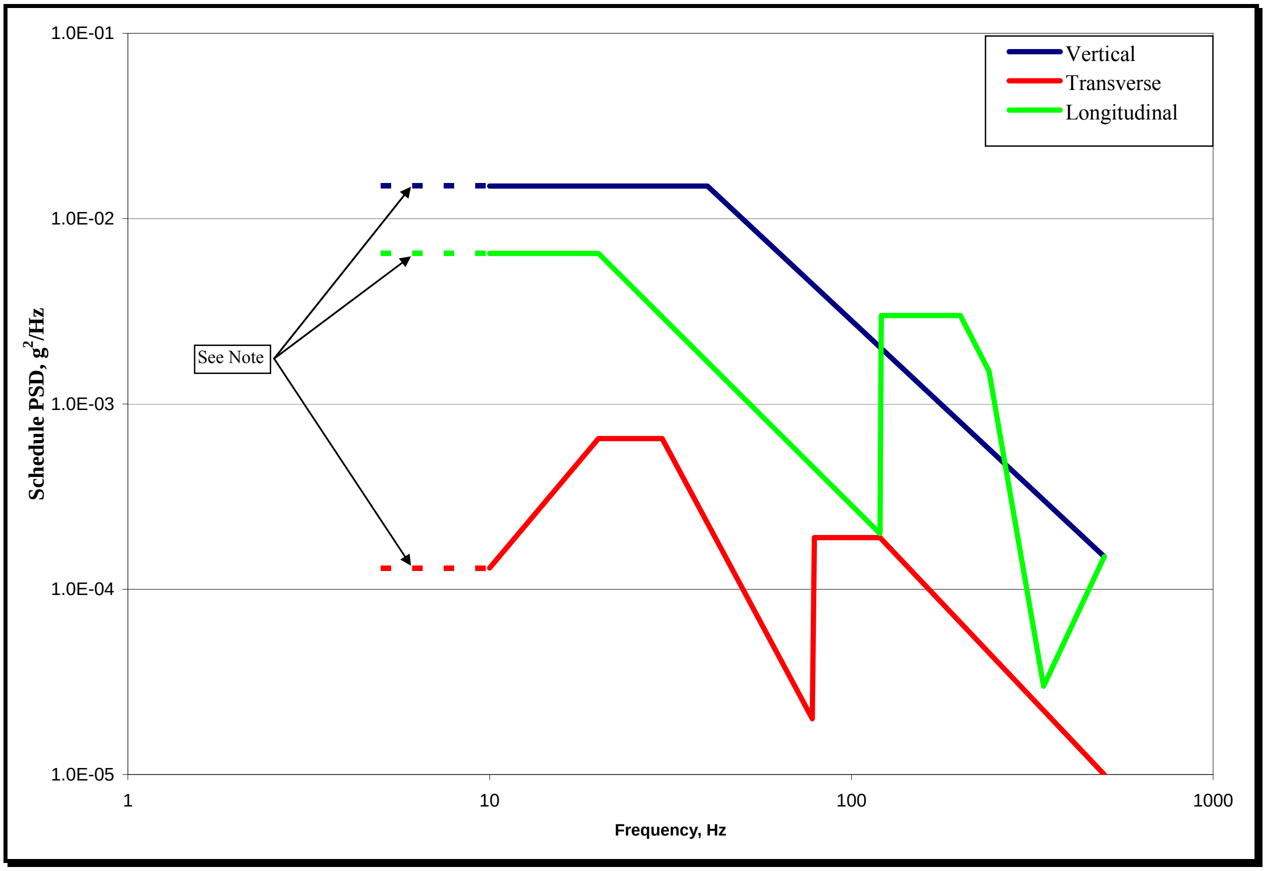


Figure 514.6C-1 – Category 4 - Common carrier (US highway truck vibration exposure).

Note: If it is known that significant excitation is expected below 10 Hz, or if the magnitude of the transfer function between the platform and test item is greater than unity for frequencies < 10 Hz, extend the curve and shape it to comply with the available data.

Table 514.6C-II. Category 4 - Common carrier (Break points for curves of Figure 514.6C-1).

Vertical		**Transverse**		**Longitudinal**	
Frequency, Hz	**PSD, g^2/Hz**	**Frequency, Hz**	**PSD, g^2/Hz**	**Frequency, Hz**	**PSD, g^2/Hz**
10	0.01500	10	0.00013	10	0.00650
40	0.01500	20	0.00065	20	0.00650
500	0.00015	30	0.00065	120	0.00020
rms = 1.04 g		78	0.00002	121	0.00300
		79	0.00019	200	0.00300
		120	0.00019	240	0.00150
		500	0.00001	340	0.00003
		rms = 0.20 g		500	0.00015
				rms = 0.74 g	

b. **Two-wheeled trailer and wheeled vehicles.**
Both trucks and two-wheeled trailers are used between the Forward Supply Point (FSP) and at the Using Unit (USU). Trailer vibration levels are significantly higher; use these to represent the wheeled vehicle environment. However, when materiel is too large for the two-wheeled trailer, use the composite wheeled levels.

(1) <u>Two wheeled trailer (TWT)</u>. Exposures are shown in Figure 514.6C-2, and are followed by the respective data table (Table 514.6C-IV). (See paragraph 6.1, references qq to ww.)

Test Schedule: Secured Cargo - Two-Wheeled Trailer

Vehicles Used for Composite: Measured vibration data from the following vehicles (Table 514.6C-III) were used to develop the Two-Wheeled Trailer Vehicle test schedule:

Table 514.6C-III. Vehicles used for TWT composite.

NOMENCLATURE	DESCRIPTION
M416	U.S. 1/4-ton trailer
M105A2	U.S. 1-1/2 ton trailer
N/A	German 1-1/2 ton trailer
M1102	U.S. 1-1/4 ton trailer

Measured Locations: 9 locations on frame under cargo bed (3X3 matrix) except as noted in the table above

Type of Test Load: Sand filled ammo boxes secured (banded) to cargo bed, and loaded to ¾ of vehicle rated load

Scenario to be Simulated: 50 km from the forward supply point to the using unit described as follows: The typical mission/field transport scenario starts at the port staging area (PSA). The movement prior to this point would include transport by commercial common carrier, military long-range aircraft, ship, and/or railroad. This movement would occur over improved road surfaces or in platforms which have been proven to impose significantly lower vibration levels than those vehicles used for transport from the port staging area to the using unit. The commercial common-carrier platform environment would be significant only if no other ground transportation is to occur after arrival at the port staging area. The typical scenario has established that 50 km of transport are expected between forward supply point to the using unit. This transport is in two-wheeled trailers. The road surfaces will be paved, secondary, and cross-country.

Assumptions (Scenario, Load, Failure Mechanism, etc.):
85 percent of scenario is off-road; 1/3 of off-road environment is as severe as courses used to collect data = 14 km (9 miles) exposure. Average speed is 26 km/hr (16 mph); fatigue is the failure mode

Test Time Compression: None; this test is run in real time.

Test Time: 32 minutes per axis

Exaggeration Factor: 1.00

Method of Combination of Spectra: A statistical method as described in paragraph 6.1, reference e, and Leaflet 2410/1, Annex C of paragraph 6.1, reference kk. This method makes use of the spectral variance from different measurement locations and test conditions and produces a spectrum which is a very conservative estimate of the actual measured environments.

Location of Control Accelerometer(s): 2 accelerometers at opposite corners, within 30 cm (12 in.) from test item

Recommended Control Scheme: Average (Extremal control may be appropriate for some applications)

For movement direction definitions, see paragraph 4.4 in the front part of this method.

RMS Acceleration:[1] (Grms): Vertical – 4.43;
Transverse – 1.30;
Longitudinal – 2.86.

Velocity (in/sec) (peak single amplitude):[1]
Vertical – 41.10
Transverse – 17.60
Longitudinal – 22.40

Displacement (in) (peak double amplitude):[1]
Vertical – 2.34;
Transverse – 0.97;
Longitudinal – 1.12.

[1] Approximate values for a Gaussian random distribution may vary based on the control system and spectral resolution, 3σ clipping was not invoked for estimates. For shaker systems that are incapable of the displacement requirements of this schedule, minor adjustments may be made to the low frequency to accommodate the shaker limitations. If the schedules needs to be modified, make sure that all parties involved (tester, customer, etc.) aware of the reason for the changes, and agree to the changes prior to test. Ensure an adequate test is performed and all deviations from the published schedules are properly documented.

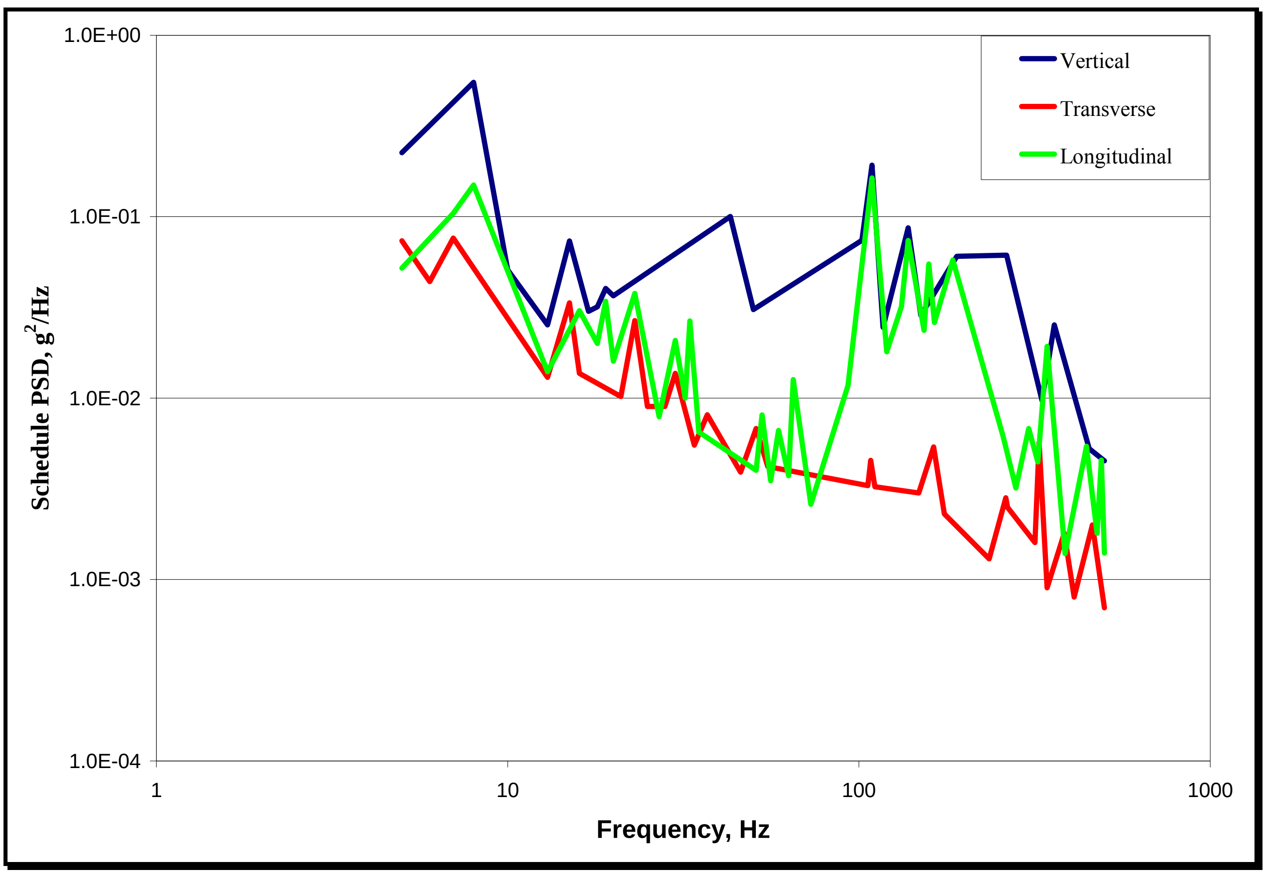


Figure 514.6C-2 – Category 4 – Composite two-wheeled trailer vibration exposure.

Table 514.6C-IV. Category 4 – Composite two-wheeled trailer vibration exposure. (Break points for curves of Figure 514.6C-2.)

Vertical		Transverse		Longitudinal	
Frequency, Hz	**PSD, g^2/Hz**	**Frequency, Hz**	**PSD, g^2/Hz**	**Frequency, Hz**	**PSD, g^2/Hz**
5	0.2252	5	0.0736	5	0.0521
8	0.5508	6	0.0438	7	0.1046
10	0.0509	7	0.0761	8	0.1495
13	0.0253	13	0.0130	13	0.0140
15	0.0735	15	0.0335	16	0.0303
17	0.0301	16	0.0137	18	0.0200
18	0.0319	21	0.0102	19	0.0342
19	0.0402	23	0.0268	20	0.0160
20	0.0366	25	0.0090	23	0.0378
43	0.1004	28	0.0090	27	0.0079
50	0.0308	30	0.0137	30	0.0208
102	0.0740	34	0.0055	32	0.0100
109	0.1924	37	0.0081	33	0.0267
117	0.0319	46	0.0039	35	0.0065
138	0.0869	51	0.0068	51	0.0040
150	0.0286	55	0.0042	53	0.0081
190	0.0605	106	0.0033	56	0.0035
263	0.0613	108	0.0045	59	0.0066
332	0.0097	111	0.0033	63	0.0037
360	0.0253	148	0.0030	65	0.0127
452	0.0053	163	0.0054	73	0.0026
500	0.0045	175	0.0023	93	0.0117
		235	0.0013	109	0.1635
rms = 4.43 g		262	0.0028	120	0.0180
		265	0.0025	132	0.0320
		317	0.0016	138	0.0738
		326	0.0057	153	0.0236
		343	0.0009	158	0.0549
		384	0.0018	164	0.0261
		410	0.0008	185	0.0577
		462	0.0020	257	0.0062
		500	0.0007	280	0.0032
				304	0.0068
		rms = 1.30 g		323	0.0045
				343	0.0193
				386	0.0014
				444	0.0054
				476	0.0018
				490	0.0046
				500	0.0014
				rms = 2.86 g	

(2) **<u>Composite wheeled vehicle (CWV)</u>**. Exposures are shown in Figure 514.6C-3, and are followed by the respective data table (Table 514.6C-VI). (See paragraph 6.1, references qq to ww.)

Test Schedule: Secured Cargo - Composite Wheeled Vehicle

Vehicles Used for Composite: Measured vibration data from the following vehicles (Table 514.6C-V) were used to develop the Composite Wheeled Vehicle test schedule:

Table C-V. Vehicles used for CWV composite.

NOMENCLATURE	DESCRIPTION
M127	US 12-ton semitrailer
M813	US 5-ton truck
M814	US 5-ton truck
M36	US 2-1/2-ton truck
M1009	US Commercial Utility Cargo Vehicle (CUCV) 1-1/2-ton truck
M998	US High-Mobility Multipurpose Wheeled Vehicle (HMMWV) 1-1/4-ton truck
M985	US Heavy Expanded Mobility Tactical Truck (HEMTT) 10-ton truck
Unimog	German 2-ton truck
MAN	German 5-, 7-, 10-, 15-ton trucks
MK27*	US Medium Tactical Vehicle Replacement (MTVR) 7-ton truck
M1083/M1084/M1085	US Medium Tactical Vehicle (MTV) 5-ton truck
M1151**/M1152	US HMMWV
M1074/M1075	US Palletized Loading System (PLS) truck
M1078***	US Light MTV 2-1/2-ton truck
MTVR-T*	US MTVR trailer
M989****	US Heavy Expanded Mobility Trailer (HEMAT)
M1076	US PLS trailer
M1095	US MTV 5-ton trailer
M1082***	US Light MTV 2-1/2-ton trailer
M871A3*****	US 22-ton semitrailer

* 2 measurement locations
** 6 measurement locations
*** 8 measurement locations
**** 4 measurement locations
***** 12 measurement locations

Measured Locations: 9 locations on frame under cargo bed (3X3 matrix) except as noted in the table above

Type of Test Load: Sand filled ammo boxes secured (banded) to cargo bed, loaded to ¾ of vehicle rated load

Scenario to be Simulated: 800km from the port staging area to the forward supply point described as follows: The typical mission/field transport scenario starts at the port staging area (PSA). The movement prior to this point would include transport by commercial common carrier, military long-range aircraft, ship, and/or railroad. This movement would occur over improved road surfaces or in platforms which have been proven to impose significantly lower vibration levels than those vehicles used for transport from the port staging area to the using unit. The commercial common-carrier platform environment would be significant only if no other ground transportation is to occur after arrival at the port staging area. The typical scenario has established that 800 km of transport are expected between the PSA and the forward supply point (FSP). This transport is in trucks and/or semitrailers. The road surfaces will be paved, secondary, and cross-country.

Assumptions (Scenario, Load, Failure Mechanism, etc.):
65 percent of scenario is off-road
1/3 of off-road environment is as severe as courses used to collect data = 172 km (108 miles) exposure
Average speed is 26 km/hr (16 mph)
Fatigue is the failure mode

Test Time Compression: Test time was computed from:

$$\frac{t_2}{t_1} = \left[\frac{W(f)_1}{W(f)_2}\right]^{m/2}$$

Where:

	t_1	=	**equivalent test time**
	t_2	=	**in-service time for specified condition**
	$W(f)_1$	=	**PSD at test condition, g^2/Hz**
	$W(f)_2$	=	**PSD at in-service condition, g^2/Hz**
	m	=	**7.5 (see paragraph 2.2 of Annex A for further explanation)**

Test Time: 120 minutes per axis

Exaggeration Factor: $\left[\frac{W(f)_1}{W(f)_2}\right] = 1.375$

Method of Combination of Spectra: A statistical method as described in paragraph 6.1, reference e and Leaflet 2410/1, Annex C of paragraph 6.1, reference kk. This method makes use of the spectral variance from different measurement locations and test conditions and produces a spectrum which is a very conservative estimate of the actual measured environments.

Location of Control Accelerometer(s): 2 accelerometers at opposite corners, within 30 cm (12 in.) from test item

Recommended Control Scheme: Average (Extremal control may be appropriate for some applications)

For movement direction definitions, see paragraph 4.4 in the front part of this method.
RMS Acceleration:[1] (Grms): Vertical – 2.24;
Transverse – 1.48;
Longitudinal – 1.90.

Velocity (in/sec) (peak single amplitude):[1]
Vertical – 39.80
Transverse – 23.30
Longitudinal – 17.00

Displacement (in) (peak double amplitude):[1]

Vertical – 2.19;
Transverse – 1.22;
Longitudinal – 0.85.

[1] Approximate values for Gaussian random distribution may vary based on the control system and spectral resolution, 3σ clipping was not invoked for estimates, For shaker systems that are incapable of the displacement requirements of this schedule, minor adjustments may be made to the low frequency to accommodate the shaker limitation. If the schedule needs to be modified, make all parties involved (tester, customer, etc.) aware of the reason for the changes, and agree to the changes prior to test. Ensure an adequate test is performed and all deviations from the published schedules are properly documented.

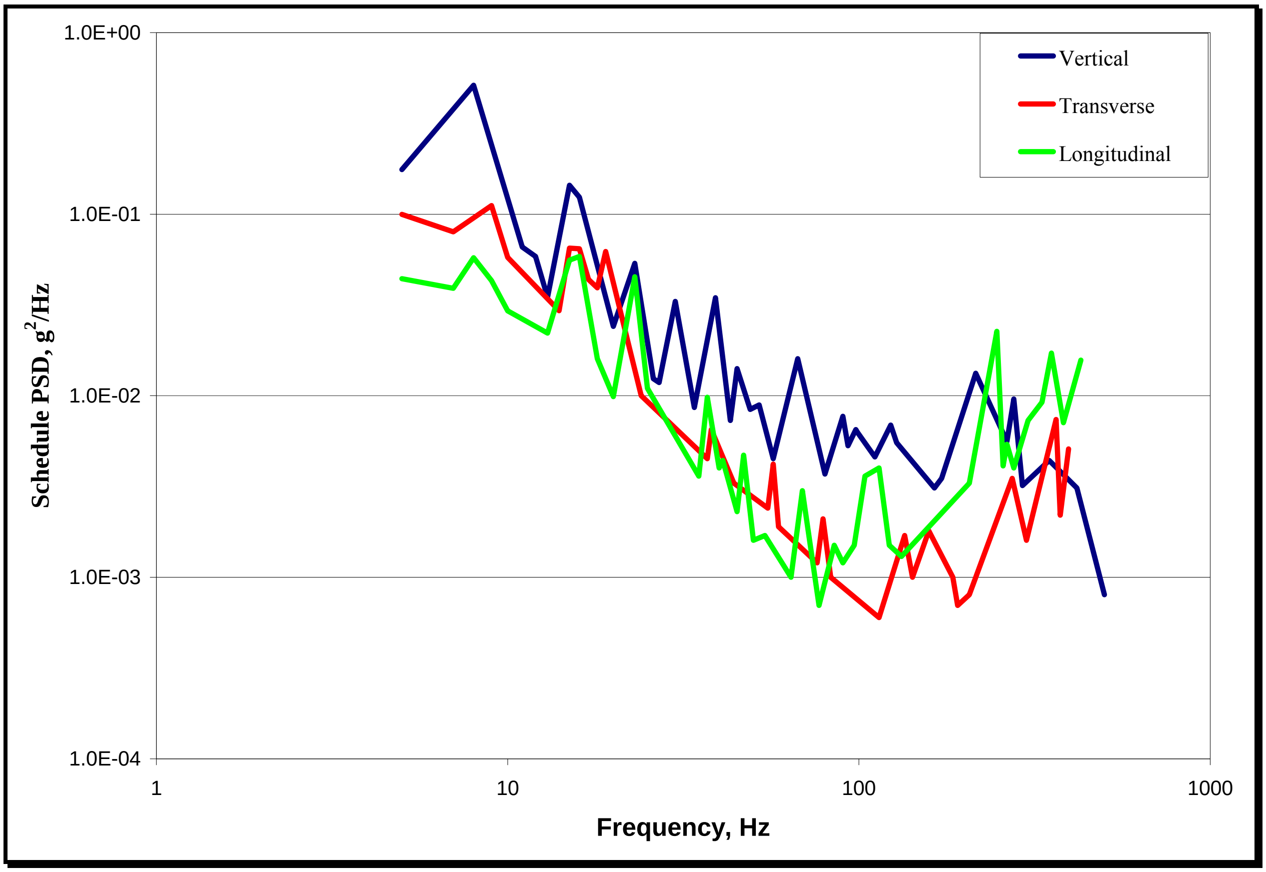


Figure 514.6C-3 – Category 4 - Composite wheeled vehicle vibration exposure.

