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METHOD 514.8

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 Annex F.

The vibration profiles provided in Annexes B through 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. In addition, Test Operations Procedure (TOP) 01-2-601 (paragraph 6.1, reference d), includes an assortment of specific ground vehicle vibration data and TOP 01-2-603 (paragraph 6.1 reference xx) includes several specific helicopter vibration data.

Organization. The main body of this Method is arranged similarly to the other methods of MIL-STD-810H. A considerable body of supplementary information is included in the Annexes. With the exception of Table 514.8-I, all tables and figures for the entire method are in Annexes B through F. Annex A provides definitions and engineering guidance useful in interpreting and applying this Method. Annexes B through F provide guidance for estimating vibration levels and durations and for selection of test procedures. Reference citations to external documents are at the end of the main body (paragraph 6). **It is highly recommended that users read Annex A before applying the vibration schedules in Annexes B through E or the vibration schedule development process in Annex F.** 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

ANNEX F – DEVELOPMENT OF LABORATORY VIBRATION TEST SCHEDULES

1. SCOPE.

1.1 Purpose.

The purpose of this Method is to provide guidance for defining vibration environments materiel may be exposed to throughout a life cycle and to provide guidance for the conduct of laboratory vibration tests. 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.

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 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 514.8-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. Test Operations Procedure (TOP) 01-2-601 (paragraph 6.1, reference d), includes an assortment of specific ground vehicle data. TOP 01-2-603 (paragraph 6.1, reference xx) includes a few specific helicopter profiles and will be updated as more data become available.

d. Manufacturing. The manufacture and acceptance testing of materiel involves vibration exposures. These exposures are not directly addressed herein. It is assumed that materiel undergoes environmental testing during the manufacturing and acceptance process and this process produces the same environmental damage for any deliverable materiel. Thus the tests described in this Method are designed to verify the field life of the 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 514.8-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. It is highly recommended that users read Annex A before applying Annex B, C, D and E vibration schedules
[3] Refer to the applicable ESS procedure (for additional guidance see Annex A, Paragraph 2.1.6).
[4] See paragraph 2.3.2 below.
[5] For Navy vessels, see Method 528.1.

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. This method does not attempt to address the validity of this assumption and leaves it to the user to determine proper treatment of a given materiel item/platform. The guidance below addresses typical platform/material interaction scenarios. Additional discussion of platform/materiel interaction is provided in Annex A, paragraph 2.4.

(1) 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). The use of control limits should be based upon field data measurements and the sensitivity of the materiel to excessive vibratory loading (e.g., a resonance condition).

(2) In certain cases in which the field measured response is well defined on a small component and the duration of the vibration is short, execution of the laboratory test under open loop waveform control based upon the field measured data is an option.

(3) For large materiel items, it is necessary to recognize that the materiel and the exciter vibrate as a single flexible system and may be difficult to control as a laboratory vibration test. An example is a shelter transported to the field as a pre-assembled office, laboratory, etc. A suitable test for such systems would be the large assembly transport test (Procedure III) of paragraph 4.4.3.

(4) Proper treatment of a given materiel item may vary throughout the life cycle. 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.

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.

d. Multiple Exciter Testing. This Method is limited to consideration of one mechanical degree-of-freedom based on a spectral reference. Refer to Method 527 for further guidance on multiple exciter testing, and Method 525 for time waveform replication.

e. Synergistic Effects. Combine the guidance of this Method with the guidance of Part One and other methods herein to account for environmental synergism.

2. TAILORING GUIDANCE

2.1 Selecting this 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 514.8-I for a general listing of vibration exposures and test procedures as related to environmental life cycle elements. See Annexes B-F for guidance on determining vibration levels and durations.

a. Fidelity of the laboratory test environment. As noted in Part I (Paragraph 1.3), laboratory test methods are limited in their abilities to simulate synergistic or antagonistic stress combinations, dynamic (time sequence) stress applications, aging, and other potentially significant stress combinations present in natural field/fleet service environments. Use caution when defining and extrapolating analyses, test criteria, and results. An assessment of the test article vulnerabilities should be used to determine the environmental variables that are essential to the laboratory test and potential for increased margin to compensate for deficiencies in the test environment. Reduction in test environment fidelity may lead to an increased risk to material life and function in the fielded environment.

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 Annex F.

c. Conservatism with default or enveloped data. Annexes B - E of this Method provide information that can be used to generate default 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. Use caution when conducting vibration test with default or enveloped vibration data if non-linear behavior is expected or observed at full test level. If non-linear behavior is a concern, a ramp up step should be added to the test schedule. The vibration amplitude of this additional ramp up step shall have an exaggeration factor of unity. This unity ramp up step duration should be at least 10 minutes. The data measured during full test level and the unity ramp up step can be used to evaluate the linearity of the materiel during accelerated test. If materiel is determined to behave non-linearly using the above technique, the organization responsible for the materiel under test shall be notified. Test options should be explored and a proposed path forward should be identified. The test options and proposed path forward should be sent to the appropriate test authority for concurrence prior to proceeding.