Table 514.6C-VI. Category - 4 - Composite wheeled vehicle vibration exposure. (Break points for curves of Figure 514.6C-3.)

Vertical		Transverse		Longitudinal	
Frequency, Hz	**PSD, g^2/Hz**	**Frequency, Hz**	**PSD, g^2/Hz**	**Frequency, Hz**	**PSD, g^2/Hz**
5	0.1759	5	0.0998	5	0.0441
8	0.5120	7	0.0799	7	0.0390
11	0.0660	9	0.1115	8	0.0576
12	0.0585	10	0.0577	9	0.0430
13	0.0348	14	0.0294	10	0.0293
15	0.1441	15	0.0651	13	0.0221
16	0.1237	16	0.0646	15	0.0558
20	0.0241	17	0.0436	16	0.0585
23	0.0536	18	0.0393	18	0.0160
26	0.0124	19	0.0622	20	0.0099
27	0.0118	24	0.0100	23	0.0452
30	0.0331	37	0.0045	25	0.0110
34	0.0086	38	0.0065	35	0.0036
39	0.0347	44	0.0033	37	0.0098
43	0.0073	55	0.0024	40	0.0040
45	0.0141	57	0.0042	41	0.0044
49	0.0084	59	0.0019	45	0.0023
52	0.0089	76	0.0012	47	0.0047
57	0.0045	79	0.0021	50	0.0016
67	0.0160	83	0.0010	54	0.0017
80	0.0037	114	0.0006	64	0.0010
90	0.0077	135	0.0017	69	0.0030
93	0.0053	142	0.0010	77	0.0007
98	0.0065	158	0.0018	85	0.0015
99	0.0063	185	0.0010	90	0.0012
111	0.0046	191	0.0007	97	0.0015
123	0.0069	206	0.0008	104	0.0036
128	0.0055	273	0.0035	114	0.0040
164	0.0031	300	0.0016	122	0.0015
172	0.0035	364	0.0074	132	0.0013
215	0.0133	374	0.0022	206	0.0033
264	0.0056	395	0.0051	247	0.0226
276	0.0096	500	0.0012	257	0.0041
292	0.0032			264	0.0054
348	0.0044	rms = 1.48 g		276	0.0040
417	0.0031			303	0.0073
500	0.0008			332	0.0092
				353	0.0172
rms = 2.24 g				382	0.0071
				428	0.0157
				500	0.0016
				rms = 1.90 g	

2.1.4 Exposure durations. Base durations on the materiel Life Cycle Environment Profile. Table 514.6C-I shows the typical field/mission transportation scenario with the most typical vehicles.

a. Truck transportation over US highways. The exposure duration for common carrier/truck is 60 minutes per 1609 kilometers (1000 miles) of road travel (per axis). (See ITOP 1-1-050 (paragraph 6.1, reference e) for guidance.)

b. Two-wheeled trailer and wheeled vehicles. The exposure duration for two-wheeled trailer is 32 minutes per 51.5 kilometers (32 miles) traveled (per axis), and the exposure duration for composite wheeled vehicles is 120 minutes per 804 kilometers (500 miles) traveled (per axis).

2.2 Category 5 - Truck/trailer - loose cargo.
The cargo has freedom to bounce, scuff and collide with other cargo and with the sides of the vehicle. The loose cargo environment includes conditions experienced by cargo transported in a vehicle traversing irregular surfaces. This test replicates the repetitive random shock environment incurred by cargo transported under these conditions. This test does not address general cargo deck vibration or individual shocks or impacts inflicted during handling or accidents.

a. Test bed. (See Figure 514.6C-4.) Cover the test bed of the package tester with a cold rolled steel plate (see note below), 5 to 10mm (0.2 to 0.4 in) thick, and secure the plate with bolts, the tops of the heads of which are slightly below the surface. Space the bolts at sufficient intervals around the four edges and through the center area to prevent diaphragming of the steel plate. Do not start a test on an area of steel plate that is severely damaged or worn through.

> **Note:** Comparison of plywood bed and steel bed data show no statistical difference. Also, steel beds require less maintenance and US Army trucks use steel beds. See paragraph 6.1, reference a.

b. Fencing. Two different setups of fencing are required depending on the type of test item. The two types are those that are more likely to slide on the test surface or “rectangular cross section items” (typically packaged items), and those most likely to roll on the surface, or “circular cross section items.” ("Multiple test items" refers to identical test items, and not to a mixture of unrelated test items.) The fence opposite the vertical impact wall is not intended as an impact surface, but is used to restrain the test item from leaving the tester. The distance to this restraining fence should be sufficient to prevent constant impact, but still prevent one or more of multiple test items from “walking” away from the others. The height of the test enclosure (sideboards, impact wall, and restraining fence) should be at least 5 cm higher than the height of the test item to prevent unrealistic impacting of the test item on the top of the enclosure.

c. Test item structure.

(1) Materiel likely to slide (e.g., flat-bottomed). Using suitable fixturing as described previously, the test item is placed on the test machine. The wooden impact walls are configured so as to allow impacting on only one end wall (no rebounding), and to prevent unlimited rotation of test items that are non-symmetrical about the vertical axis. Multiple test items are not separated from one another by sideboards. The test item is positioned in its most likely transport orientation. In the event the most likely transport orientation cannot be determined, the test item is placed on the bed with the longest axis horizontal and parallel to the plane of rotation of the bed. After one-half the total designated test time, stop the test, reposition the test item to an alternate orientation, and continue the test.

(2) Materiel likely to roll (e.g., circular cross section). For the circular cross section items, place the impact walls and sideboards so as to form a square test area. The size of the test area is determined by a series of equations presented below. S_W and S_B are chosen based on test item geometry to provide realistic impacting with the test bed impact walls and between test items. A typical value for both S_W and S_B is 25 mm. Use the following formulae to determine the test area dimension:

For values of the number of test items, N > 3, compute the required slenderness ratio, R_r, from Equation (1):

$$R_r = \frac{N\ L}{0.767\,L\sqrt{N} - 2\,S_W - (N-1)S_B} \qquad \text{Equation (1)}$$

R_r = required slenderness ratio
L = length of the test item, cm
D = diameter of the test item, cm
N = number of test items
S_W = space between test item and wall, cm
S_B = space between each test item, cm

Compute the test item actual slenderness ratio, R_a, from:

$$R_a = L/D \qquad \text{Equation (2)}$$

and it is independent of the number of test items, N.

If the actual test item slenderness ratio, R_a, is greater than the required ratio, R_r, computed in Equation (1), then:

$$X = 0.767\ L\ \sqrt{N} \qquad \text{Equation (3)}$$

X = length of each side of the square test area

If the actual test item slenderness ratio, R_a, is less than the required ratio, R_r, computed in Equation (1), then:

$$X = N\,D + 2S_W + (N-1)S_B \qquad \text{Equation (4)}$$

For values of N ≤ 3, the required slenderness ratio, R_r, is computed from Equation (5):

$$R_r = \frac{N\ L}{1.5L - 2S_W - (N-1)S_B} \qquad \text{Equation (5)}$$

If the actual test item slenderness ratio, R_a, is greater than the required ratio, R_r, computed in Equation (5), then:

$$X \geq 1.5\,L \qquad \text{Equation (6)}$$

Otherwise:

X is computed from Equation (3).

Generally, if the actual slenderness ratio, L/D, is greater than 4, Equations (3) or (6), (depending upon the number of test items) are applicable.

d. Test item placement. For either type test item, the materiel is placed on the test machine in a non-uniform manner. Because part of the damage incurred during testing of these rolling items is due to them impacting with each other, the number of test items should be greater than three. After the designated test time, stop the test.

e. Exposure levels. This environment is a function of package geometry and inertial properties, vehicle geometry, and the complex vibratory motion of the vehicle cargo bed. No database exists for input vibration to simulate this environment. However, the test discussed below will provide a generally conservative simulation of the environment.

(1) Two methodology studies (paragraph 6.1, references g and h) determined that a standard package tester (300 rpm, circular synchronous mode) (Figure 514.6C-4), provides a reasonable simulation of the loose cargo transportation environment. The movement of the package tester bed is a 2.54 cm (1.0 inch) diameter orbital path at 5 Hz (each point on the bed moves in a circular path in a plane

perpendicular to the horizontal plane). The test item is allowed to collide with established test setup restraints.

(2) This test is not tailorable and cannot be directly interpreted in terms of materiel design requirements.

f. Exposure durations. A duration of 20 minutes represents 240 km (150 miles) of transportation (encompassing truck, two-wheeled trailer, and tracked vehicle), over the various road profiles found in the transport scenario from the Corps Staging Area to a Using Unit (see Table 514.6C-I). Ratio scenario times in the materiel Life Cycle Environment Profile to define exposure times.

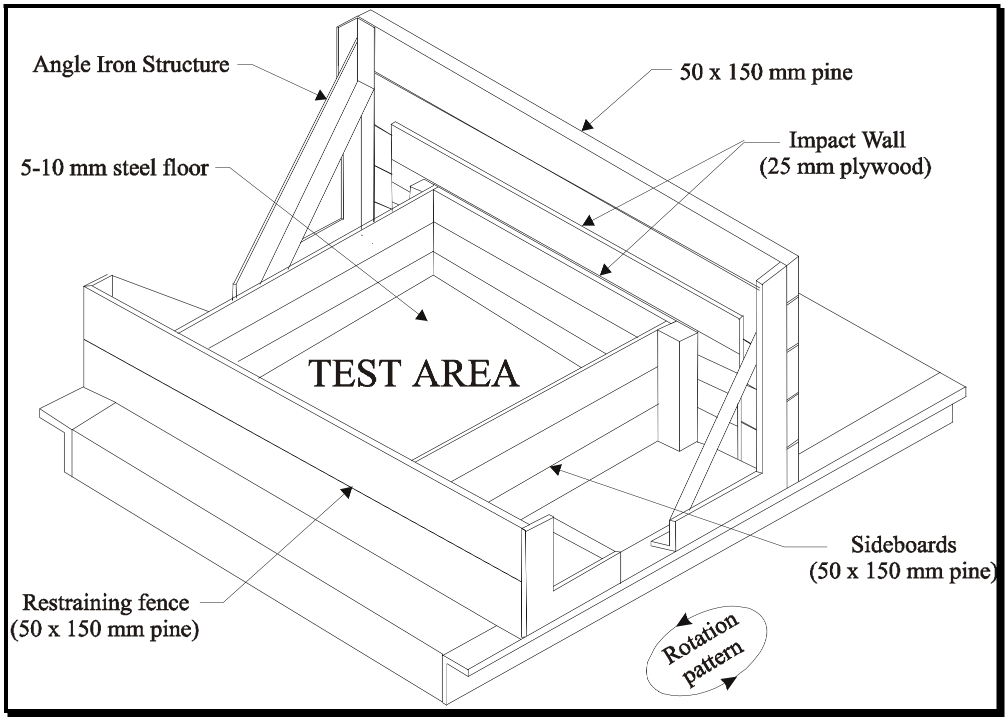


Figure 514.6C-4. Category 5 - Loose cargo test setup.

2.3 Category 6 - Truck/trailer - large assembly transport.

For large materiel, it is necessary to recognize that the materiel and the transport vehicle vibrate as a flexible system (see Annex A, paragraph 2.4). In such cases, transportation conditions may be simulated using the actual transport vehicle as the vibration exciter. The test assemblage may consist of materiel mounted in a truck or trailer, or materiel mounted in a shelter that is then mounted on a truck, trailer, or dolly set. Ensure the materiel is mounted and secured on the transport vehicle(s) that is used during actual transport. Provide instrumentation to measure vertical vibration of the materiel mounts, cargo floor, or shelter floor. Provide additional instrumentation as needed to determine the vibration of the materiel and critical subassemblies.

> **Note**: This procedure is suitable for measuring or testing for the transportation or ground mobile environment of materiel of any size or weight. For smaller cargo loads, the assemblage should be either the specific design cargo load or the most critical cargo load(s) for the transport vehicle as appropriate.

a. Exposure levels. The assemblage should be in its deployment configuration and mounted on the vehicle for which it was designed. If the assemblage is to be contained in a shelter, it should be installed within the shelter in the deployment configuration. The exposure consists of traversing the transport vehicle over a prepared test course. The test course and vehicle speeds should represent the transportation terrain/road conditions of the Life Cycle Environment Profile. Transport vehicle speeds may be limited either by the vehicle's safe operating speed over a specific course profile, or by the speed limit set for the specific course. An example based on test surfaces available at the US Army Aberdeen Test Center (paragraph 6.1, reference b) is as follows. Drive the test vehicle over each of the following test surfaces. Operate at the specified speeds unless these exceed safe driving conditions. In this case, define and coordinate maximum safe operating speeds with the authority responsible for the environmental requirements.

	Vehicle Speed MPH	(km/hr)	Course Length Ft.	(m)
(1) Coarse washboard (150 mm waves 2 m apart)	5	(8)	798	(243)
(2) Belgian block	20	(32)	3940	(1201)
(3) Radial washboard (50 mm to 100 mm waves)	15	(24)	243	(74)
(4) Two inch washboard (50 mm)	10	(16)	822	(251)
(5) Three inch spaced bump (75 mm)	20	(32)	764	(233)

b. Exposure durations. Ensure the durations (distances) of each test course segment/speed combination are in accordance with the scenario(s) of the Life Cycle Environment Profile. If the LCEP in-service road information is not available, the minimum test duration is defined by operation of the vehicle five individual times on the full length of each test course above, or an equal total distance at the indicated or test plan defined speed(s).

2.4 Category 7 - Aircraft - jet.

Cargo vibration environments on jet aircraft are broadband random in nature. The maximum vibrations are usually engine exhaust noise generated and occur during takeoff. Levels drop off rapidly after takeoff to lower level cruise levels that are boundary layer noise generated. These sources are discussed in Annex D, paragraph 2.1.

a. Low frequency vibration. Vibration criteria typically begins at 15 Hz. At frequencies below 15 Hz, it is assumed that the cargo does not respond dynamically (see Annex A, paragraph 2.4). Airframe low frequency vibration (gust response, landing impact, maneuvers, etc.) is experienced as steady inertial loads (acceleration). That part of the environment is included in Method 513.6.

b. Large cargo items. Cargo items that are large relative to the airframe in dimensions and/or mass may interact with aircraft structural dynamics (see Annex A, paragraph 2.4). This is particularly true if the materiel has natural frequencies below 20 Hz. This interaction may have serious consequences with regard to aircraft loads and flutter. Evaluate materiel that fits this description by the aircraft structural engineers prior to carriage. Contact the Aircraft Product Center Wings responsible for the aircraft type for this evaluation.

c. Exposure levels.

(1) Vibration qualification criteria for most jet cargo airplanes are available through the Aircraft Product Center Wings responsible for the aircraft type. These criteria are intended to qualify materiel for permanent installation on the airplanes and are conservative for cargo. However, function criteria for materiel located in the cargo deck zones can be used for cargo if necessary. The guidance of Annex D, paragraph 2.1 can also be used to generate conservative criteria for specific airplanes and cargo.

(2) Figure 514.6C-5 shows the cargo compartment zone functional qualification levels of the C-5, C/KC-135, C-17, C-141, E/KE-3, KC-10, and T-43A aircraft. These are recommended criteria for jet aircraft cargo. Also, shown on the figure is a curve labeled "General Exposure." This curve is based on the worst case zone requirements of the most common military jet transports, so that even though it does not envelope all peaks in the various spectra, it should still be mildly conservative for cargo. Also, since it does not allow the valleys in the individual spectra, it should cover other jet transports with different frequency characteristics. The envelope represents take-off, the worst case for cargo. Vibration during other flight conditions is substantially less.

d. Exposure durations. When Figure 514.6C-5 is used, select a duration of one minute per takeoff. Determine the number of takeoffs from the Life Cycle Environment Profile.

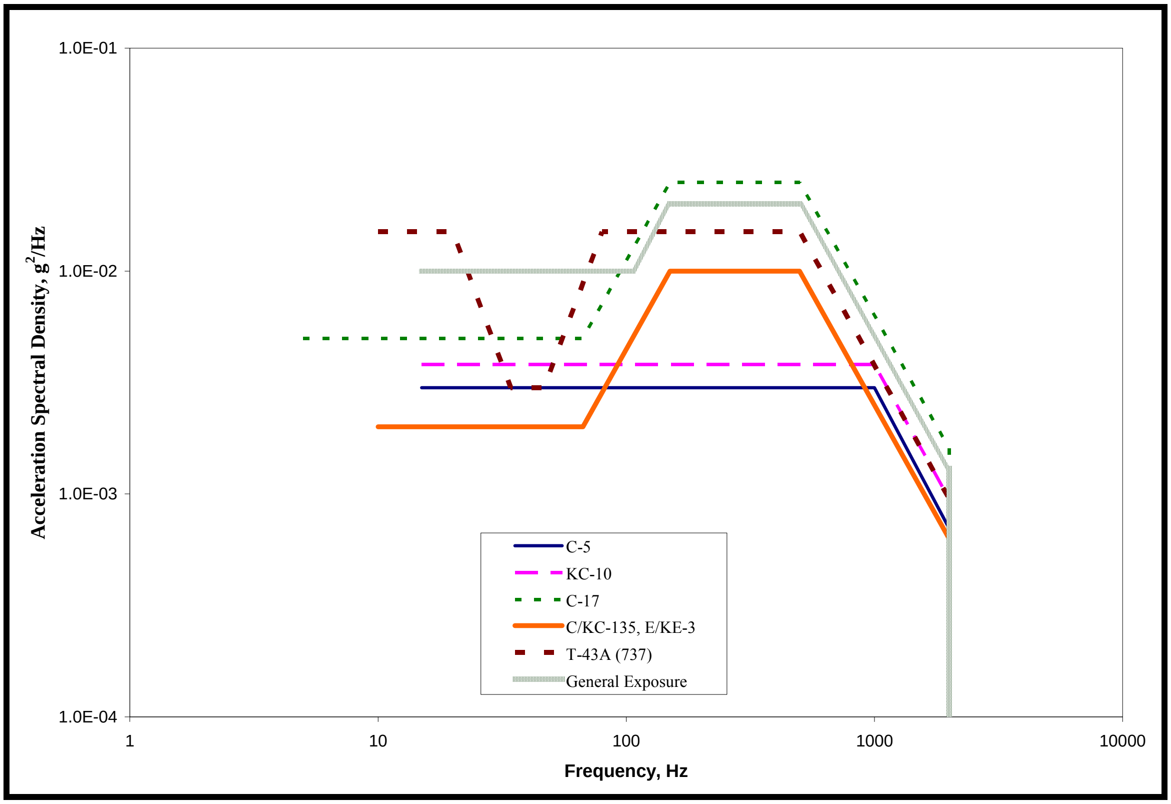


Figure 514.6C-5. Category 7 - Jet aircraft cargo vibration exposure.[1]

[1] The C-141 aircraft is no longer in the US inventory; the vibration profile has been retained for historical purposes.

Table 514.6C-VII. Category 7 - Jet aircraft cargo vibration exposure - Break points for Figure 514.6C-5.

C-5		
Hz	g^2/Hz	dB/Oct
15	0.003	
1000	0.003	
		-6
2000	7.5E-4	
rms = 2.11 g		

KC-10		
Hz	g^2/Hz	dB/Oct
15	0.0038	
1000	0.0038	
		-6
2000	9.5E-4	
rms = 2.38 g		

KC-135, E-3		
Hz	g^2/Hz	dB/Oct
10	0.002	
66.897	0.002	
		6
150	0.01	
500	0.01	
		-6
2000	6.3E-4	
rms = 2.80 g		

C-17		
Hz	g^2/Hz	dB/Oct
5	0.005	
66.897	0.005	
		6
150	0.025	
500	0.025	
		-6
2000	1.6E-3	
rms = 4.43 g		

Note: C-17 levels apply to the primary cargo floor. Levels for items carried on the aft ramp are higher.

T-43A (737)		
Hz	g^2/Hz	dB/Oct
10	0.015	
20	0.015	
		-9
34.263	0.003	
46.698	0.003	
		9
80	0.015	
500	0.015	
		-6
2000	9.5E-4	
rms = 3.54 g		

General Exposure		
Hz	g^2/Hz	dB/Oct
15	0.01	
105.94	0.01	
		6
150	0.02	
500	0.02	
		-6
2000	1.3E-3	
rms = 4.02 g		

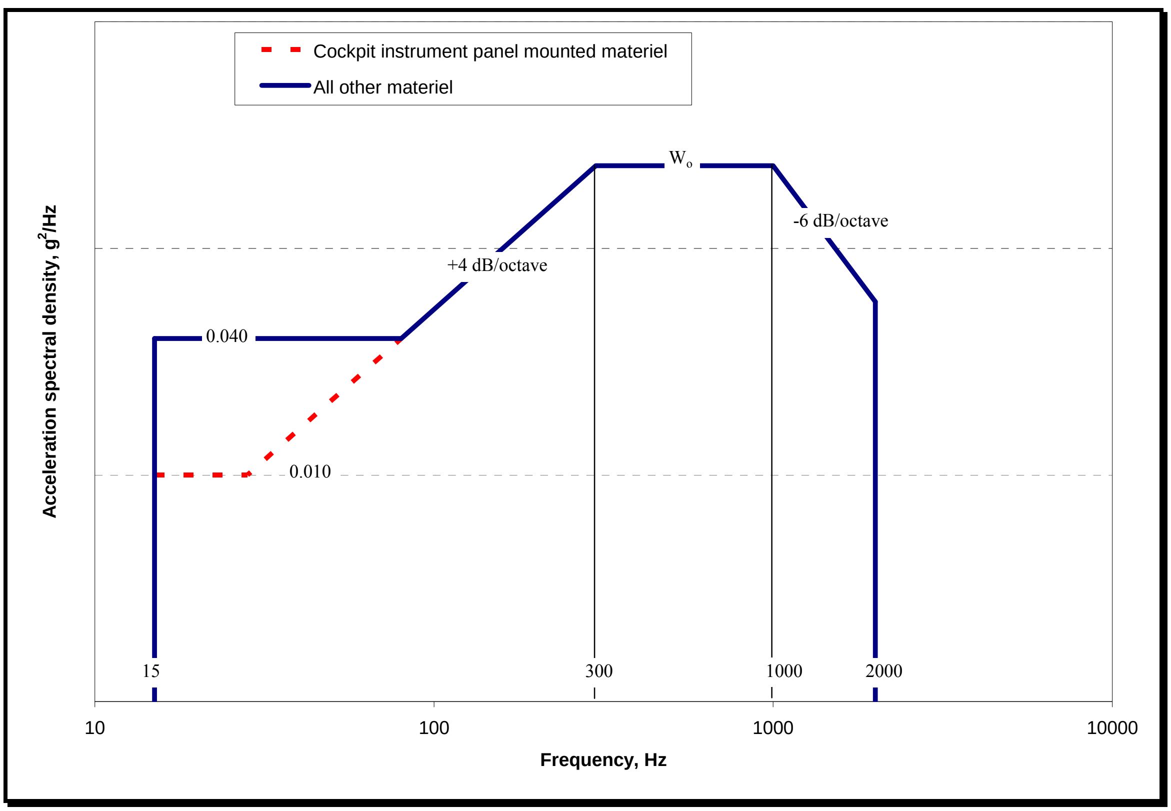


Figure 514.6C-6. Category 7 - Jet aircraft vibration exposure.

Table 514.6C-VIII. Category 7 - Jet aircraft vibration exposure.

$W_0 = W_A + \sum_1^n (W_J)$					
W_0, W_A, W_J - Exposure levels in acceleration spectral density (g^2/Hz).					
Aerodynamically induced vibration $W_A = a \times b \times c \times (q)^2$					
Jet engine noise induced vibration $W_J = \{[0.48 \times a \times d \times \cos^2(\theta)/R] \times [D_c \times (V_c / V_r)^3 + D_f \times (V_f / V_r)^3]\}$					
a	-	Platform / Materiel interaction factor (see Annex A, paragraph 2.4). Note that this factor applies to W_o and not to the low frequency portion (15 Hz to break) of Figure 514.6C-6.			
	=	1. 0 for materiel mounted on vibration isolators (shock mounts) and materiel weighing less than 36.3 kg.			
	=	$1.0 \times 10^{(0.6 - W/60)}$ for materiel weighing between 36.3 and 72.6 kg.(w = weight in kg)			
	=	0. 25 for materiel weighing 72.6 kg or more.			
b	-	Proportionality factor between vibration level and dynamic pressure (SI units).	$\sum_1^n$	-	Jet noise contribution is the sum of the W_J values for each engine.
	=	2.96×10^{-6} for materiel mounted on cockpit instrument panels.	d	-	Afterburner factor.
	=	1.17×10^{-5} for cockpit materiel and materiel in compartments adjacent to external surfaces that are smooth and free from discontinuities.		=	1. 0 for conditions where afterburner is not used or is not present.
				=	4. 0 for conditions where afterburner is used.
			R	-	Vector distance from center of engine exhaust plane to materiel center of gravity, m (ft).
	=	6.11×10^{-5} for materiel in compartments adjacent to or immediately aft of external surface discontinuities (cavities, chines, blade antennae, speed brakes, etc.), fuselage aft of wing trailing edge, wing, empennage, and pylons.	θ	-	Angle between R vector and engine exhaust vector (aft along engine exhaust centerline), degrees For $70° < \theta \le 180°$ use 70°.
c	=	Mach number correction. Note that this factor applies to W_0 and not to the low frequency portion (15 to intersection frequency at 0.04 g^2/Hz based on W_0) of Figure 514..6C-6. (Annex D, paragraph. 2.1)	D_c	-	Engine core exhaust diameter, m (ft).
			D_f	-	Engine fan exhaust diameter, m (ft).
			V_r	-	Reference exhaust velocity, m/sec (ft/sec).
				=	564 m /sec
	=	1.0 for $0 \le Mach \le 0.9$	V_c	-	Engine core exhaust velocity Engine core exhaust velocity (without afterburner), m/sec (ft/sec).
	=	$(-4.8M + 5.32)$ for $0.9 \le Mach \le 1.0$ (where M = Mach number)			
	=	0.52 for Mach number greater than 1.0	V_f	-	Engine fan exhaust velocity (without afterburner), m/sec (ft/sec).
q	-	Flight dynamic pressure, kN/m^2 (lb/ft^2). (See Annex A, para. 2.6.1 and Table 514.6D-V)			
If Dimensions are in feet and pounds then:					
a	=	1. 0 for materiel mounted on vibration isolators (shock mounts) and materiel weighing less than 80 lb.			
	=	$1.0 \times 10^{(0.60 - 0.0075 W)}$ for materiel weighing between 80 and 160 lb.			
	=	0. 25 for materiel weighing 160 lb. or more.			
b	=	6.78×10^{-9}, 2.70×10^{-8}, or 1.40×10^{-7} in the order listed above.			
V_r	=	1850 feet / second			

2.5 Category 8 - Aircraft - propeller.
Cargo vibration environments on propeller aircraft are dominated by relatively high amplitude, approximately sinusoidal spikes at propeller passage frequency and harmonics. Because of engine speed variations, the frequencies of the spikes vary over a bandwidth. There is wide band vibration at lower levels across the spectra. This wide band vibration is primarily due to boundary layer flow over the aircraft. These sources are discussed in Annex D, paragraph 2.2.

a. Low frequency vibration. Vibration criteria typically begin at 15 Hz. At frequencies below 15 Hz it is assumed that the cargo does not respond dynamically (see Annex A, paragraph 2.4). Airframe low frequency vibration (gust response, landing impact, maneuvers, etc.) are experienced as steady inertial loads (acceleration). That part of the environment is included in Method 513.6.

b. Large cargo items. Cargo items that are large relative to the airframe in dimensions and/or mass may interact with aircraft structural dynamics (see Annex A, paragraph 2.4). This is particularly true if the materiel has natural frequencies below 20 Hz. This interaction may have serious consequences with regard to aircraft loads and flutter. Materiel that fits this description must be evaluated by aircraft structural engineers prior to carriage. Contact the Aircraft Product Center Wing responsible for the aircraft type for this evaluation.

c. Exposure levels. Contact the Aircraft Product Center Wing responsible for the aircraft for vibration criteria. If no criteria are available, measurements of cargo deck vibration in the aircraft are recommended. As a last resort, the guidance of Annex D, paragraph 2.2 can be used.

d. Exposure durations. Take durations from the Life Cycle Environment Profile. If Life Cycle Environmental Profile data are not available for development of the test durations, tests should be conducted for one hour per axis.

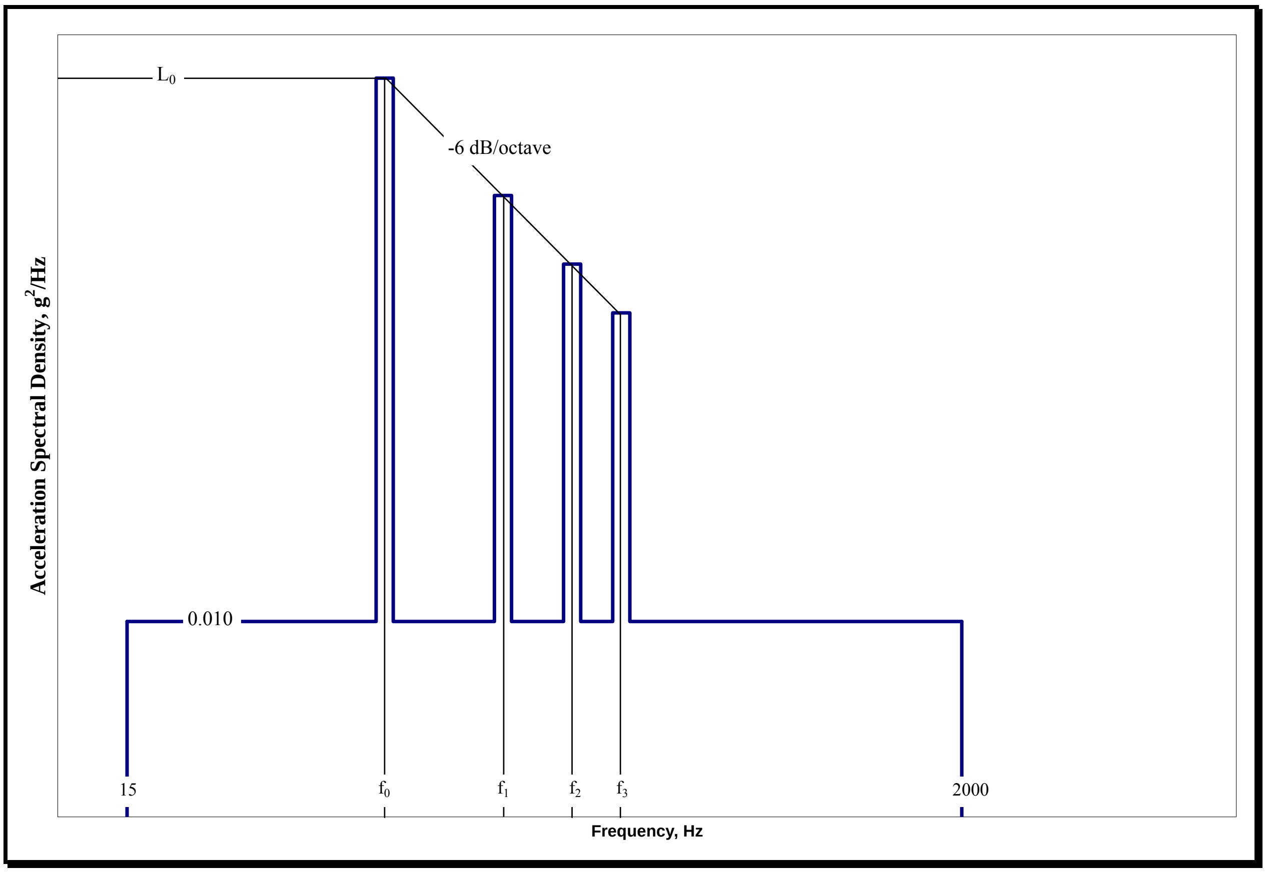


Figure 514.6C-7. Category 8 - Propeller aircraft vibration exposure.

Table 514.6C-IX Category 8 - Propeller aircraft vibration exposure.

MATERIEL LOCATION 1/, 2/, 3/, 4/	VIBRATION LEVEL L_o (g^2/Hz)
In fuselage or wing forward of propeller	0.10
Within one propeller blade radius of propeller passage plane	1.20
In fuselage or wing aft of propeller	0.30
In engine compartment, empennage, or pylons	0.60

1/ For Materiel mounted to external skin, increase level by 3 dB.

2/ f_0 = blade passage frequency (propeller rpm times number of blades) (Hz).

$f_1 = 2 \times f_0$ $f_2 = 3 \times f_0$ $f_3 = 4 \times f_0$

3/ Spike bandwidths are ± 5 percent of center frequency.

4/ C-130 Aircraft

3 blade propeller - f_0 = 51 Hz

4 blade propeller - f_0 = 68 Hz

6 blade propeller - f_0 = 102 Hz (C-130J)

2.6 Category 9 - Aircraft - helicopter.

a. Environment characterization. Vibration of cargo carried in helicopters is characterized by a continuous wideband, low-level background with strong narrowband peaks superimposed. This environment is a combination of many sinusoidal or near sinusoidal components due to main and tail rotors**,** rotating machinery and low-level random components due to aerodynamic flow. These sources are discussed in Annex D, paragraph 2.3.

b. Sling loads. Cargo carried as sling loads below a helicopter is normally subjected to low level random vibration due to turbulent flow around the cargo with narrow band peaks due to helicopter main rotor blade passage. In addition, there will be low frequency (primarily vertical) motions due to the sling suspension modes (similar to vibration isolator modes, see Annex A, paragraph 2.4.2). Choose slings based on sling stiffness and suspended mass such that suspension frequencies (f_s) do not coincide with helicopter main rotor forcing frequencies (f_i). Ensure suspension frequencies are not within a factor of two of forcing frequencies ($f_s < f_i / 2$ or $f_s > 2 f_i$). Determine main rotor forcing frequencies (shaft rotation frequency, blade passage frequency, and harmonics) for several helicopters from Table 514.6C-X. **When inappropriate combinations of cargo and slings are used, violent vibration can occur.** The cargo is likely to be dropped to protect the helicopter.

c. Exposure levels.

(1) Helicopter internal cargo vibration is a complex function of location within the helicopter cargo bay and the interaction of the cargo mass and stiffness with the helicopter structure. Measurements of the vibration of the cargo in the specific helicopter are necessary to determine vibration with any accuracy. Approximate criteria may be derived from Annex D, paragraph 2.3. These levels are intended to envelope potential worst-case environments, and have been aggressively compressed in time. Additional tailored helicopter vibration schedules are provided in paragraph 6.1, reference d.

(2) Slung cargo levels are low and should not be a significant factor in design of materiel that has a reasonable degree of ruggedness.

d. Exposure durations. Take durations from the Life Cycle Environment Profile or from paragraph 6.1, reference f.

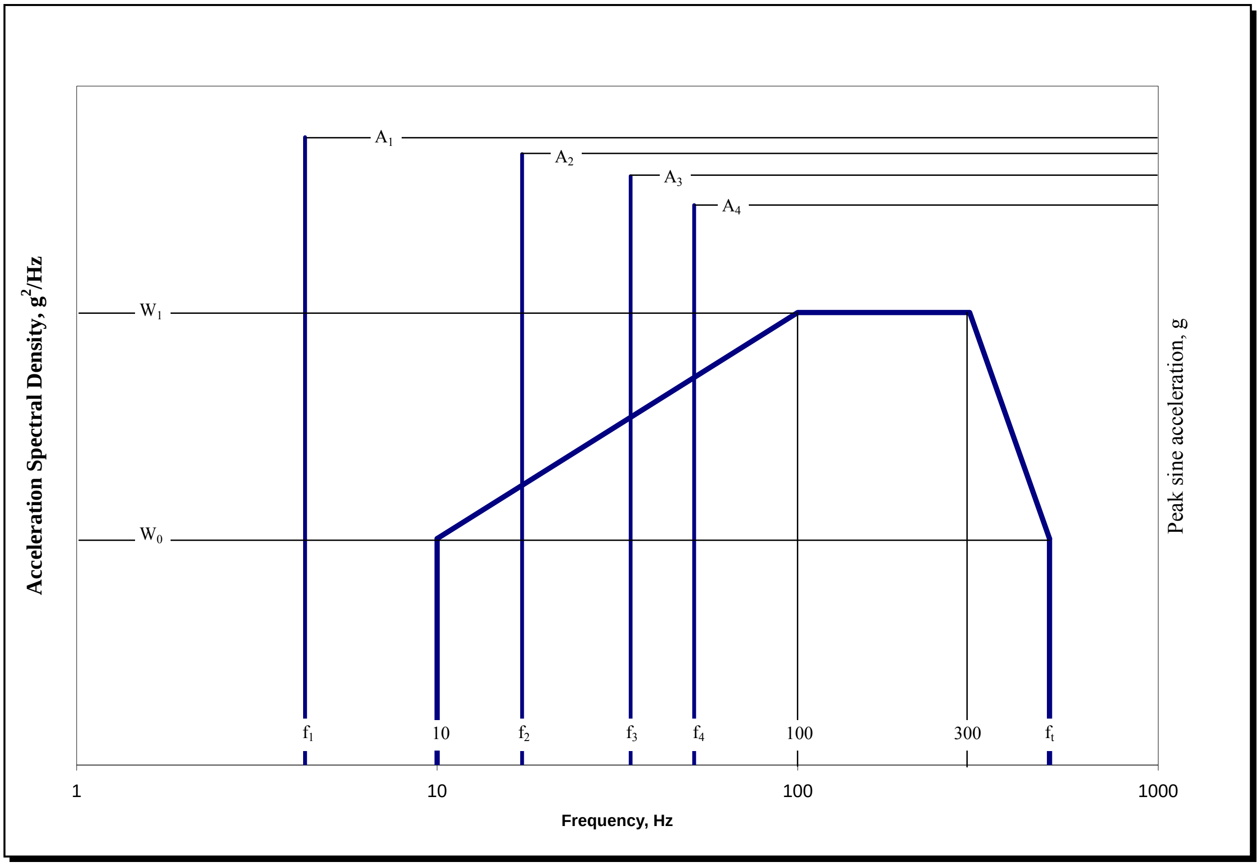


Figure 514.6C-8. Category 9 - Helicopter vibration exposure.

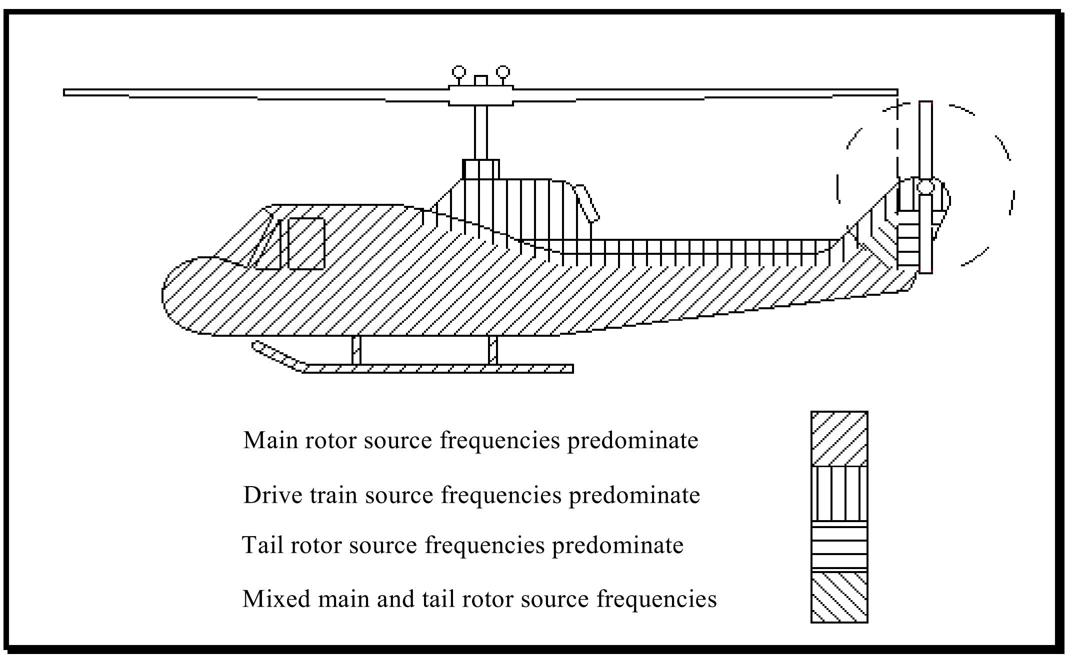


Figure 514.6C-9. Category 9 - Helicopter vibration zones.

Table 514.6C-X. Category 9 - Helicopter vibration exposure. (Same as Annex D, Table 514.6D-III.)

MATERIEL	RANDOM LEVELS	SOURCE FREQUENCY (f_X) RANGE (Hz)	PEAK ACCELERATION (A_x) at f_x (GRAVITY UNITS (g))
General	$W_0 = 0.0010\ g^2/Hz$ $W_1 = 0.010\ g^2/Hz$ $f_t = 500$ Hz	3 to 10 10 to 25 25 to 40 40 to 50 50 to 500	$0.70/(10.70 - f_x)$ $0.10 \times f_x$ 2.50 $6.50 - 0.10 \times f_x$ 1.50
Instrument Panel	$W_0 = 0.0010\ g^2/Hz$ $W_1 = 0.010\ g^2/Hz$ $f_t = 500$ Hz	3 to ≤ 10 >10 to 25 25 to 40 40 to 50 50 to 500	$0.70/(10.70 - f_x)$ $0.070 \times f_x$ 1.750 $4.550 - 0.070 \times f_x$ 1. 050
External Stores	$W_0 = 0.0020\ g^2/Hz$ $W_1 = 0.020\ g^2/Hz$ $f_t = 500$ Hz	3 to ≤ 10 >10 to 25 25 to 40 40 to 50 50 to 500	$0.70/(10.70 - f_x)$ $0.150 \times f_x$ 3.750 $9.750 - 0.150 \times f_x$ 2.250
On/Near Drive System Elements	$W_0 = 0.0020\ g^2/Hz$ $W_1 = 0.020\ g^2/Hz$ $f_t = 2000$ Hz	5 to ≤ 50 > 50 to 2000	$0.10 \times f_x$ $5.0 + 0.010 \times f_x$

Main or Tail Rotor Frequencies (Hz) Determine 1P and 1T from the Specific Helicopter or from the table (below).			**Drive Train Component Rotation** Frequency (Hz) Determine 1S from Specific Helicopter and Component.	
$f_1 = 1P$	$f_1 = 1T$	fundamental	$f_1 = 1S$	fundamental
$f_2 = n \times 1P$	$f_2 = m \times 1T$	blade passage	$f_2 = 2 \times 1S$	1st harmonic
$f_3 = 2 \times n \times 1P$	$f_3 = 2 \times m \times 1T$	1st harmonic	$f_3 = 3 \times 1S$	2nd harmonic
$f_4 = 3 \times n \times 1P$	$f_4 = 3 \times m \times 1T$	2nd harmonic	$f_4 = 4 \times 1S$	3rd harmonic

Helicopter	MAIN ROTOR		TAIL ROTOR	
	Rotation Speed 1P (Hz)	Number of Blades n	Rotation Speed 1T (Hz)	Number of Blades m
AH-1	5.40	2	27.7	2
AH-6J	7.95	5	47.3	2
AH-6M	7.92	6	44.4	4
AH-64 (early)	4.82	4	23.4	4
AH-64 (late)	4.86	4	23.6	4
CH-47D	3.75	3	2 main rotors and no tail rotor	
MH-6H	7.80	5	47.5	2
OH-6A	8.10	4	51.8	2
OH-58AC	5.90	2	43.8	2
OH-58D	6.60	4	39.7	2
UH-1	5.40	2	27.7	2
UH-60	4.30	4	19.8	4

2.7 Category 10 - Watercraft – Marine Vehicles.
The vibration environment of cargo carried in ships is fundamentally the same as for materiel installed on ships. See Annex D, paragraph 2.10. For Navy vessels, see Method 528.

2.8 Category 11 - Railroad - train.
Cargo vibration levels for rail transport are generally low in level and moderately wideband. Vertical axis vibration is typically more severe than lateral and longitudinal. See NATO AECTP 400, Method 401 (paragraph 6.1, reference jj).

a. Exposure levels. Figure 514.6C-10 provides a general definition of railcar vibration. The levels are such that this environment will not significantly affect materiel or packaging design in most cases. In those cases where the levels of Figure 514.6C-10 are significant to materiel, take measurements to determine the actual environments.

b. Exposure durations. Take durations from the Life Cycle Environment Profile (LCEP). If LCEP information is not available, the default test durations is 10 hours/axis.