NOTE: The materiel's anticipated Life Cycle Environmental Profile (LCEP) may reveal other vibration scenarios that are not specifically addressed in the procedures. Tailor the procedures as necessary to capture the LCEP variations, but do not reduce the basic test requirements reflected in the below procedures without proper justification. (See paragraph 2.3 below.)

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.

Use the anticipated life cycle sequence of events as a general sequence guide (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 514.8-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 the 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 (see Annexes B-E, paragraphs 1.2).

2.2.1 Procedure selection considerations.

Vibration test profiles may be omitted from an overall test series depending on relative profile severity. Profile severity comparisons shall include fatigue damage potential (test duration and bandwidth), vibration amplitude, and spectral content within the profile bandwidth. Analytical estimates of fatigue damage potential should be made on the basis of simple, well-understood models of the materiel, when and if possible.

Another method for reducing test duration is through a combination of spectra techniques. Combinations of random vibration test profiles may be performed if the reference spectra and bandwidths are similar by either employing the fatigue damage spectrum (FDS) or via statistical methods (refer to Annex F). Combination of vibration tests should not be performed with dissimilar spectra or spectra with dissimilar bandwidths. Examples of dissimilar spectra are random, sine, sine on random, sweeping sine on random, or sweeping random on random. For example, combining a broadband random (e.g. wheeled vehicle) spectrum with a sine-on-random spectrum (e.g. helicopter) should be avoided. Observe that the FDS example provided in Annex F is quite liberal in combining spectral shapes. Factors such as vibration magnitudes and unit under test (UUT) robustness should always be considered in establishing combined spectra based requirements.

Extreme caution should be used if test schedule compression is used to combine tests. Too much compression could result in entering non-linear regions of mechanical response which is undesirable. Highly conservative specifications with no correlation to actual discrete environmental conditions can lead to unnecessary overdesign. Furthermore, combining spectra can result in the inability to relate a failure mechanism to a discrete vibration environment. Finally, careless combination of spectra has the potential to yield a test that is difficult to conduct and control. Additionally, enveloping or combining spectra could result in the loss of vehicle anti-resonances which may be necessary for laboratory replication. These considerations are especially important for multi-axis test setups and profile definitions.

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.

c. Any omission or combination of spectra techniques employed should be agreed to by the responsible test authority prior to the conduct of testing and should be thoroughly documented in the test report.

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 (Methods 501.6 and 502.6) of this Standard include guidance for determining levels of other environmental loads. 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 procedure 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 impact 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 secured 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 527.1 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 can 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 514.8 are used as reference curves in a multiple-axis test, it should be recognized that Cross Spectral Density (CSD) terms will be undefined. Method 527 recommends that the coherence terms be near zero. Some reduction in levels (e.g., lower conservatism factors) may be justified if it can be shown that the multiple degree-of-freedom (MDOF) test produces significantly higher stress levels or lower fatigue life than the sequential single degree-of-freedom (SDOF) tests.

2.4 Test Item Operation.

Where vibration tests are conducted to determine operational capability while exposed to the environment, operate the test item during the vibration test. Otherwise, verify operation before and after the vibration test. Use caution when applying combined or enveloped vibration profiles during operational tests as the levels may not be representative of any particular operational environment. During operational vibration tests, monitor and record sufficient data to define the achieved performance and sensitivity of the materiel to the vibration environment. See Annex A, paragraph 2.1.2.1 for additional functional test considerations.

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 (applicable to Procedures I through IV).

(1) Test schedule(s) and duration of exposure(s).

(2) Locations and specifications for all control and/or response transducers.

(3) Test equipment limitations. Assure that test requirements (force, acceleration, velocity, displacement) can be met. Seek approval for variation if required. Document any variation.

(4) Test shutdown procedures for test equipment or test item problems, failures, etc. (See paragraph 4.3).

(5) Test interruption recovery procedure. (See paragraph 4.3).

(6) Test completion criteria.

(7) 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 I and IV- General and captive carriage/free flight vibration.

i. Test fixture requirements.
ii. Test fixture modal survey requirements / procedure.
iii. Test item / fixture modal survey requirements / procedure.
iv. Vibration exciter control strategy.
v. Test tolerances.
vi. Test temperature conditioning requirements.
vii. Combined environment requirements (e.g., temperature, humidity).
viii. Axes of exposure.

(2) Procedure II - Loose cargo vibration.

i. Orientation of test item(s) in relation to the axis of throw of the test table
ii. Number of possible test item orientations.
iii. Test time per orientation.
iv. Test item temperature conditioning requirements.
v. Test fixture requirements.

(3) Procedure III - Large assembly transport.

i. Test vehicle(s).
ii. Vehicle load configuration(s).
iii. Required road surface(s).
iv. Required distance(s) on each road surface.
v. Required speed(s) on each road surface.
vi. Vehicle suspension configuration(s) i.e., tire pressures (or Central Tire Inflation System

(CTIS) settings), suspension settings (as applicable) etc.

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 may result in significant 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, if applicable, 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 (7))

(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 514.8C-8) 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 Procedure 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 secured 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 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, Tolerances, and Instrumentation.