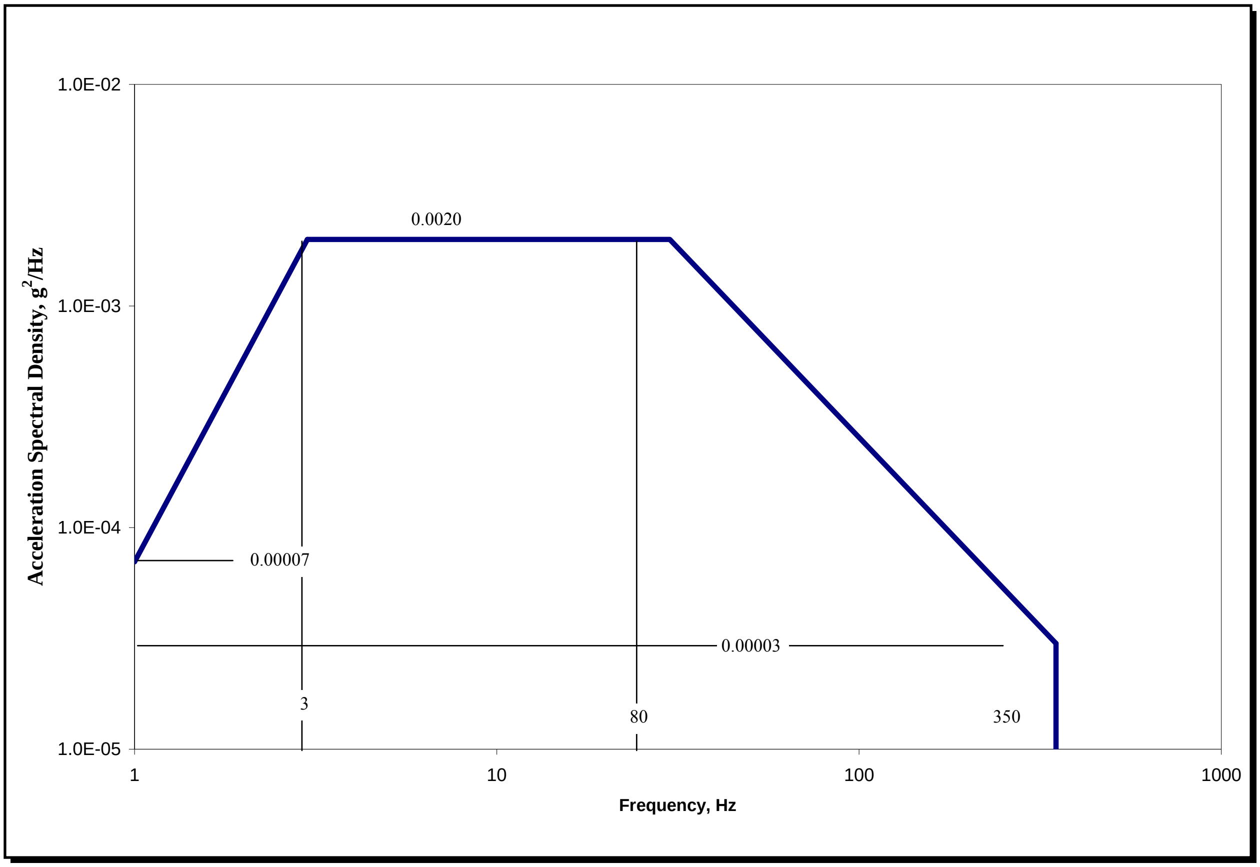


Figure 514.6C-10. Category 11 - Rail cargo vibration exposure.

METHOD 514.6 ANNEX D

Operational Tailoring Guidance for Vibration Exposure Definition

NOTE: Unless specifically noted, all document references refer to paragraph 6.1 of the front part of this method.

1. SCOPE.

1.1 Purpose.
This Annex provides information intended to be useful in determining the vibration levels and durations of operational environmental life cycle events, and in defining the tests necessary to develop materiel to operate in and survive these environments.

1.2 Application.
Recommend actual environments be measured and materiel life cycle durations be used to develop materiel design and test criteria whenever possible. Existing databases can sometimes be used in lieu of measurements. A preliminary environmental life cycle based on data provided herein can be useful as a planning tool. A preliminary life cycle definition can be used to concentrate limited resources on those vibration exposures most significant to the materiel. Guidance for setting design and test exposure values is given below with descriptions of vibration environments of many typical life cycle events. Suggested alternate criteria (levels and durations) or other guidance is recommended for those cases where measured data defining the actual environments are not available. Table 514.6-I in the front part of this method contains an outline of the following section with references to the paragraph numbers.

1.3 Limitations.
See paragraph 1.3 in the front part of this method.

2. OPERATIONAL SERVICE.
This section applies to materiel installed in a vehicle, aircraft store, turbine engine, or carried by personnel. Such materiel may be permanently installed or removable.

2.1 Category 12 - Fixed wing aircraft - jet aircraft.
The vibration environment for materiel installed in jet aircraft (except engine-mounted (see paragraph 2.11 of this annex)), and gunfire-induced, (see Method 519.6) stems from four principal mechanisms. These are (1) engine noise impinging on aircraft structures; (2) turbulent aerodynamic flow over external aircraft structures, (3) turbulent aerodynamic flow and acoustic resonance phenomena within cavities open to the external airflow, particularly open weapon bays, and (4) airframe structural motions due to maneuvers, aerodynamic buffet, landing, taxi, etc. Vibration can also be produced by installed materiel items. These vibrations are generally important only locally at or near the source and may not be significant even in that local area.

a. Airframe structural response. Airframe structural motions are the responses of flexible airframe structures to transient events. Examples of such events are landing impact, arrested landings, catapult, rebound of wings and pylons when heavy stores are ejected, and separated flow or shed vortex excitation of flight surfaces during maneuvers. Catapult take-off and arrested landing also result in structural motions. These are included in Method 516.6 as transient vibrations. Airframe structural motions are most important for the outer regions of flexible structures (i.e., outer 1/2 of wings, empennage, pylons, etc.). These vibrations are characteristic of the particular airframe involved and must be evaluated through measured data. In other areas of the airframe (fuselage, inboard wing, etc.) these vibrations are relatively mild and are generally covered by the fallback criteria described below or by minimum integrity criteria (Annex E, paragraph 2.1).

b. Jet noise and aerodynamically induced vibration. Jet noise induced vibration is usually dominant in vehicles that operate at lower dynamic pressures, i.e., limited to subsonic speeds at lower altitudes and transonic speeds at high altitudes (paragraph 6.1, reference i). Aerodynamically induced vibration usually predominates in vehicles that operate at transonic speeds at lower altitudes, or supersonic speeds at any altitude (paragraph 6.1, references j and k).

c. Cavity noise induced vibration. Where there are openings in the aircraft skin with airflow across the opening, the corresponding cavity within the aircraft is subject to very high levels of aerodynamic and acoustic fluctuating pressures. This is because of general flow disruption and, more importantly, to a phenomenon known as cavity resonance. The fluctuating pressures can be crudely predicted analytically (see paragraph 6.1, references l and m) and somewhat more accurately measured in wind tunnel measurements. Flight test measurement is the only accurate method available to determine these pressures. Further, given the pressures, it is very difficult to predict the resulting vibration and no simple method is available. This vibration should be measured. These vibrations are likely to be important in the local areas surrounding small cavities such as flare launchers, cooling air exhaust openings, etc. With large cavities (particularly weapons bays), the resulting vibration is likely to be a major element of the overall aircraft environment. Method 515.6 contains an acoustic test simulating this environment. That procedure may be used for materiel located inside the cavity, but it is not suitable for simulating the vibration environments for areas near the cavity. Where cavities remain open continuously, the vibration is continuous. When doors or covers open, there will be a transient vibration. While the doors remain open, there is a steady state vibration, followed by another transient vibration as the doors close. When doors open and close quickly, the entire event can sometimes be characterized as a single transient vibration.

d. Materiel induced vibration. In addition, installed materiel can produce significant vibration. Any materiel that involves mechanical motion may produce vibration. This is particularly true of those that have rotating elements such as motors, pumps, and gearboxes. The vibration output of installed materiel varies widely and is highly dependent on the mounting as well as the characteristics of the materiel. There is no basis for predicting local environments due to materiel. Materiel items must be evaluated individually. General aircraft environments as discussed above can generally be expected to cover the contribution of installed materiel.

e. Exposure levels. Vibration criteria in the form of qualification test levels (see Annex A, paragraph 2.1.2) have been established for most airplanes developed for the military. Obtain these criteria through the program office responsible for the particular aircraft. This is the recommended basis for developing exposure levels. In cases where satisfactory criteria are not available, measured data may be available through the aircraft program office. Otherwise, measurements of actual vibrations are recommended.

(1) As a last resort, the guidance of Figure 514.6D-1 and Table 514.6D-I may be used to develop levels. Define both jet noise induced and aerodynamic noise induced levels for each flight condition of interest. The level for that flight condition is the envelope of the two.

(2) This applies to materiel that is small (light) relative to the structure that supports it. As materiel gets heavier, dynamic interaction with supporting structures increases. For typical full-scale manned aircraft, this effect is usually ignored for materiel weighing less than 36 kg (80 lb). A simple mass loading factor is included in Table 514.6D-I for heavier materiel. However, evaluate the installation of materiel weighing more than roughly 72 kg (160 lb.) for dynamic interaction. (See Annex A, paragraph 2.4.)

(3) Materiel mounted on vibration isolators (shock mounts) is dynamically uncoupled from the support structure. Unless it is very large (heavy) relative to the support structure (see Annex A, paragraph 2.4.1), its influence on vibration of the support structure will be minimal and the mass loading factor discussed above does not apply. Use the exposure levels discussed above as input to the vibration isolators.

f. Exposure durations. Take durations from the Life Cycle Environment Profile.

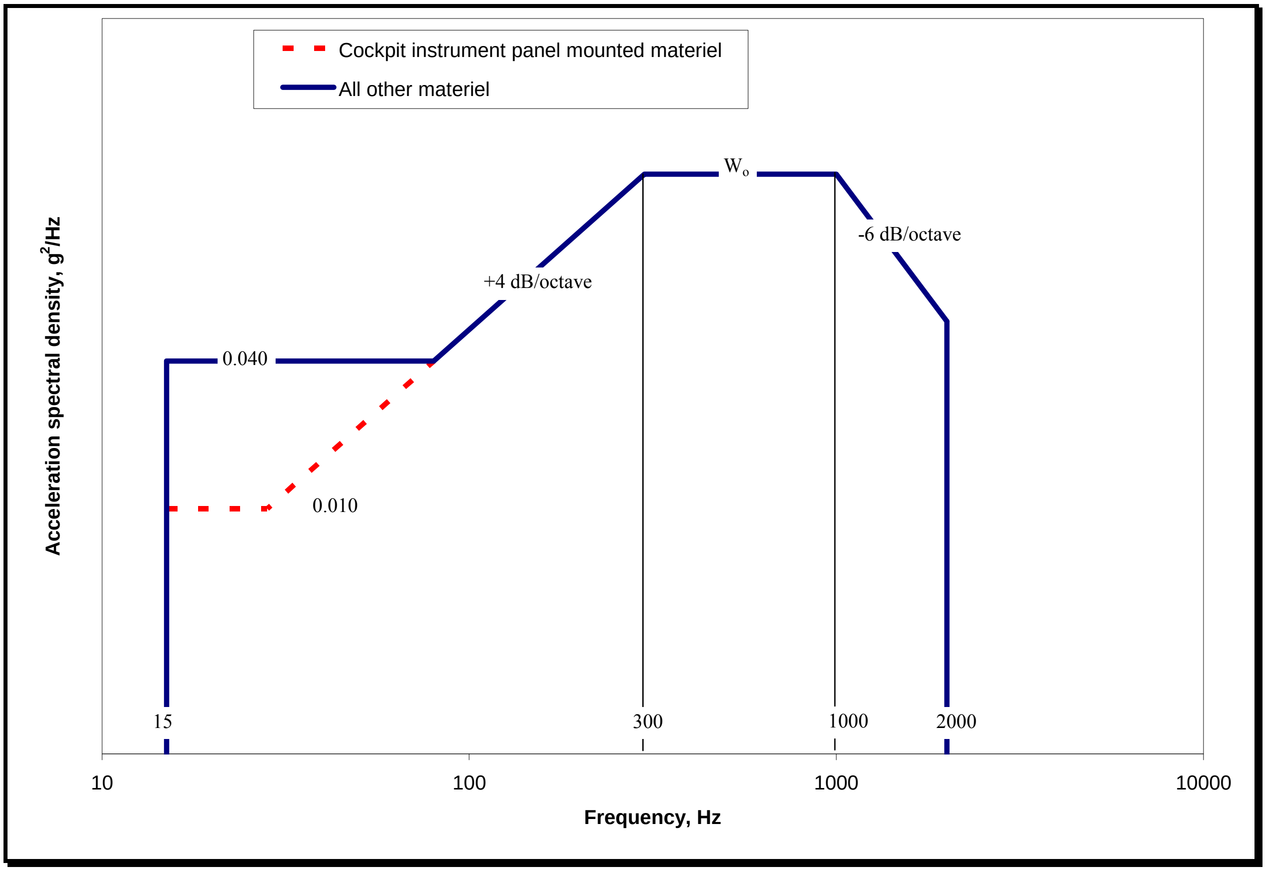


Figure 514.6D-1 - Category 12 - Fixed wing aircraft - jet aircraft. (Same as Annex C, Figure 514.6C-6.)

Table 514.6D-I – Category 7 - Jet aircraft vibration exposure. (Same as Annex C, Table 514.6C-VIII.)

$W_0 = W_A + \sum_1^n (W_J)$ W_0, W_A, W_J - Exposure levels in acceleration spectral density (g^2/Hz).					
Aerodynamically induced vibration $W_A = a \times b \times c \times (q)^2$					
Jet engine noise induced vibration $W_J = \{[0.48 \times a \times d \times \cos^2(\theta)/R] \times [D_c \times (V_c / V_r)^3 + D_f \times (V_f / V_r)^3]\}$					
a	-	Platform / Materiel interaction factor (see Annex A, paragraph 2.4). Note that this factor applies to W_o and not to the low frequency portion (15 Hz to break) of Figure 514.6C-6.			
	=	1. 0 for materiel mounted on vibration isolators (shock mounts) and materiel weighing less than 36.3 kg.			
	=	$1.0 \times 10^{(0.6 - W/60)}$ for materiel weighing between 36.3 and 72.6 kg.(w = weight in kg)			
	=	0. 25 for materiel weighing 72.6 kg or more.			
b	=	Proportionality factor between vibration level and dynamic pressure (SI units).	$\sum_1^n$	-	Jet noise contribution is the sum of the W_J values for each engine.
	=	2.96×10^{-6} for materiel mounted on cockpit instrument panels.	d	-	Afterburner factor.
				=	1. 0 for conditions where afterburner is not used or is not present.
	=	1.17×10^{-5} for cockpit materiel and materiel in compartments adjacent to external surfaces that are smooth and free from discontinuities.		=	4. 0 for conditions where afterburner is used.
			R	-	Vector distance from center of engine exhaust plane to materiel center of gravity, m (ft).
	=	6.11×10^{-5} for materiel in compartments adjacent to or immediately aft of external surface discontinuities (cavities, chines, blade antennae, speed brakes, etc.), fuselage aft of wing trailing edge, wing, empennage, and pylons.	θ	-	Angle between R vector and engine exhaust vector (aft along engine exhaust centerline), degrees For $70° < \theta \le 180°$ use 70°.
c	-	Mach number correction. Note that this factor applies to W_0 and not to the low frequency portion (15 to intersection frequency at 0.04 g^2/Hz based on W_0) of Figure 514..6C-6. (Annex D, paragraph. 2.1)	D_c	-	Engine core exhaust diameter, m (ft).
			D_f	-	Engine fan exhaust diameter, m (ft).
			V_r	-	Reference exhaust velocity, m/sec (ft/sec).
				=	564 m/sec
	=	1. 0 for $0 \le$ Mach ≤ 0.9	V_c	-	Engine core exhaust velocity Engine core exhaust velocity (without afterburner), m/sec (ft/sec).
	=	(-4.8M + 5.32) for $0.9 \le$ Mach ≤ 1.0 (where M = Mach number)			
	=	0.52 for Mach number greater than 1.0	V_f	-	Engine fan exhaust velocity (without afterburner), m/sec (ft/sec).
q	-	Flight dynamic pressure, kN / m^2 (lb/ft^2). (See Annex A, paragraph. 2.6.1, and Table 514.6D-V)			
If Dimensions are in feet and pounds then:					
a	=	1. 0 for materiel mounted on vibration isolators (shock mounts) and materiel weighing less than 80 lb.			
	=	$1.0 \times 10^{(0.60 - 0.0075 W)}$ for materiel weighing between 80 and 160 lb.			
	=	0. 25 for materiel weighing 160 lb. or more.			
b	=	6.78×10^{-9}, 2.70×10^{-8}, or 1.40×10^{-7} in the order listed above.			
V_r	=	1850 feet / second			

2.2 Category 13 - Fixed wing propeller aircraft.

The vibration environment for materiel installed in propeller aircraft (except engine-mounted, see paragraph 2.11, and gunfire induced (see Method 519.6)) is primarily propeller induced. The vibration frequency spectra consists of a broadband background with superimposed narrow band spikes (see paragraph 6.1, references n through t). The background spectrum results from various random sources (see paragraph 2.1) combined with many lower level periodic components due to the rotating elements (engines, gearboxes, shafts, etc.) associated with turboprops. The spikes are produced by the passage of pressure fields rotating with the propeller blades. These occur in relatively narrow bands centered on the propeller passage frequency (number of blades multiplied by the propeller rpm) and harmonics.

a. Constant propeller speed. Most current propeller aircraft are constant-speed machines. This means that rpm is held constant and power changes are made through fuel flow changes and variable-pitch blades, vanes, and propellers. These machines produce the fixed frequency spikes of Figure 514.6D-2. These spikes have a bandwidth because there is minor rpm drift, the vibration is not pure sinusoidal (Annex A, paragraph 2.3.3), and to account for materiel resonant frequency differences as modeled or tested and as manufactured and installed on the aircraft.

b. Varying propeller speed. When propeller speed varies during operation, a spectrum or set of spectra similar to Figure 514.6D-2 is required to define vibration levels. The spikes on these spectra would have bandwidths encompassing the propeller speed variations of operation. Separate spectra may be required to describe individual mission segments.

c. Source dwell testing. These vibration environments can be approximated in the laboratory by the source dwell test described in Annex A, paragraph 2.3.3. Vibration problems in this type of environment are typically associated with the coincidence of materiel vibration modes and excitation spikes. Intelligent designs use notches between spikes as safe regions for materiel vibration modes. It is particularly important to assure that vibration isolation frequencies do not coincide with spike frequencies. Source dwell tests minimize the likelihood that materiel will be overstressed at non-representative conditions, and ensure reasonable design provisions will not be subverted.

d. Exposure levels. Whenever possible, use flight vibration measurements to develop vibration criteria. In the absence of flight measurements, the levels of Table 514.6D-II can be used with the spectra of Figure 514.6D-2. These levels are based on C-130 and P-3 aircraft measurements (paragraph 6.1, references p through t) and are fairly representative of the environments of these aircraft. The decline of spike acceleration spectral density with frequency is based on data analyzed in a spectral density format.

e. Exposure durations. Take durations from the Life Cycle Environment Profile. If Life Cycle Environmental Profile data are not available for development of the test durations, tests should be conducted for one hour per axis.

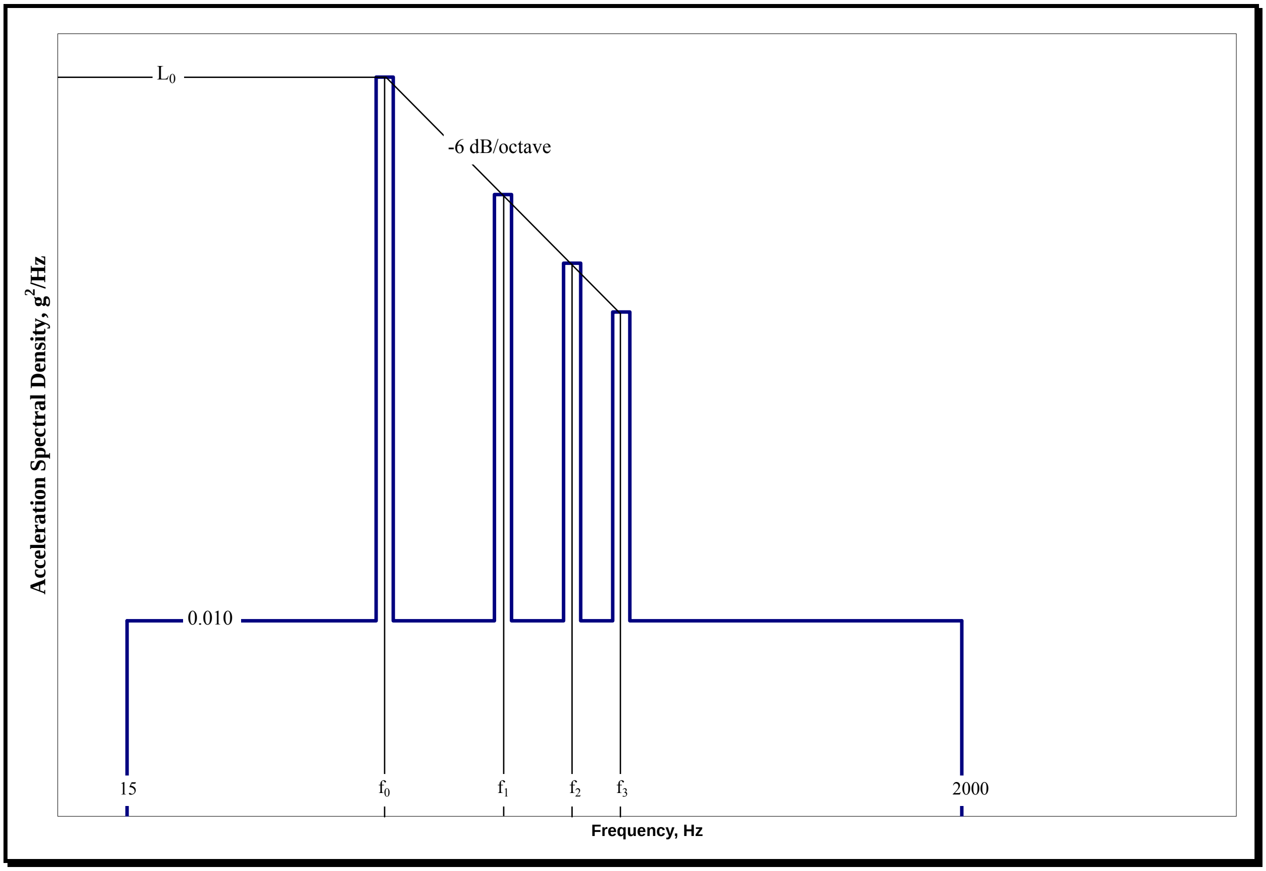


Figure 514.6D-2 – Category 13 - Propeller aircraft vibration exposure. (Same as Annex C, Figure 514.6C-7.)

Table 514.6D-II Category 13 - Propeller aircraft vibration exposure (Same as Annex C, Table 514.6C-IX).

MATERIEL LOCATION 1/, 2/, 3/, 4/	VIBRATION LEVEL Lo (g^2/Hz)
In fuselage or wing forward of propeller	0.10
Within one propeller blade radius of propeller passage plane	1.20
In fuselage or wing aft of propeller	0.30
In engine compartment, empennage, or pylons	0.60
1/ For Materiel mounted to external skin, increase level by 3 dB.	
2/ f_0 = blade passage frequency (propeller rpm times number of blades) (Hz). $f_1 = 2 \times f_0$ $f_2 = 3 \times f_0$ $f_3 = 4 \times f_0$	
3/ Spike bandwidths are ± 5 percent of center frequency.	
4/ C-130 Aircraft 3 blade propeller - f_0 = 51 Hz 4 blade propeller - f_0 = 68 Hz 6 blade propeller - f_0 = 102 Hz (C-130J)	

2.3 Category 14 - Rotary wing aircraft - helicopter.

Helicopter vibration (for engine-mounted materiel, see paragraph 2.11 below, and for gunfire induced vibration, see Method 519.6) is characterized by dominant peaks superimposed on a broadband background, as depicted in Figure 514.6D-3. The peaks are sinusoids produced by the major rotating components (main rotor, tail rotor, engine, gearboxes, shafting, etc.). The peaks occur at the rotation speed (frequency) of each component (i.e., 1P for main rotor, 1T for tail rotor, and 1S where S designates a locally predominate rotating element) and harmonics of these speeds (e.g., 2P, 3P, 4P). The broadband background is a mixture of lower amplitude sinusoids and random vibrations due to sources such as aerodynamic flow noise (see paragraph 2.1). Vibration levels and spectrum shapes vary widely between helicopter types and throughout each helicopter, depending on strength and location of sources and the geometry and stiffness of the structure. Thus, the need for measured data is acute.

a. Broadband background. The broadband background is expressed as random vibration for design and test purposes as a matter of expediency. The definition of and application to design and test of all lower level sinusoidal and random components is not practical.

b. Dominant sinusoids. The dominant sinusoids are generated by rotating components of the helicopter, primarily the main rotor(s), but also tail rotor, engine(s), drive shafts, and gear meshing. The normal operating speeds of these components are generally constant, varying less than five percent. However, recent designs have taken advantage of variable rotor speed control that generates a pseudo steady state rotor speed at values between 95 and 110 per cent of the nominal rotor speed. This complicates the materiel design and test process since all rotating component speeds, pseudo or otherwise, should be accounted for.

c. Variable rotor speeds. Variable speed helicopters are also possible; in this case they also account for the full range of rotation speeds. A range of 0.975 times minimum speed to 1.025 times maximum speed is recommended.

d. Design practice. An obvious requirement for helicopter materiel design is to avoid a match or near match between materiel resonant frequencies and the dominant sinusoids. A minimum clearance between operating speed and resonant frequency of at least five per cent is recommended. It is important to note that helicopter frequencies and amplitudes are unique for each helicopter type and, to some degree, each model of a given type.

e. Exposure levels.

(1) For reasons stated above, the exposure levels for materiel installed in helicopters should be derived from field measurement (additional tailored helicopter vibration schedules are provided in paragraph 6.1, reference d). When measured data are not available, levels can be derived from Table 514.6D-III, and Figures 514.6D-3 and 514.6D-4. These levels are intended to envelope potential worst-case environments, and have been aggressively compressed in time (paragraph 6.1, reference xx indicates a time compression from 2500 hours to 4 hours using the equation shown in paragraph 2.3f with a value of m=6). They do not represent environments under which vibration sensitive materiel should be expected to perform to specification. However, the materiel is expected to survive undamaged, and to function to specification at the completion of the test. Materiel costs are often strongly influenced by the performance required in a vibration environment. Consequently, field measurement based vibration criteria can be very important and are strongly recommended.

(2) To determine levels, divide the aircraft into zones as shown in Annex C, Figure 514.6C-9. Use the source frequencies of the main rotor in determining the values of A_1, A_2, A_3, and A_4 (Annex C, Table 514.6C-VIII) for all materiel locations except those defined below. For materiel located in the horizontal projection of the tail rotor disc, use the source frequencies of the tail rotor. In addition, ensure criteria for materiel located in an overlap of main and tail rotor zones includes both sets of frequencies. Fundamental main and tail rotor source frequencies of several helicopters are given in Annex C, Table 514.6C-VIII. For materiel located on or in close proximity to drive train components such as gearboxes and drive shafts, use the source frequencies of that drive train component (i.e., gear mesh frequencies, shaft rotational speeds). Determine these from the drive train data for the particular helicopter.

f. Exposure durations. When measured data are used to establish exposure levels, take durations from the Life Cycle Environment Profile. When levels are derived from Table 514.6D-III, and Figures 514.6D-3 and 514.6D-4, use a duration of four (4) hours in each of three (3) orthogonal axes for a total test time of twelve (12) hours. This represents a 2500-hour operational life. This duration may be tailored based on the LCEP of the test item. The fatigue relationship shown below may be used to trade test time for exposure level. Make the calculation separately for each sinusoid and each segment of the broadband background.

$$\frac{t_2}{t_1} = \left[\frac{S_1}{S_2}\right]^m$$

where

t_1 = equivalent test time

t_2 = in-service time for specified condition

S_1 = severity (rms) at test condition

S_2 = severity (rms) at in-service condition

[The ratio S_1/S_2 is commonly known as the exaggeration factor.]

m = 6 (materiel exponent for sinusoidal vibration, see Annex A, paragraph 2.2)

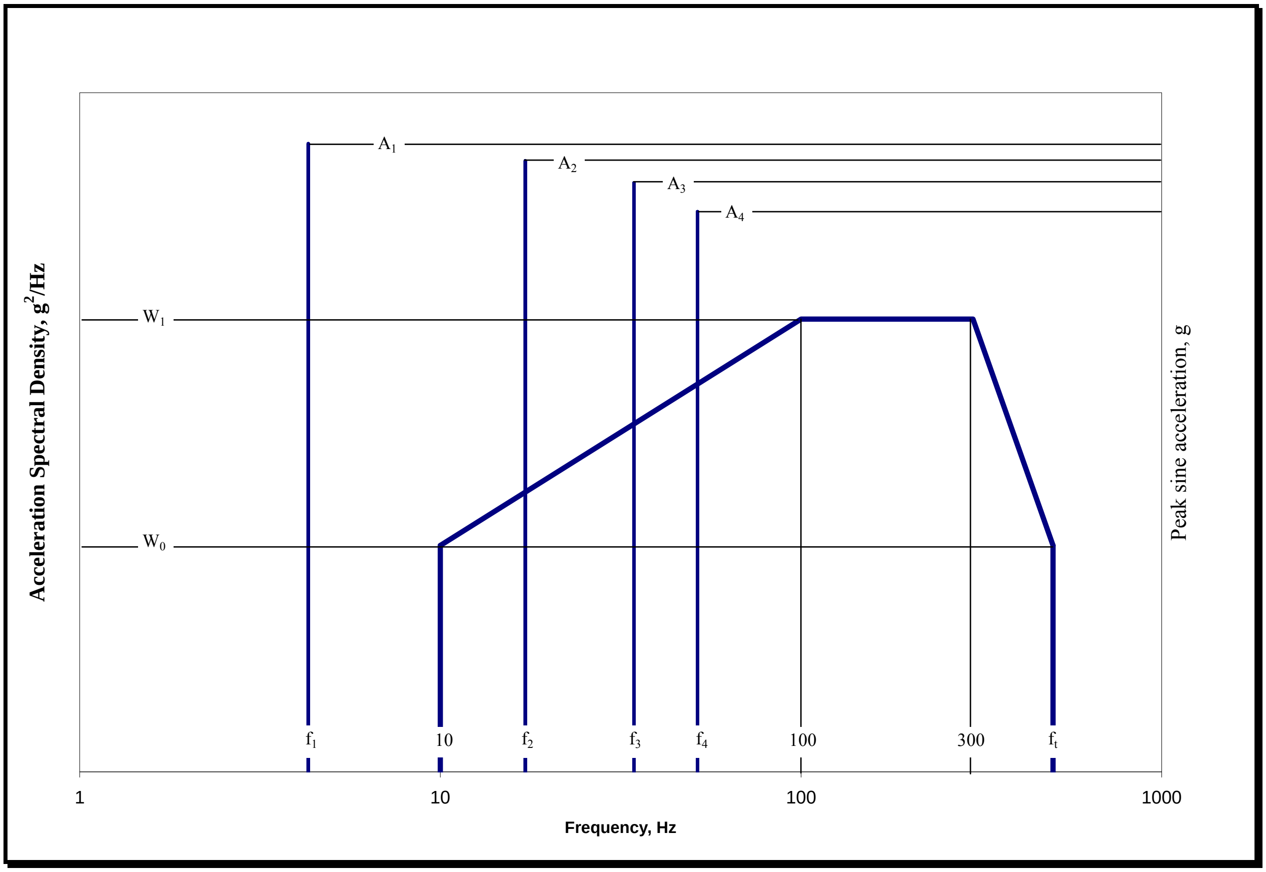


Figure 514.6D-3 Category 14 – Helicopter vibration (Same as Annex C, Figure514.6C-8).

Table 514.6D-III – Category 14 - Helicopter vibration exposure. (Same as Annex C, Table 514.6C-X.)

MATERIEL	RANDOM LEVELS	SOURCE FREQUENCY (f_x) RANGE (Hz)	PEAK ACCELERATION (A_x) at f_x (GRAVITY UNITS (g))
General	W_0 = 0.0010 g^2/Hz W_1 = 0.010 g^2/Hz f_t = 500 Hz	3 to 10 10 to 25 25 to 40 40 to 50 50 to 500	0.70 /(10.70 - f_x) 0.10 x f_x 2.50 6.50 - 0.10 x f_x 1.50
Instrument Panel	W_0 = 0.0010 g^2/Hz W_1 = 0.010 g^2/Hz f_t = 500 Hz	3 to ≤ 10 >10 to 25 25 to 40 40 to 50 50 to 500	0.70 /(10.70 - f_x) 0.070 x f_x 1.750 4.550 - 0.070 x f_x 1. 050
External Stores	W_0 = 0.0020 g^2/Hz W_1 = 0.020 g^2/Hz f_t = 500 Hz	3 to ≤ 10 >10 to 25 25 to 40 40 to 50 50 to 500	0.70 /(10.70 - f_x) 0.150 x f_x 3.750 9.750 - 0.150 x f_x 2.250
On/Near Drive System Elements	W_0 = 0.0020 g^2/Hz W_1 = 0.020 g^2/Hz f_t = 2000 Hz	5 to ≤ 50 > 50 to 2000	0.10 x f_x 5.0 + 0.010 x f_x

Main or Tail Rotor Frequencies (Hz) Determine 1P and 1T from the Specific Helicopter or from the table (below).			**Drive Train Component Rotation** Frequency (Hz) Determine 1S from Specific Helicopter and Component.	
f_1 = 1P	f_1 = 1T	fundamental	f_1 = 1S	fundamental
f_2 = n x 1P	f_2 = m x 1T	blade passage	f_2 = 2 x 1S	1st harmonic
f_3 = 2 x n x 1P	f_3 = 2 x m x 1T	1st harmonic	f_3 = 3 x 1S	2nd harmonic
f_4 = 3 x n x 1P	f_4 = 3 x m x 1T	2nd harmonic	f_4 = 4 x 1S	3rd harmonic

Helicopter	MAIN ROTOR		TAIL ROTOR	
	Rotation Speed 1P (Hz)	Number of Blades n	Rotation Speed 1T (Hz)	Number of Blades m
AH-1	5.40	2	27.7	2
AH-6J	7.95	5	47.3	2
AH-6M	7.92	6	44.4	4
AH-64 (early)	4.82	4	23.4	4
AH-64 (late)	4.86	4	23.6	4
CH-47D	3.75	3	2 main rotors and no tail rotor	
MH-6H	7.80	5	47.5	2
OH-6A	8.10	4	51.8	2
OH-58ÃC	5.90	2	43.8	2
OH-58D	6.60	4	39.7	2
UH-1	5.40	2	27.7	2
UH-60	4.30	4	19.8	4

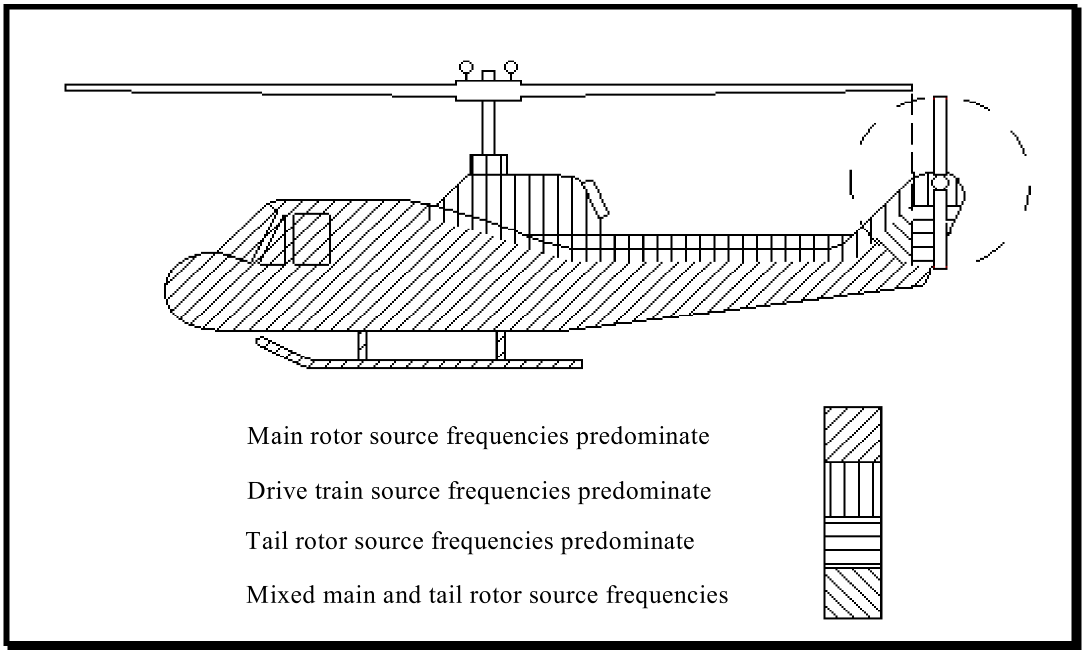


Figure 514.6D-4 – Category 14 - Helicopter vibration zones (Same as Annex C, Figure 514.6C-9).

2.4 Category 15 – Aircraft stores – assembled, jet aircraft.
Assembled jet aircraft stores may encounter three distinct vibration environments; external captive carriage, internal captive carriage, and free flight.

Note: High frequency vibration (beginning at or below 1000 Hz) cannot be practically transmitted to a store mechanically. Combine store vibration and acoustic testing (Method 523.3). These test excitations in combination produce a much more realistic test.

2.4.1 Captive flight – external carriage.
Vibration (for gunfire induced vibration, see Method 519.6) experienced by a store carried externally on a jet aircraft arises primarily from four sources:

a. Engine noise is produced by turbulence in the boundary of the jet exhaust plume. This turbulence is maximum at initiation of takeoff when the velocity difference between the jet and ambient air is maximum. This source is generally of primary importance when the store is carried on an aircraft that uses pure jet or very low bypass engines since these engines have the highest exhaust velocities. Further, it is important at higher frequencies because sources discussed below dominate at lower frequencies (paragraph 6.1, references u, v, and w).

b. In-flight store vibration is primarily caused by aerodynamic turbulence distributed over the surface of the store.

   (1) In single carriage, excitation is relatively independent of the carrying aircraft and mounting location on the aircraft. Local flow disturbances such as pylon wakes will vary considerably between aircraft and between store stations on a given aircraft. In general, these do not greatly effect overall store vibration. But, they may severely affect local structures such as tail fins that, in turn, may increase levels of store vibration. See Annex E, paragraph 2.1.2 for guidance on local flow effects. When stores are carried close together, the turbulence field around each is increased. A store carried behind another store is exposed to the turbulence generated by the forward store.

(2) An extensive program of measurement and analysis was accomplished to characterize this environment (paragraph 6.1, references u, v, and w). Vibratory excitation is influenced by store configuration, structural configuration, mass density, and flight dynamic pressure. The high frequency portion of the resulting vibration is best represented by a combination of mechanical vibration and the acoustic noise exposures of Method 523.3. The low and medium frequency portion of this environment is better simulated by mechanical excitation. The studies mentioned above resulted in a method to accomplish this defining the response vibration of the store rather than specifying input vibration. This method also includes low frequency vibration transmitted from the carrying aircraft (see below).

c. Vibrations of the carrying aircraft are transmitted to the store through the attaching structures. The total vibrating system (aircraft, pylon, bomb rack, and store) is a low frequency system. That is, the lowest natural frequency of the system is typically below 20 Hertz and the store is isolated from high frequency aircraft vibration. Depending on the particular circumstances, these vibrations are often best represented as transient vibration (see Annex A, paragraph 2.3.4).

(1) The low frequency vibration of the airframe transmitted to the store is not separable in the general case from the low frequency turbulence generated vibration. This vibration is accounted for by the method discussed under “Aerodynamic turbulence” (paragraph 2.4.1b).

(2) Flight test measurements on the F-15 with various external stores, (paragraph 6.1, reference x) have shown intense, very low frequency vibrations associated with aircraft buffet during high angle of attack maneuvers. Other aircraft, such as F-14, F-16, and F-18, or next generation fighters, have the potential to produce intense buffet vibrations during maneuvers.

(3) The F-15 buffet maneuver envelope is roughly bounded by speeds of 0.7 to 1.0 Mach and altitudes of approximately 3 to 10.7 kilometers (10,000 to 35,000 ft). Flight test measurements have shown the maximum F-15 buffet vibration to occur in the flight regime of 0.8 to 0.9 Mach, 4.6 to 7.6 km (15,000 to 25,000 ft) altitude, 8° to 12° angle of attack, and dynamic pressure less than 26.3 kN/m^2 (550 lb/ft^2). Similar measurements on F/A-18 have shown the maximum buffet maneuver vibration to occur in the regime of 0.85 to 0.95 Mach, 1.5 to 4.6 km (5,000 to 15,000 ft.), 8° to 10° angle of attack, and dynamic pressure less than 33.5 kN/m^2 (700 lb/ft^2). Although the vibration levels during high-performance maneuvers are very intense, they generally do not last for more than 10 seconds, reaching maximum in less than a second and deteriorating in 5 to 10 seconds. Typically F-15 external stores will experience 30 seconds of maneuver buffet vibration for each hour of captive-carriage flight.

(4) Buffet vibration is typically concentrated between 10 and 50 Hz. Vibration response of the store is dominated by store structural resonances. Store loads that occur at frequencies below the lowest store natural frequency are effectively static loads. Buffet levels vary over a wide range on a given aircraft as well as between aircraft. Thus, buffet vibration requirements should be derived from in-flight vibration measurement when possible. As an alternative to measurements, the lowest store vibratory modes can be exercised at conservative levels to show that the store will be robust enough for any encountered buffet vibration. This does not cover the static loads associated with buffet. In order to include these loads, it is necessary to duplicate flight measured dynamic bending moments as discussed as an option in the front part of this method (paragraph 4.2.1.2, Force control strategy). This would require extending the test frequency down to the lowest frequency of airplane buffet response and must be done in coordination with the responsible strength and loads engineers.

d. Stores are also susceptible to vibration generated by internal materiel and local aerodynamic effects. There are no accepted criteria or methodology for predicting these environments. However, these environments can be dominating vibration sources and should not be ignored. Whenever they are present, they should be accounted for through development tests and measurements.

(1) Internal materiel vibration is typically produced by rotating elements such as electric or hydraulic motors. Any device that generates or incorporates physical motion can produce vibration. Ram air turbines (RAT) are sometimes used to generate electrical or hydraulic power. A RAT can produce high levels of rotating element vibration in addition to severe aerodynamic turbulence at and behind the rotating blades.

(2) Acoustic resonance of simple cavities is typically handled as an acoustic environment (see Method 515.6). Any hole, cavity, opening, inlet, etc., that allows airflow to enter the store or a cavity in the store can produce high intensity acoustic resonance responses.

2.4.2 Captive flight – internal carriage.

There are two distinct vibration environments for stores carried in a closed, internal, aircraft bay. These environments occur when the bay is closed to the aircraft external environment and when the bay is open to this environment. Aircraft capable of high angle of attack maneuvers may be susceptible to buffet. Since buffet vibration is mechanically transmitted to the store, the bay will provide no protection. Thus the buffet vibration method discussed above applies.

a. The general vibration environment of a store in a closed bay is very mild. The store is protected from the jet engine noise and aerodynamic turbulence environments and isolated from aircraft vibration. If a store is qualified for external carriage on any jet aircraft, this should more than adequately account for this case. There is no known method to predict this environment for the general case. Measured data may be available for specific aircraft, but generally measurements will be necessary if this environment must be defined.

b. When the bay is opened in flight, a dramatic event occurs. This event is referred to as cavity resonance (paragraph 6.1, references l and m) and results in high levels of turbulence inside the bay. This is wide band turbulence, and unless suppression devices are installed in the bay, with very high spikes across the spectrum. The low frequency portions of the disturbance are not likely to drive the store because disturbance wavelengths greatly differ from store dimensions. The high frequency part of the spectrum will significantly affect the store. Store vibration resulting from this turbulence cannot be adequately predicted. Acoustic characterizations of the turbulence exist for most active aircraft and the resulting vibration is best represented by the acoustic noise exposures of Method 515.6.

(1) Generally, store flight surfaces (control surfaces, wings, stabilizers, etc.) are small enough (small surface area) and/or stiff enough (lowest resonant frequency above 100 Hz) that they are not significantly excited by this environment. However, in cases in which the control surfaces of the store are relatively large or soft, they may be excited by the open-bay environment. In these cases the store response can result in flight surface failure, high levels of store vibration, or both.

(2) In some instances, a store is carried in one configuration or position until use. Just prior to use, the configuration or position may change. For example, a weapon carried on a rotary launcher inside a weapons bay of a large bomber. The weapon moves from clock position to clock position as other weapons on the launcher are launched. The weapon is exposed to the bay open environment either each time another weapon is launched, or for a relatively long period while several are launched. Another example is a weapon that is extended out of the bay on the launch mechanism prior to launch. Here the environment will change considerably with position. A third example is an optical sensor pod. This type of store can be carried internally, extended into the air stream, configuration changed (e.g., covers over optical windows retract), operated, configuration changed back, and retracted into the closed bay many times in a lifetime. Account for such variations in environment and configuration.

Note: Door opening, position changes, configuration changes, door closing, etc., should be expected to happen rapidly. Each of these events and possibly a whole sequence of events can happen rapidly enough so that they should be treated as transient (see Annex A, paragraph 2.3.4, and method 516.6) rather than steady state vibration.

2.4.3 Free flight.

Vibration will be experienced by stores that are deployed from aircraft, ground vehicles, or surface ships. The sources of vibration for the free flight environment are engine exhaust noise, vibration and noise produced by internal equipment, and boundary layer turbulence.

a. Generally, engine exhaust noise levels will be too low to excite significant vibration in the store. This is because the engine only operates when the ratio of the exhaust velocity to the ambient air speed is low and (except in unusual cases) the exhaust plume is behind the store.

b. Vibration produced by onboard materiel can be severe in specific cases. Examples are ram air turbines, engines, and propellers. There is no general basis for predicting store vibrations from such sources. Each case must be evaluated individually, and it is likely that measurements will be required.

c. Boundary layer turbulence induced vibration should be as for captive carriage except that store vibration mode frequencies may shift, flight dynamic pressures may be different, and turbulence from the carrier aircraft and nearby stores will be absent.

2.4.4 Exposure levels.
Select test levels and spectra for captive flight and free flight from Table 514.6D-IV and Figures 514.6D-5 and D-6. Buffet test spectra and levels are provided in Figure 514.6D-6. The use of these tables and figures is suggested only when there is an absence of satisfactory flight measurements. Except for buffet portions, these criteria are closely based in paragraph 6.1, references u, v, and w. These document the results of an extensive study and include a large amount of information and insight. The buffet criteria are based on paragraph 6.1, reference x and additional measurements and experience with the F-15 aircraft. It represents F-15 wing pylon buffet that is the worst known buffet environment. F-15 fuselage store stations buffet environments are generally less severe. Criteria for the other environments must be determined for each specific case.

2.4.5 Exposure durations. Take durations from the Life Cycle Environment Profile.

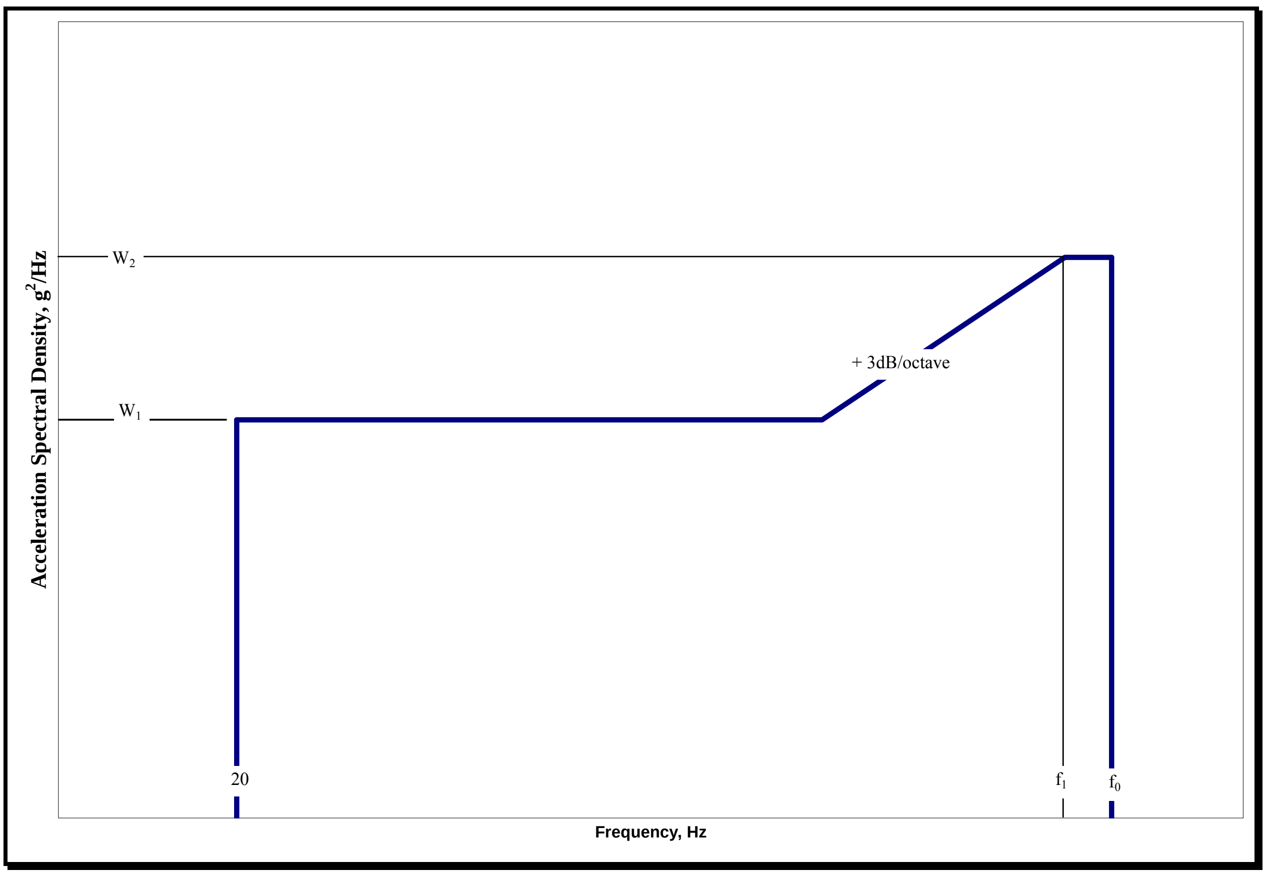


Figure 514.6D-5. Category 15 - Jet aircraft store vibration response.

Table 514.6D-IV. Category 15 - Jet aircraft external store vibration exposure.

$$W_1 = 5 \times 10^{-3} \times K \times A_1 \times B_1 \times C_1 \times D_1 \times E_1 \; ; \quad (g^2/Hz) \quad \underline{1}/$$

$$W_2 = H \times (q/\rho)^2 \times K \times A_2 \times B_2 \times C_2 \times D_2 \times E_2 : \quad (g^2/Hz) \quad \underline{1}/$$

$M \le 0.90$, $K = 1.0$; $0.90 \le M \le 1.0$, $K = -4.8 \times M + 5.32$; $M \ge 1.0$, $K = 0.52$ 2/

$f_1 = 10^5 C(t/R^2)$, (Hz) 3/, 4/, 5/: $f_2 = f_1 + 1000$, (Hz) 3/:

$f_0 = f_1 + 100$, (Hz) 6/, 7/

Configuration	Factors		Configuration	Factors	
Aerodynamically clean	**A_1**	**A_2**		**B_1**	**B_2**
Single store	1	1	Powered missile, aft half	1	4
Side by side stores	1	2	Other stores, aft half	1	2
Behind other store(s)	2	4	All stores, forward half	1	1
Aerodynamically dirty 8/	**C_1**	**C_2**		**D_1**	**D_2**
Single and side by side	2	4	Field assembled sheet metal fin / tail cone unit	8	16
Behind other store(s)	1	2			
Other stores	1	1	Powered missile	1	1
	E_1	**E_2**	Other stores	4	4
Jelly filled firebombs	1/2	1/4			
Other stores	1	1			

M – Mach number.
H – Constant = 5.59 (metric units) ($= 5 \times 10^{-5}$ English units).
C – Constant $= 2.54 \times 10^2$ (metric units) (= 1.0 English units).
q – Flight dynamic pressure (see Table 514.6D-V) – kN/m^2 (lb/ft^2).
ρ – Store weight density (weight/volume) - kg/m^3 (lb/ft^3).
Limit values of ρ to $641 \le \rho \le 2403$ kg/m^3 ($40 \le \rho \le 150$ lb/ft^3).
t – Average thickness of structural (load carrying) skin - m (in).
R – Store characteristic (structural) radius m (in) (Average over store length).
= Store radius for circular cross sections.
= Half or major and minor diameters for elliptical cross section.
= Half or longest inscribed chord for irregular cross sections.

1/ – When store parameters fall outside limits given, consult references.
2/ – Mach number correction (see Annex B).
3/ – Limit f_1 to $100 \le f_1 \le 2000$ Hz
4/ – Free fall stores with tail fins, $f_1 = 125$ Hz
5/ – Limit length ratio to:: $0.0010 \le C(t/R^2) \le 0.020$
6/ – $f_o = 500$ Hz for cross sections not circular or elliptical
7/ – If $f_0 \ge 1200$ Hz, then use $f_0 = 2000$ Hz
8/ – Configurations with separated aerodynamic flow within the first ¼ of the store length. Blunt noses, optical flats, sharp corners, and open cavities are some potential sources of separation. Any nose other than smooth, rounded, and gently tapered is suspect. Aerodynamics engineers should make this judgment.

Representative parameter values

Store type	Max q		ρ		f_1	f_2
	kN/m^2	(lb/ft^2)	kg/m^3	(lb/ft^3)	Hz	Hz
Missile, air to ground	76.61	(1600)	1602	(100)	50	1500
Missile, air to air	76.61	(1600)	1602	(100)	50	1500
Instrument pod	86.19	(1800)	801	(50)	50	1500
Dispenser (reusable)	57.46	(1200)	801	(50)	20	1200
Demolition bomb	57.46	(1200)	1922	(120)	12	1100
Fire bomb	57.46	(1200)	641	(40)	10	1100

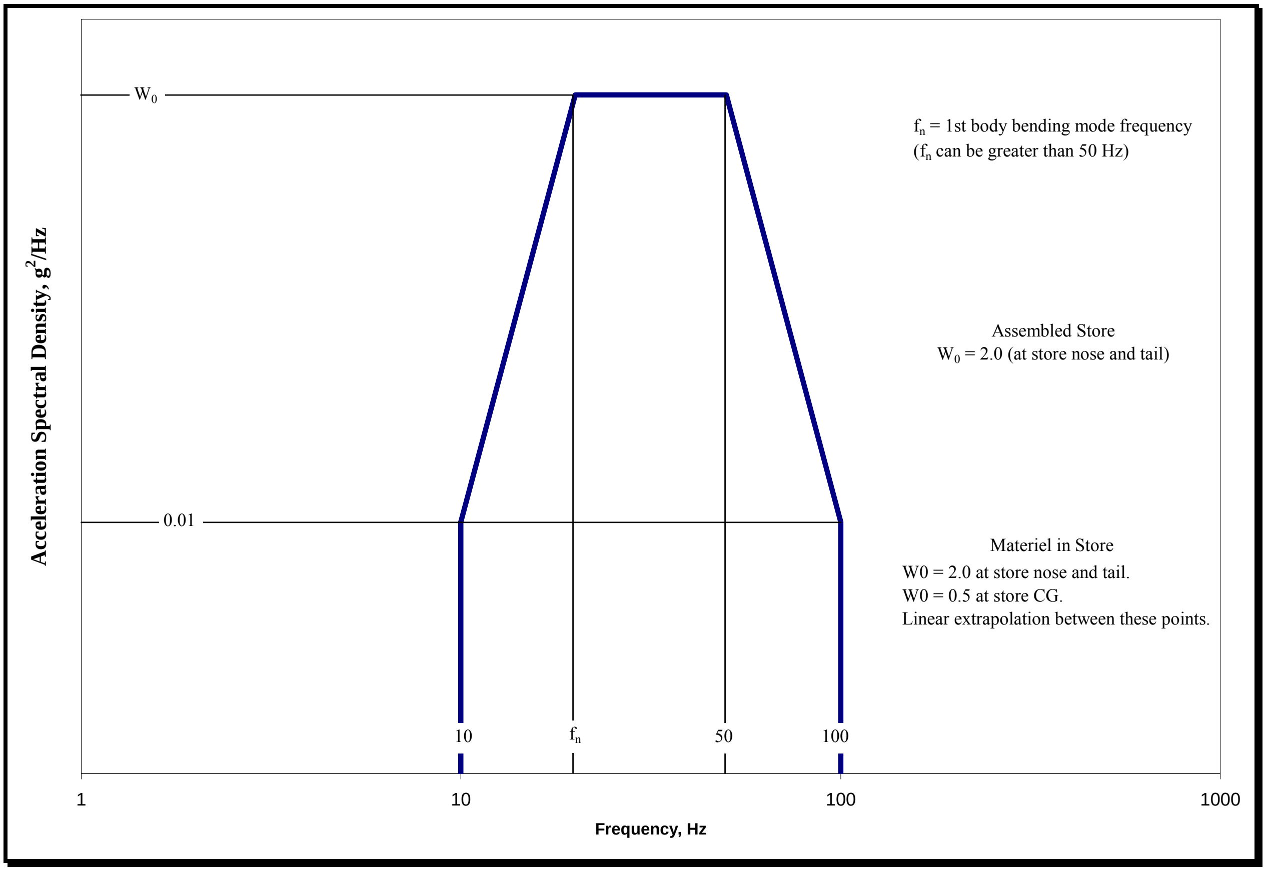


Figure 514.6D-6. Category 15 - Jet aircraft store buffet response.

Table 514.6D-V. Dynamic pressure calculation.

(See Annex A, paragraph 2.6.2 for definitions and details)

1. Dynamic pressure calculation valid only for Mach numbers less than 1.0 (one).
2. Mach number may be used at any airspeed.
3. Unless specifically stated otherwise, assume airspeeds to be in calibrated airspeed (K_{cas}).
4. When airspeed values are given as indicated airspeed (K_{ias}), assume K_{ias} equal K_{cas}.
5. Altitude (h) is pressure altitude and not height above terrain.

$$q = 2.5\, \rho_o \sigma V_a^2 [(1/\delta\{[1 + 0.2(V_{cas}/V_{ao})^2]^{3.5} - 1\} + 1)^{2/7} - 1]$$

$$q = 1/2\ \rho_o \sigma V_a^2 M^2 \qquad q = 1/2\ \rho_o V_{eas}^2 \qquad q = 1/2\ \rho_o \sigma V_{tas}^2$$

	$h \le 11000$ m	$11000 < h \le 20056$ m	($h \le 36089$ ft)	$36089 < h \le 65800$ ft
θ	$1 - 2.2556 \times 10^{-5}\ h$	0.75189	$1 - 6.8750 \times 10^{-6} \times h$	0.75189
δ	$\theta^{5.2561}$	$0.2234\ e^{\phi}$	$\theta^{5.2561}$	$0.2234\ e^{\phi}$
V_a	$V_{ao} \times \theta^{1/2}$	295.06	$V_{ao} \times \theta^{1/2}$	968.03
σ	$\theta^{4.2561}$	$0.2971\ e^{\phi}$	$\theta^{4.2561}$	$0.2971\ e^{\phi}$
ϕ	-------	$(11000 - h) / 6342.0$	------	$(36089 - h) / 20807$
ρ_o	1.2251×10^{-3}	1.2251×10^{-3}	2.377×10^{-3}	2.377×10^{-3}
V_{ao}	340.28	-------	1116.4	-------
T_o	288.16°K	------	518.69°R	------

V_{cas} – Calibrated airspeed, m/sec (ft/sec)	ρ_o – Sea level atmospheric density kg/m^3 (slugs/ft^3 or lb sec^2/ft^4)
V_{ias} – Indicated airspeed, m/sec (ft/sec)	
V_{eas} – Equivalent airspeed, m/sec (ft/sec)	δ – Ratio of local atmospheric pressure to sea level atmospheric pressure
V_{tas} – True airspeed, m/sec (ft/sec) ($V_{tas} = V_{eas} = V_{cas} = V_{ias}$ at sea level)	σ – Ratio of local atmospheric density to sea level atmospheric density (standard atmosphere)
V_{ao} – Sea level speed of sound, m/sec (ft/sec)	
V_a – Local speed of sound, m/sec (ft/sec)	
M – Mach number	θ – Ratio of temperature at altitude to sea level temperature (standard atmosphere)
q – Dynamic pressure, kN/m^2 (lb/ft^2)	
h – Pressure altitude, m (ft), standard atmosphere	ϕ – Stratospheric altitude variable
T_o – Sea level atmospheric temperature °K (°R)	

Airspeeds are typically expressed in knots as follows:

V_{kcas} - knots calibrated air speed
V_{kias} - knots indicated air speed
V_{keas} - knots equivalent air speed
V_{ktas} - knots true air speed

[knots = nautical miles per hour (knots x 0.51478 = m/sec)(knots x 1.6889 = ft/sec)]

Calculation Examples

Airspeed	**Pressure Altitude - h**							
	1500m	**(4921 ft)**	**3048m**	**(10000 ft)**	**7000m**	**(22966 ft)**	**10668m**	**(35000 ft)**
	kN/m^2	**lb/ft^2**	**kN/m^2**	**lb/ft^2**	**kN/m^2**	**lb/ft^2**	**kN/m^2**	**lb/ft^2**
500 V_{kcas}	q = 39.6	q = 827	q = 38.5	q = 803	NA (M>1)		NA (M>1)	
500 V_{ktas}	q = 35.0	q = 731	q = 29.9	q = 625	q = 19.5	q = 407.2	q = 12.5	q = 262
M = 0.8	q = 37.9	q = 791.6	q = 31.2	q = 652	q = 18.4	q = 384.2	q = 10.7	q = 223
300 V_{keas}	q = 14.5	q = 302.8	q = 14.6	q = 304	q = 14.6	q = 304.9	q = 14.6	q = 304

2.5 Category 16 - Aircraft stores - materiel, jet aircraft.
Materiel installed within a jet aircraft store will experience the store vibration discussed in paragraph 2.4. The input exposure levels for materiel within the store are essentially the same as response levels of the store. If gunfire, cavity resonance, buffet-maneuver, and free-flight conditions occur for the store, the materiel will also be exposed to these conditions.

a. Exposure levels. Base vibration criteria on in-flight measurements when possible. If satisfactory flight measurements are not available, derive levels from Table 514.6D-IV and Figure 514.6D-7.

Note: Use input control for vibration testing of this materiel rather than response control (see paragraph 4.2.1 in the front part of this method).

b. Exposure durations. Take durations from the Life Cycle Environment Profile.

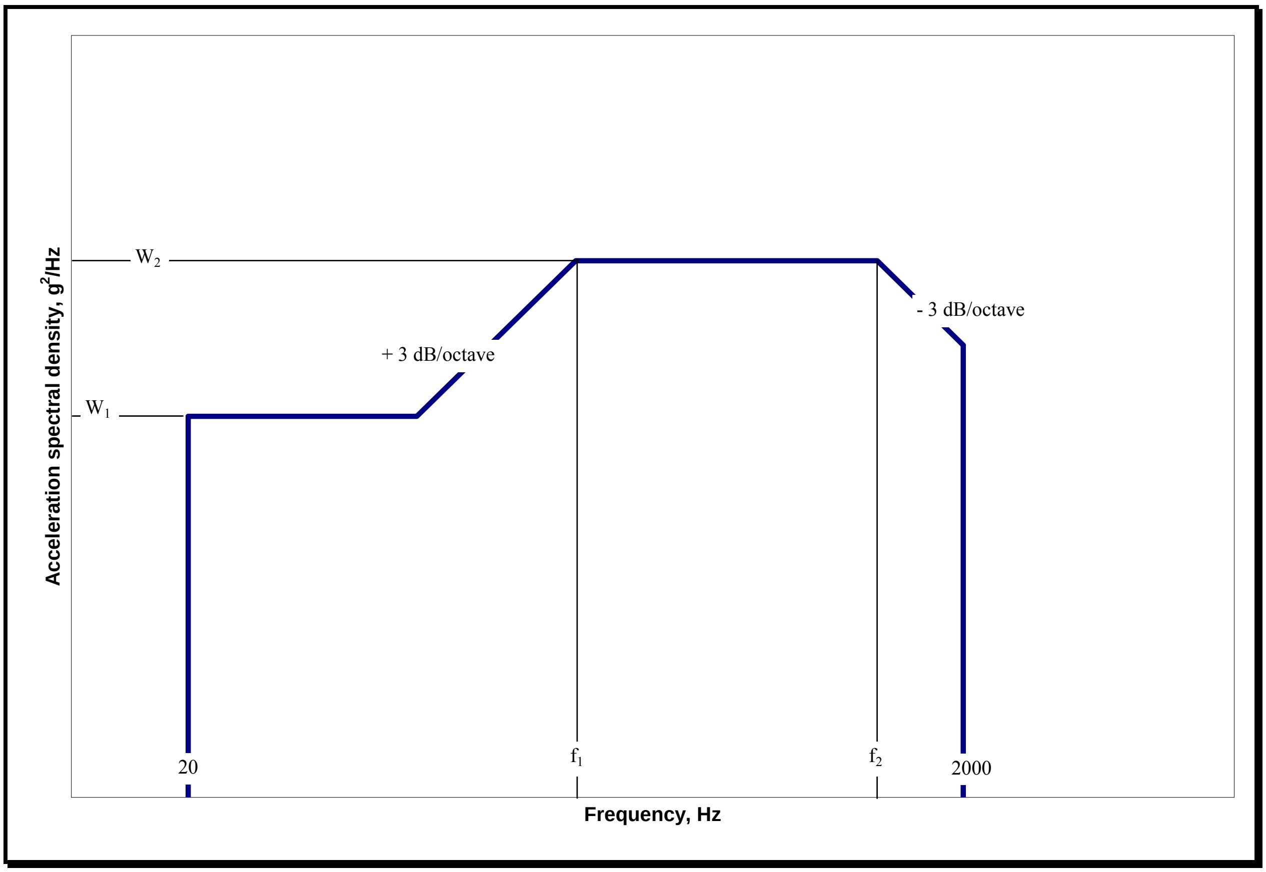


Figure 514.6D-7. Category 16 - Jet aircraft store equipment vibration exposure.

2.6 Category 17 - Aircraft stores - assembled/materiel, propeller aircraft.
There is no known source of general guidance or measured data for the vibration of propeller aircraft stores (except gunfire induced, see Method 519.6). However, since the excitation sources are the same, it seems likely that store vibration will be similar to that of the carrying aircraft. See paragraph 2.2 and Annex A, paragraph 2.3.3 for a discussion of this vibration. Maneuver buffet vibration experienced by stores of highly maneuverable propeller aircraft should be similar to that experienced by jet aircraft stores. See the buffet vibration portion of paragraph 2.4.1c.

a. Exposure levels. There is no known source of data. For accurate definition of propeller aircraft store vibration, measurement of the actual environment is essential. The criteria of Table 514.6D-II and Figure 514.6D-2 may be used to develop preliminary estimates of general vibration. The criteria of Figure 514.6D-6 may be applied for maneuver buffet vibration.

b. Exposure durations. Take durations from the Life Cycle Environment Profile (LCEP).

2.7 Category 18 - Aircraft stores - assembled/materiel, helicopter.
Complex periodic waveforms characterize the service environment encountered by assembled stores externally carried on helicopters. Unlike stores carried on fixed-wing aircraft, externally mounted helicopter stores receive little aerodynamic excitation, particularly when compared with the rotor-induced vibration. Thus, most of the vibratory energy reaches the store and materiel through the attachment points between the aircraft and the store. Some excitation, however, is added along the entire store structure due to periodic rotor induced pressure fluctuations. The result is a complex response, unique to the particular aircraft-store configuration. Therefore, realistic definition of the environment depends almost totally upon the use of in-flight vibration measurements. For stores exposed to gunfire, refer to Method 519.6.

a. Exposure levels. Derive exposure levels for helicopter-carried store materiel from field measurements (paragraph 6.1, reference f contains criteria for specific helicopters). When measured data are not available, initial estimates can be derived from Table 514.6D-III, and Figures 514.6D-3 and 514.6D-4, prior to acquisition of field data. These levels are intended as worst-case environments and represent environments for which it may be difficult to develop vibration sensitive materiel. Materiel costs are often strongly influenced by the performance required in a vibration environment. Consequently, field measurement based vibration criteria are very important. To determine levels, locate the store relative to the helicopter zones as shown in Figure 514.6D-4. Most stores will be inside a vertical projection of the main rotor disc and should use the source frequencies of the main rotor in determining the values of A_1, A_2, A_3, and A_4 (see Annex D, Table 514.6D-III). Also in Table 514.6D-III are the fundamental main rotor source frequencies of several helicopters.

b. Exposure durations. When measured data are used to establish exposure levels, take durations from the Life Cycle Environment Profile. When levels are derived from Table 514.6D-III, and Figures 514.6D-3 and 514.6D-4, use a duration of four (4) hours in each of three (3) orthogonal axes for a total time of twelve (12) hours. This represents a 2500-hour operational life. Use the fatigue relationship of Annex A, paragraph 2.2 to trade test time for exposure level. Perform the calculation separately for each sinusoid and each segment of the broadband background.

2.8 Category 19 - Missiles - Tactical missiles (free flight).
There is no known source of general guidance or measured data for tactical missile carriage or launch vibration environments. Environments for jet aircraft, propeller aircraft, and helicopter carried missiles (stores) are discussed in paragraphs 2.4 through 2.7. Tactical carriage ground environments are discussed in paragraph 2.9. Free flight environments are covered in paragraphs 2.4c and 2.5 in regard to aircraft carried missiles. These environments should be generally applicable to tactical missiles during free flight mission segments.

a. Exposure levels. There is no known source of data. For accurate definition of tactical missile store vibration, measurement of the actual environment is essential. The criteria of Table 514.6D-IV and Figures 514.6D-5 and 514.6D-7 may be used to develop preliminary estimates of free flight vibration.

b. Exposure durations. Take durations from the Life Cycle Environment Profile.

2.9 Category 20 - Ground vehicles - ground mobile. (See paragraph 6.1, references qq to ww.)
The ground mobile environment consists of broadband random vibration with peaks and notches. These peaks and notches are considerably higher and lower than the mean level. (See paragraph 6.1, reference d.) Terrain, road, and surface discontinuities, vehicle speed, loading, structural characteristics, and suspension system all affect this vibration. Gunfire criteria (Method 519.6) are not applicable since it is based on the response of aircraft-type structures that are significantly different than ground vehicle structures.

a. Wheeled vehicles. There is presently no analytical model of these environments suitable for generalized application. A smooth spectrum similar to Annex C, Figure 514.5C-3 will be overly conservative at notches in the frequency spectrum. The spectra of Annex C, Figures 514.6C-2 and 514.6C-3 are typical of cargo bed responses in wheeled vehicles and trailers. This may be unrealistic for installed materiel since it does not consider vehicle structural response beyond the heavily supported cargo bed. The large assembly cargo test of Annex C, paragraph 2.3 can be adapted to provide highly accurate tests for this materiel.

b. Tracked vehicles. The tracked vehicle environment is characterized by the strong influence of track patter which is related to the track pitch (length of a single track block) and the vehicle speed. The track induced component overlays a basic random environment similar to that discussed above for wheeled vehicles. This environment is best represented by superimposing narrowband random (track induced component) vibration at selected frequencies over a broadband random base. A representative tracked vehicle spectrum is given in Figure 514.6D-8. Test execution requires sweeping across the narrow band regions (rectangular shapes in Figure 514.6D-8) while maintaining the random floor. The sweeping action simulates varying vehicle speeds, and the bandwidths and sweep rates should be chosen accordingly. Because the track pitch and the mechanical vibration transmission path through the vehicle are unique to each vehicle, vibration amplitudes and frequencies are vehicle and location dependent. Detailed criteria for many tracked vehicles can be found in paragraph 6.1, reference d. Testing to this requirement will require a narrow band random-on-random vibration exciter control strategy.

c. Exposure levels. As discussed above, generalized methodology for estimating ground vehicle vibration levels have not been developed. Whenever possible, actual vibration environments should be measured and the results used to formulate accurate levels and spectrum shapes. When this is not possible or when preliminary estimates are made, for wheeled vehicles, the information, levels, and curves referenced in Annex C, paragraph 2.1 (Category 4) may be adapted. Numerous measurements have been made and used to develop test criteria for tracked vehicles. Paragraph 6.1, reference f contains criteria that may be used directly or adapted as necessary.

d. Exposure durations. Take durations from the Life Cycle Environment Profile. Guidance is given in paragraph 6.1, reference f, relating durations to exposure levels for various tracked vehicles.

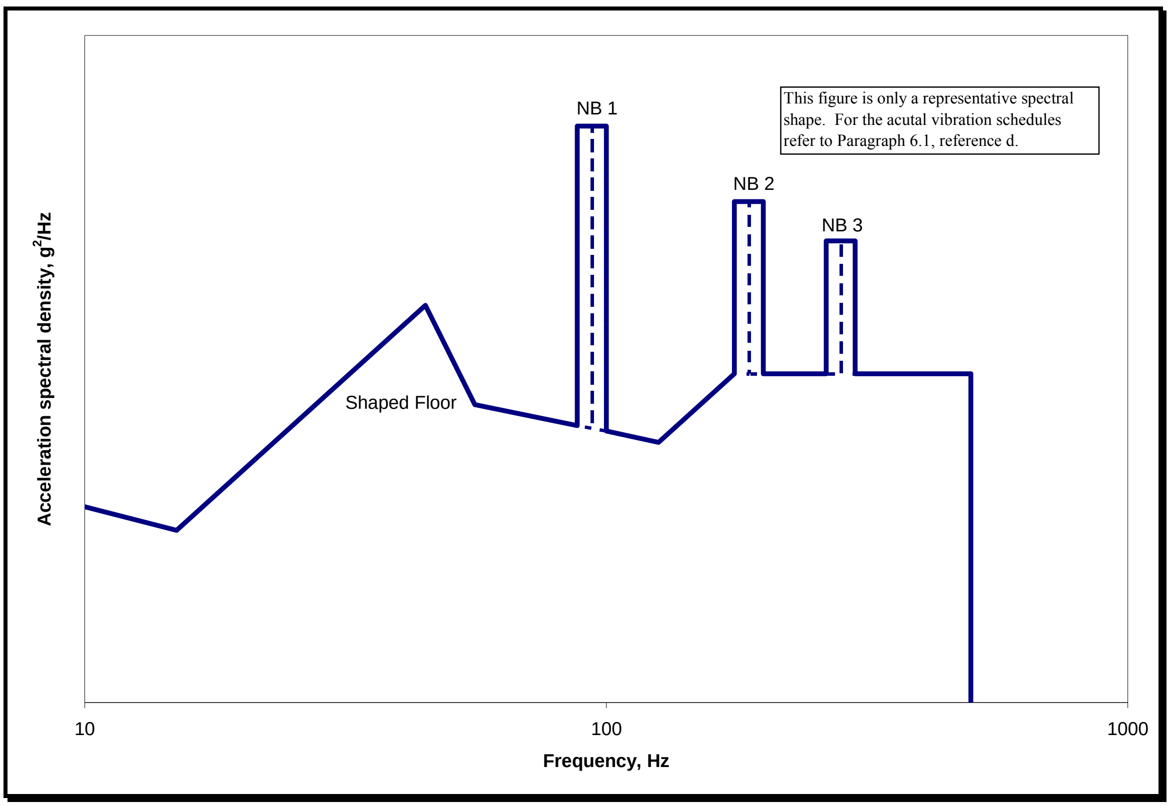


Figure 514.6D-8. Category 20 - Tracked vehicle representative spectral shape.

2.10 Category 21 - Watercraft - marine vehicles.

Note: For U.S. Navy applications refer to Method 528.

Marine vibration spectra have a random component induced by the variability of cruising speeds, sea states, maneuvers, etc., and a periodic component imposed by propeller shaft rotation and hull resonance. Materiel mounted on masts (such as antennas) can be expected to receive higher input than materiel mounted on the hull or deck. The overall ship's structure, materiel mounting structure, and materiel transmissibility (amplifications) greatly affect materiel vibration. Development of shipboard materiel should address both the levels of environmental inputs and the coincidence of materiel/mounting resonances and input frequencies. Gunfire vibration criteria per Method 519.6 are not applicable since they are based on the response of aircraft type structures that are significantly different than marine vehicle structures.

a. Exposure levels.

(1) Ship/watercraft vibrations are a very complex function of natural environmental forcing function (wave action, wind), induced forcing function (propeller shaft speeds, operation of other equipment, etc.), ship/watercraft structure, materiel mounting structure and materiel response. Even roughly accurate general vibration criteria are not available. Use measurements of actual environments to develop exposure criteria.

(2) An arbitrary qualification test requirement has been developed for shipboard materiel. This may be used as a crude definition of a total onboard life exposure. It consists of the random levels of Figure 514.6D-9 for a duration of two hours along each of three orthogonal axes, and the sinusoidal requirements of MIL-STD-167-1A, Type I (see Method 528) (paragraph 6.1, reference hh), with levels enveloping the highest values for each frequency. This criterion applies to ships and not to other watercraft. No criteria are known to be available for other watercraft.

b. Exposure durations. Take durations from the Life Cycle Environment Profile.

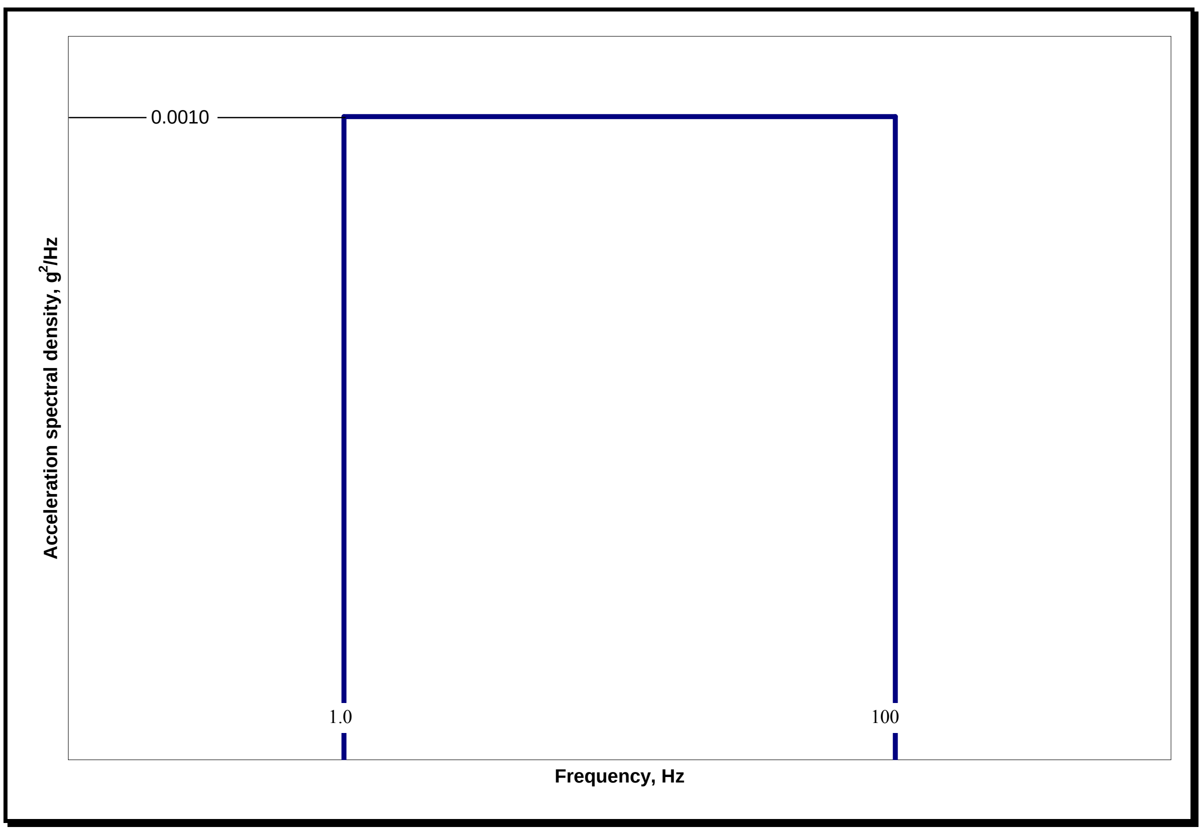


Figure 514.6D-9. Category 21 - Shipboard random vibration exposure.

2.11 Category 22 - Engines - turbine engines.

Vibration spectra for materiel mounted directly on turbine engines consists of a broadband background with narrow band spikes superimposed. The broadband background is the sum of random flow turbulence and low-level quasi-sinusoidal peaks generated by various rotating machinery elements. The narrow band spikes are due to the rotation of the main engine rotor(s) and the frequencies are the rotor rotational speed(s) and harmonics.

a. Constant speed. Many turbine engines are constant speed. This means that the rpm is held constant and power changes are made through fuel flow changes and variable pitch blades, vanes, and propellers. These machines produce the fixed frequency spikes of Figure 514.6D-10. These spikes have an associated bandwidth because there is minor rpm drift, the vibration is quasi-sinusoidal (see Annex A, paragraph 2.3.3), and the materiel resonant frequencies vary with serial number and mounting conditions.

b. Variable speed. Other turbine engines are not constant speed machines. For these engines, the rpm varies with power setting. To represent these engines, adjust the spikes of Figure 514.6D-10 to include the engine rpm range. or alternatively use swept sinusoidal over the engine rpm range.

c. Multiple rotors. Multiple rotors and output shaft. Turbofan and turboshaft engines usually have two and sometimes three mechanically independent rotors operating at different speeds. Modify the spectra of Figure 514.6D-10 to include spikes for each rotor or, alternatively, used swept sinusoids for each rotor. Additionally, turboshaft engines sometimes employ gearboxes to reduce the engine output shaft speed. If the engine output shaft speed is different from one of the engine rotor speeds, modify the spectra of Figure 514.6D-10 to include spikes for the output shaft speed or, alternatively, use swept sinusoids for the output shaft speed range.

d. Design criteria. These vibration environments can be approximated in the laboratory by the narrowband random over broadband random test described in Annex A, paragraph 2.3. Many vibration problems in this type of environment are associated with the coincidence of materiel resonant modes and the excitation spikes. The notches between spikes are used in intelligent design as safe regions for critical vibration modes. Source dwell tests minimize the likelihood that materiel will be overstressed at non-representative conditions and that reasonable design provisions will not be subverted.

e. Engine mounts. Engine vibration levels are affected by the engine mounting structure (see Annex A, paragraph 2.4). Thus, the same engine mounted in two different platforms may produce differing levels. Engine test stand levels are very likely to be different than platform levels. The locations of frequency peaks in the vibration spectrum are engine driven and will not change with the installation.

f. Exposure levels. Measured values should be used when possible. For those tests employing time compression, test levels can be increased above measured values (see Annex A, Section 2.2) for the endurance portion of the test while measured values can be used for the performance portion of the test. Typically, component functional performance is checked at the beginning and at the end of the endurance test in each axis. Figure 514.6D-10 levels can be used when measured data are not obtainable. These levels are rough envelopes of data measured on several Air Force constant speed propeller applications.

g. Exposure durations. Take durations from the Life Cycle Environment Profile.

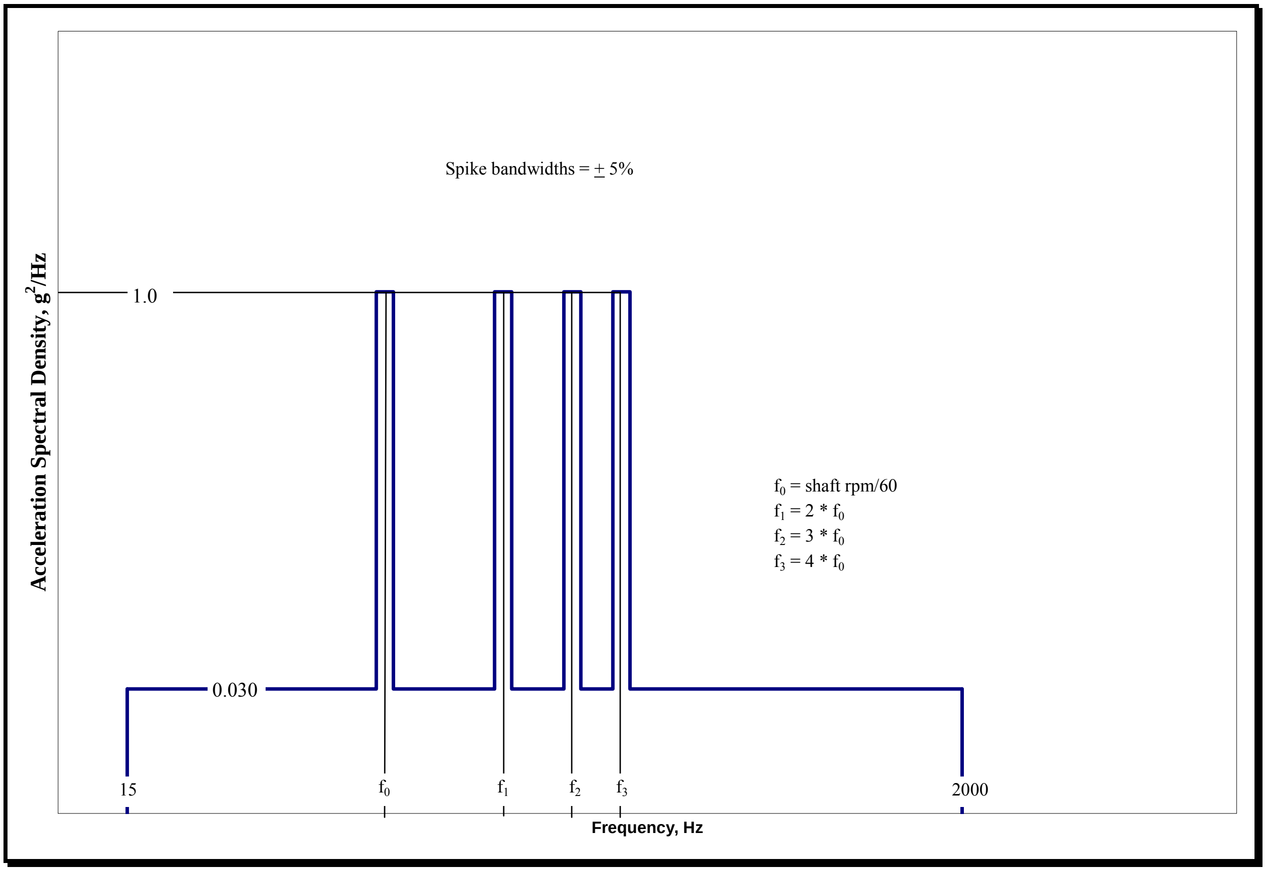


Figure 514.6D-10. Category 22 - Turbine engine vibration exposure.

2.12 Category 23 - Personnel - materiel carried by/on personnel.

The human body has highly damped, low frequency modes of vibration. Materiel carried on the body is protected from the vibration environment. Vibrations sufficient to harm materiel would be intolerable if transmitted through the body. Develop personnel materiel to withstand typical vibration environments (shipping, transportation, etc.) when the materiel is not carried by personnel.

a. Exposure levels. No personal materiel vibration exposures are required.

b. Exposure durations. No personal materiel vibration exposure durations are required.

METHOD 514.6 ANNEX E

Supplemental Tailoring Guidance for Vibration Exposure Definition

> **NOTE:** Unless specifically noted, all document references refer to paragraph 6.1 in the front part of this method.

1. SCOPE.

1.1 Purpose.

This Annex provides information intended to be useful in determining the vibration levels and durations of environmental life cycle events and in defining the tests necessary to develop materiel to operate in and survive these environments.

1.2 Application.

Recommend actual environments be measured and materiel life cycle durations be used to develop materiel design and test criteria whenever possible. Existing databases can sometimes be used in lieu of measurements. A preliminary environmental life cycle based on data provided herein can be useful as a planning tool. A preliminary life cycle definition can be used to concentrate limited resources on those vibration exposures most significant to the materiel. Guidance for setting design and test exposure values is given below with descriptions of vibration environments of many typical life cycle events. Suggested alternate criteria (levels and durations) or other guidance is recommended for those cases where measured data defining the actual environments are not available. Table 514.6-I in the front part of this method contains an outline of the following section with references to the paragraph numbers.

1.3 Limitations.

See paragraph 1.3 in the front part of this method, as well as paragraph 2.1.1a(1) below.

2. SUPPLEMENTAL TESTS.

2.1 Supplemental Considerations.

2.1.1 Category 24 : All materiel - minimum integrity tests.

Minimum Integrity Test (MIT) methods are generally relatively unsophisticated tests that can be adopted when a precise simulation is not necessary to establish suitability for service. These are normally coupled to generalized or fallback test severities which may be used in the earlier phases of a materiel development program when adequate information may not be available to allow use of project specific severities.

> **Note:** **Tailored test methods are preferred** over MIT and should be employed whenever possible. MIT can not be used for qualification.

The MIT test category is still employed and, therefore, continues to be included within the MIL-STD-810 guidelines; however, it is placed under the category "supplemental" due primarily to the unorthodox non-tailored nature of the test category with advice to implement with care.

The minimum integrity test is intended to provide reasonable assurance that materiel can withstand transportation and handling including field installation, removal, and repair. This is particularly important for materiel that was designed and tested to requirements based only on operational service environments in which the item is mounted on vibration isolators. The same hardware is often subjected to handling, transportation, etc., without isolators, and should be tested in such configurations. Subsequent to introduction of MIT in MIL-STD-810D, Environmental Stress Screening (ESS) has become a common practice in many production facilities. Generally, ESS testing is conducted at lower levels than those proposed in Figures 514.6E-1 and 514.6E-2, and spectral shaping based on structural characteristics of the materiel may be employed. Additionally, ESS testing is generally conducted in a hard mount configuration that may address the transportation test shortcomings addressed earlier in this paragraph pertaining to otherwise shock mounted equipment.

Many agencies use some form of MIT based on historical knowledge of their particular service environments, and their spectra may vary from those provided within this document.

a. Basis for levels. Vibration levels and durations of Figures 514.6E-1 and 514.6E-2 are not based on application environments. Rather, experience has shown that materiel that withstands these exposures functions satisfactorily in the field (unfortunately, much of the original documentation leading to the MIT levels was not carefully documented). Since the MIT levels may be severe relative to most environments, failure to pass an MIT does not imply that the materiel will fail in its service environment. Failure to function subsequent to exposure to an MIT test should serve as grounds to make an attempt to define the test environment and make an effort at developing a tailored test.

(1) Limitations. Do not apply minimum integrity tests to materiel that has been designed and tested to all environments of its life cycle, or to materiel that is otherwise tested to levels and durations that are equivalent to the minimum integrity test by the vibratory fatigue relationships of Annex A, paragraph 2.2. MIT cannot be used for qualification tests.

(2) Delicate materiel. Use care with delicate materiel. Do not apply this test when the levels are felt to be too high for the materiel. Rather, evaluate the full environmental life cycle and make provisions to ensure the materiel is adequately protected from vibration and shock during all phases of the environmental life cycle - to include the transportation phase.

(3) Exposure levels. Test levels are shown in Figure 514.6E-1 for general use, and in Figure 514.6E-2 for helicopter materiel. These exposures are to be applied directly to the materiel (hard mounted) and not through vibration isolation devices. These exposures are based on typical electronic boxes. When materiel is too large, unnecessarily high loads are induced in mounting and chassis structures, while higher frequency vibrations at subassemblies are too low. In these cases, apply the minimum integrity test to subassemblies. The maximum test weight of a materiel or subassembly should be approximately 36 kg (80 lb).

(4) Exposure durations. Test durations are shown in Figure 514.6E-1 for general use, and in Figure 514.6E-2 for helicopter materiel.

In many cases, materiel is designed and tested to requirements based only on operational service environments. Other phases of the environmental life cycle are assumed to be less stringent or not considered. The minimum integrity test is intended to provide reasonable assurance that materiel can withstand transportation and handling including field installation, removal, and repair. This is particularly important for materiel mounted on vibration isolators in service and subjected to handling, transportation, etc., without isolators.

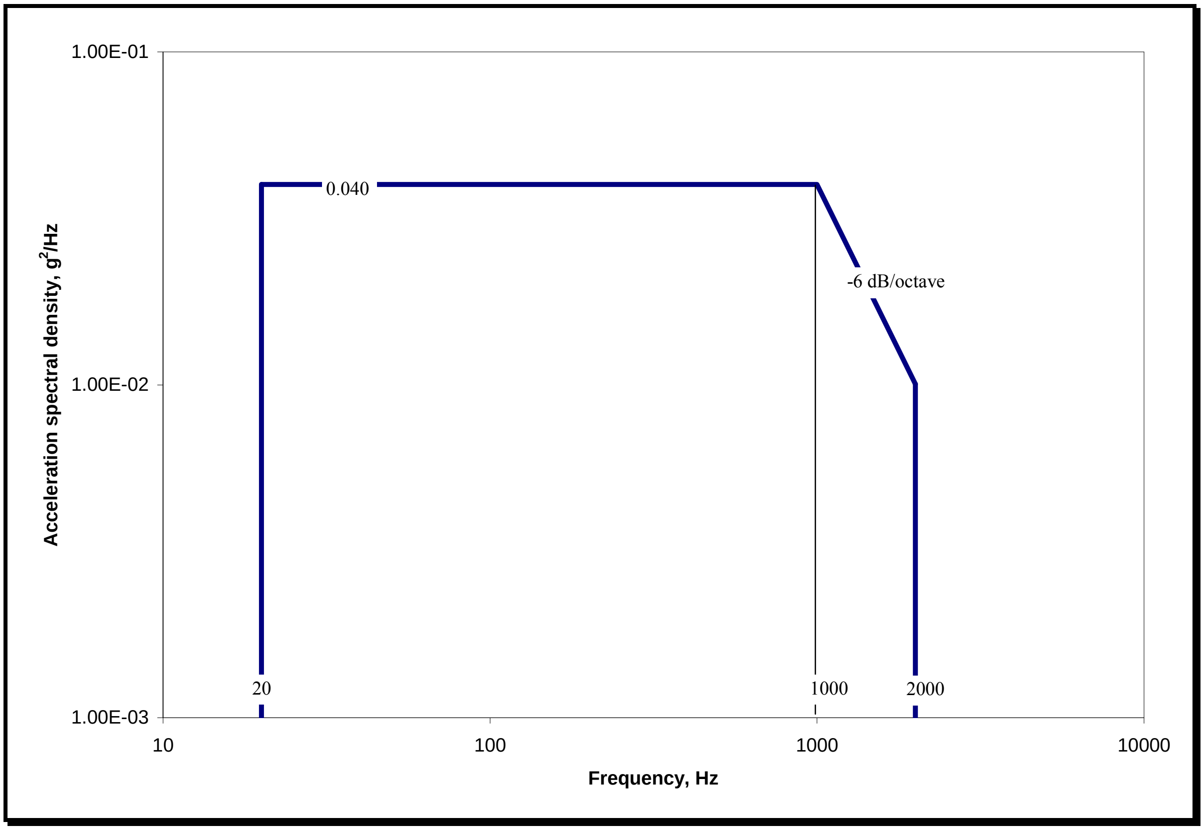


Figure 514.6E-1. Category 24 - General minimum integrity exposure.
(Test duration: One hour per axis; rms = 7.7 gs)

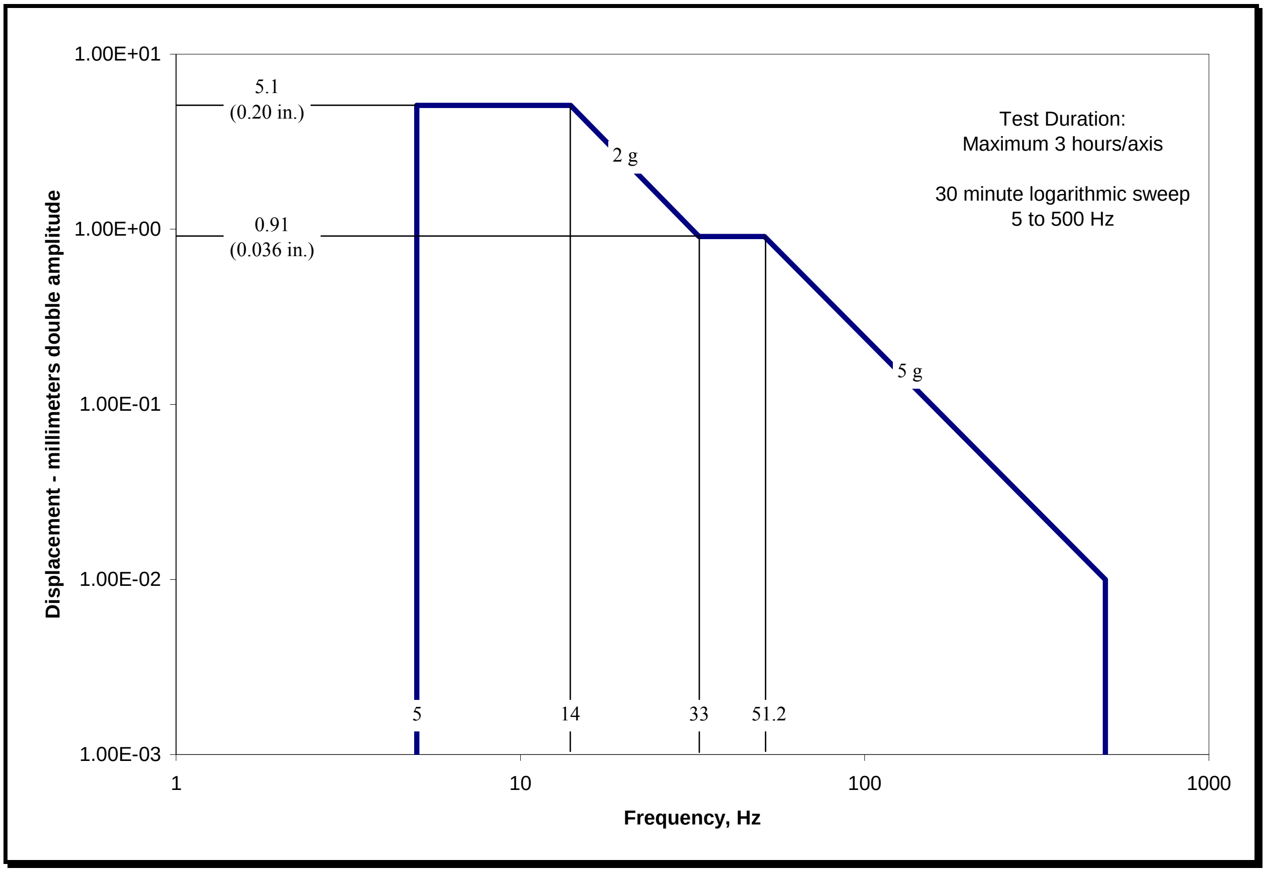


Figure 514.6E-2. Category 24 - Helicopter minimum integrity exposure. (Test duration: Maximum three hours per axis – 30 minute logarithmic sweep 5 to 500 Hz.)

2.1.2 Category 25 - All vehicles - cantilevered external materiel.

Materiel that consists of, or includes cantilever elements mounted external to a platform are subject to special problems. These problems are relatively rare but when they occur usually result in rapid and complete failure. These problems occur when the cantilevered elements are excited to vibrate in their cantilever bending or torsion modes by interaction with fluid flows.

a. Excitation mechanisms. Cantilever elements immersed in a fluid flow can vibrate due to several types of self excited vibration, and by forced response to pressure fluctuations. The three primary mechanisms are introduced below. For a general discussion of self-excited vibrations and more information on these three mechanisms, see paragraph 6.1, reference y, Chapter 7, and paragraph 6.1, reference z, section 3.6, and chapters 5 and 6.

(1) Flutter is a mechanism where the vibrations of a "wing" in a flow are such as to produce lift forces and moments that reinforce and amplify the vibration. A "wing" is a cantilever beam with slender cross section (i.e., the dimension parallel to the airflow is much larger than the dimension perpendicular to the flow). Flutter is not the result of an environmental forcing function. It is a mechanism inherent in a design and once started it needs no further environmental excitation to sustain and amplify the motion. Flutter is a separate engineering specialty and should be handled by flutter engineers. The vibration engineer needs to recognize flutter and the difference between flutter and other vibrations. Many artificial problems have been generated when other types of vibrations have been mislabeled as flutter. Conversely, flutter problems will not be solved until recognized as such and treated by flutter engineers.

(a) A simple form is known as stall or stop sign flutter. Stop sign flutter can be seen when a plate (sign) mounted on a single central metal post flaps violently in the wind. This happens when the wind blows roughly parallel, but at a small angle to the vertical plane of the plate. A pressure distribution forms over the plate as with a "wing." These pressures combine as a lifting force located upstream (1/4 mean chord) of the post. This off center force causes the plate to twist the post, increasing the angle between the plate and the wind (angle of attack). Increased angle of attack causes increased lift, more twist of the post, and larger angle of attack. This continues until either the post torsional stiffness is sufficient to stop further twisting, or until the airflow over the plate stalls. When stall occurs, the center of lift shifts to the plate center (1/2 mean chord) and the twisting moment disappears. The post (torsional spring) returns the sign to the original angle, the flow reestablishes and the plate twists again, repeating the cycle. The cycle then repeats at the frequency of the plate/post torsion mode. With road signs this cycling can go on for long periods of time without failing the simple steel post. However, when a similar oscillation occurs with more sophisticated structures, failure usually occurs rapidly.

(b) Classical flutter is a mechanism that involves two (or more) modes. Typically these are the first bending and first torsion modes. As flow speed increases the fluid interacts with the modal masses and stiffnesses, changing modal frequencies. Flutter occurs when modal frequencies converge and the motions of the two modes couple in a mechanism that extracts energy from the fluid flow. For additional information see paragraph 6.1, reference z, section 7.10 or section 3.6.

(2) When air flows over a blunt cross section (depth ≈ height), vortices are shed alternately from one side, and then the other side, producing an oscillating force. These vortices are parallel to the length of the cantilever and propagate downstream as individual elements, dissipating rapidly. A blunt cross section cantilever attached to a platform moving through a fluid is subject to this force. When the excitation frequency is close to a cantilever resonant frequency, vibration will occur. When the vibrating mode is low, damped vibration can be substantial. This is another self-excited rather than an environment driven vibration. However, in this case, unlike flutter, the vibration engineer is usually expected to handle the problem.

(a) Vibration due to vortex shedding can often be seen in the radio antennae commonly used on automobiles (the single piece non-telescoping type). When moving at speeds of roughly 80 to 97 kilometers per hour (50 to 60 miles per hour) and when there is water on the antenna, the antenna often vibrates at easily visible amplitudes. It would appear that the antennae are not failing because the vibration is in the second bending mode (2 node points). The strain distribution (mode shape) is such (again clearly visible) that dynamic bending stresses are not very high at the root of the cantilever. (It is also suspected that the antennae are made of a low-strength steel that fortuitously has good fatigue properties.)

(b) Shed frequency and force generated are approximately equal to:

$$f = 0.22\, V/D$$

$$F = (\tfrac{1}{2}\rho V^{2} DL)\sin(2\pi f t)$$

f = frequency
V = velocity
D = cantilever cross section diameter
F = force
ρ = density
t = time
L = the exposed length (perpendicular to the cross section)

(For non-circular cross sections, D becomes the dimension perpendicular to the flow in the frequency equation and the dimension parallel to the flow in the force equation. See paragraph 6.1, reference y, paragraph 7.6 for more information.)

(3) Forced vibration of external cantilevers by fluctuations in a fluid flow is the same response to aerodynamic turbulence that is a primary source of vibration in aircraft. The factors that make this a special case for cantilevers are the dynamic characteristics of the cantilevers. First, a cantilever exposes a large surface area to the excitation relative to the cross section of the support structure. Second, a cantilever tends to respond with high amplitude motion and large root stresses in the supporting base. Third, when the cantilever has the form of a "wing," aerodynamic lift and drag forces can be produced that add to the fluctuating pressure loads. These aerodynamic forces are produced because the turbulence is a tumbling of the fluid with variations in flow direction and flow velocity. These variations affect the "wing" as variations in angle of attack and flow velocity.

(a) There are two types of excitation that are important. One is the broadband random turbulence behind any relatively blunt flow obstruction or behind a stalled airfoil. The other is vortices. A vortex forms when the pressures on two sides of a "wing" are different. The flow from the high pressure side wraps around the tip to the low pressure side. This results in a rotating flow trailing downstream of the tip. This rotating flow or vortex is left in the wake of the "wing," is highly stable, and persists for long distances downstream. Such a vortex is highly structured with a sharply peaked frequency distribution.

(b) Vortex generators (small "wings") are often seen on airplane wings. The vortices generated help to hold the flow in the desired locations over the wing. This phenomenon can be clearly seen during takeoff of Boeing 737 aircraft equipped with CFM 56 (large diameter) engines when the air is humid. There is a vortex generator (small "wing") roughly 20 centimeters by 20 centimeters (8 inches by 8 inches) on the inboard side of each engine cowling. When the aircraft rotates to takeoff attitude, a vortex is formed that moves up over the wing and extends back parallel to the fuselage. Moisture condenses in the vortex, making it clearly visible to passengers seated at windows beside the engine and over the wing.

b. <u>Platform environments</u>.

(1) Fixed wing aircraft and external stores.

(a) Any "wing" can flutter. However, this is not likely with blade antennas or the wings, control surfaces, and fins on stores. This is because first bending and first torsion mode frequencies are typically well separated. Any "wing" that has closely spaced bending and torsion mode frequencies should be evaluated by flutter engineers.

(b) Fixed wing aircraft usually do not have blunt cross section external cantilevers. Anything outside the mold lines is generally streamlined (i.e., airfoil shaped) to reduce drag. However, if blunt cross sections are used, care should be exercised to ensure that shed frequencies and cantilever frequencies are well separated.

(c) Many fixed wing aircraft have problems due to turbulence forced vibration. Typical problems are failed blade antennae, failed fins on external stores, and failed wings and control surfaces on missiles. Blade antenna problems are usually caused by locating the antenna down stream of a flow disturbance such as a cockpit canopy, a radome that projects into the air stream, or a cavity in the aircraft skin. Severe broadband flow turbulence carries downstream behind the disturbing element for a distance of three to five times the maximum cross sectional dimension of the disturbing element.

(d) Fins on external stores are typically exposed to turbulence behind the carrying pylon, rack, or leading store. There is a case where a vortex forms in a corner of an engine inlet during high speed throttle chops. This vortex drops down and moves toward the airplane centerline as it extends aft. There is a single fuselage external store station that is wiped by this vortex. A specific missile carried at this station experienced high vibration levels of wings and control surfaces leading to rapid failure. The missile had to be redesigned to allow carriage on that one station.

(2) Helicopters and external stores.

(a) Flutter of "wings" on a helicopter is not likely due to the relatively low air speeds. However, if otherwise unexplainable failures occur in "wing" like elements, a flutter engineer should be consulted.

(b) Flight speeds of helicopters are lower than fixed wing aircraft and streamlining is not as important. Thus, blunt cross section cantilevers are more likely to be used. When blunt cross sections are used, care should be exercised to ensure that vortex shed frequencies and cantilever frequencies are well separated.

(c) Helicopters are also subject to turbulence. However, turbulence produced vibratory loads are proportional to flow speed and helicopter speeds make problems due to turbulence relatively unlikely. It is still prudent to locate cantilevered materiel away from known turbulence.

(3) Ground vehicles.

(a) The flapping of the fabric cover of an open truck is a form of flutter. Structures of this type will "flutter" and must be strong enough and tied down well enough to prevent carrying away. However, to replace a fabric cover with a stiffened structure is not reasonable. Flutter problems at ground vehicle speeds should be limited to cases of this type.

(b) Streamlining is usually not a significant factor in ground vehicle design. Thus, blunt cross-section cantilevers and vortex shedding are relatively likely. Exercise care to ensure vortex shed frequencies and cantilever frequencies are separated.

(c) Forced vibration problems should be extremely rare due to low flow speeds. However, turbulence does exist at any flow speed and could possibly affect large, low frequency structures. The low frequency turbulence produced by large trucks affects the handling of smaller vehicles in close proximity. Vortices in the wakes of large trucks can often be seen in disturbances of roadside dust.

(4) Watercraft.

(a) For the portion of the platform above water, the discussion for ground vehicles applies. Portions of the platform below water are in a higher density fluid, even though flow speeds are low, the pressures are high. Wake turbulence of watercraft is clearly visible at the water surface. "Wing" materiel is subject to flutter and blunt cantilevers including "wing" elements with blunt trailing edges are subject to vortex shedding. Much of the original work in this technology dealt with watercraft problems.

(b) Hulls and externally mounted underwater materiel are generally designed for smooth flow at the bow and along the sides but with squared off "boat tail" sterns. Turbulence driven forced vibration should not be a problem in smooth flow areas. However, anything located downstream of a "boat tail" will be subjected to high levels of flow turbulence.

c. Exposure levels.

(1) Exposure levels are not pertinent to flutter or other instabilities. These mechanisms, if they occur, will either drive the system to rapid, complete failure or will persist at high levels resulting in rapid fatigue or wear failure. The correct procedure is to design the materiel such that these mechanisms do not occur. When instabilities are discovered, the correct procedure is to understand and then eliminate the mechanism. This is accomplished by determining the mode shapes and frequencies of those resonances participating in the instability and, if possible, the characteristics of the flow field. Eliminating the mechanism is done by changing modal frequencies, mode shapes, modal damping, and/or flow characteristics. This is accomplished by changing modal mass, stiffness, or damping and/or by changing aerodynamic shapes. (See paragraph 6.1, reference z, section 6.1.) Dynamic absorbers are often useful in changing modal properties (see paragraph 6.1, reference y, paragraphs 3.2 and 3.3).

(2) Vortex shedding driven vibration also generally leads to rapid fatigue or wear failure. This problem typically involves a single mode of vibration of the materiel. If possible, the problem should be eliminated by separating the shed frequency and the resonant frequency (ideally by a factor of 2). If this is not practical, it may be possible to survive this mechanism for useful periods of time with good design. Good design consists of using materials with good fatigue properties, elimination of high stress points, and adding damping. In order to define exposure levels, it is necessary to

measure the motions of the cantilever on the platform in the operating environment. These measurements are used to define modal responses. When laboratory tests are required, response control is necessary. This is because the primary energy input is directly from the fluid flow. Response of the cantilever to this input is greater than the response to the vibration environment at the mount.

(3) Local turbulence is not predictable except in a very general sense. Problems of this type should be avoided whenever possible by locating materiel away from known turbulence areas. Beyond this, it is necessary to operate the platform through its operational envelope and evaluate problems as they occur. When problems are discovered, the first approach should be to determine the source of the turbulent wake that is causing the problem and to move the materiel out of this wake. If this is not possible, proceed as discussed for vortex shedding problems.

d. Exposure durations. As discussed above, problems should be solved by eliminating instability mechanisms or by moving materiel away from turbulence. If it is necessary to define exposure durations, take them from the life cycle profile. These problems may occur in very specific regions of an operating envelope. It may be necessary to break missions down to a very detailed level in order to define realistic durations.