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.

For Procedures I and IV, 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.

The vibration excitation is controlled to within specified bounds by sampling the vibratory motion of the test item at specific locations. These locations may be at, or in close proximity to, the test item fixing points (controlled input) or at defined points on the test item (controlled response). The vibratory motions may be sampled at a single point (single point control), or at several locations (multi-point control). The control strategy will be specified in the Test Plan. However, it should be noted that it could be influenced by:

a. The results of preliminary vibration surveys carried out on materiel and fixtures;

b. Meeting the test specifications within the tolerances of paragraph 4.2.2;

c. The capability of the test facility.

In view of the possibility of frequency drift, it is essential when conducting fixed frequency sinusoidal "resonance dwell" tests that the frequency be constantly adjusted to ensure a maximum response. Two methods are available:

a. Search for the maximum dynamic response;

b. Maintain the phase between the control and monitoring points.

4.2.1.1.1 Single Point Control Option

This option can be used when the preliminary vibration survey indicates a rigid vibration fixture, or when one control accelerometer accurately represents an average of the inputs at each fixing point. However, given the increased risk associated with transducer or instrumentation failure and/or calibration or scaling error attributable to a single channel, this option is not recommended. A single control point is selected:

a. Either from among the fixing points;

b. Or, in such a way that it provides the best possible solution for achieving the tolerances at the fixing points.

4.2.1.1.2 Multiple Point Control (average) Option.

This option can be used when the preliminary vibration survey shows that inputs to the test item vary significantly between fixing points. The control points, usually two or three, will be selected using the same criteria listed in paragraph 4.2.1.1.1 for the single control point option. However, the control for:

a. Random will be based on the average of the ASD of the control points selected.

b. Sine will be based on the average of the peak response values of the control points selected.

4.2.1.1.3 Multiple Point Control (maximum) Option

This option can be used when responses are not to exceed given values, but care is needed to avoid an undertest. Preliminary vibration survey results are used to aid the definition of the control points on the test item at which maximum response motions occur. The control points, usually two or three, will be selected using the same criteria listed in paragraph 4.2.1.1.1 for the single point option. However, the control for:

a. Random, will be based on the maximum spectrum response at any of the selected control points.

b. Sine, will be based on the maximum peak response at any of the selected control points.

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 transducers (typically accelerometers or strain gages) 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 transducers 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. 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 525.1 and 527.1.

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.

The test facility should be capable of exciting the test item to the random vibration conditions specified in the Test Plan. The motion induced by the random vibration should be such that the fixing points of the test item move substantially parallel to the axis of excitation. In these conditions the amplitudes of motion should exhibit a normal distribution. The tolerances defined in Table 514.8-II below should be used and checked with the test item installed. The tolerances associated with the test severity parameters are not to be used to overtest or undertest the test item. Any deviations to the test or test tolerances from the values in Table 514.8-II must be approved by the appropriate test authority and must be clearly documented. In addition to the tolerances specified in Table 514.8-II, the following factors should also be considered:

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.

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. Since the control loop time depends on the number of degrees of freedom and on the analysis and overall bandwidths, it is important to select these parameters so that test tolerances and control accuracy can be achieved. If possible, ensure the number of statistical degrees of freedom is greater 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.

e. When possible, an identical analysis bandwidth should be used for both control and monitoring. When this is not possible, adequate allowance should be made to the results of the monitoring analysis.

f. For swept narrow band random tests, the tolerances on the swept components of the test requirement should, wherever possible, be the same as for a wide band random component. However, at some sweep rates, these tolerances may not be achievable. Therefore, the tolerance requirements for these components shall be stated in the Test Plan.

g. The complete test control system including checking, servoing, recording, etc., should not produce uncertainties exceeding one third of the tolerances listed in Table 514.8-II.

h. The tolerances associated with the test severity parameters are not to be used to overtest or undertest the test item. If tolerances are not met, the difference observed should be noted in the test report.

Table 514.8-II. Random Vibration Test Tolerances.

<table>
<tr><td colspan="3">Specific Tolerances For All Random Vibration Tests (including the broadband component of mixed random and sinusoidal vibration tests and the fixed and swept narrowband components of mixed broadband and narrowband random vibration tests)</td></tr>
<tr><th>Parameter</th><th colspan="2">Tolerance</th></tr>
<tr><td>Number (n) of independent statistical degrees of freedom (DOF) for control of the specified ASD.</td><td colspan="2">n > 120</td></tr>
<tr><td>Composite Control: Maximum deviation of the composite control ASD in relation to the specified ASD.[1]</td><td colspan="2">± 3 dB below 500 Hz
± 6 dB above 500 Hz
± 10% overall grms</td></tr>
<tr><td>Multi-point Control: Maximum deviation of any individual control channel ASD in relation to the specified ASD.[2,]</td><td>Average Control
± 6 dB below 500 Hz
± 9 dB above 500 Hz
± 25% overall grms</td><td>Extremal Control
- 6 dB / + 3 dB below 500 Hz
- 9 dB / + 6 dB above 500 Hz
± 25% overall grms</td></tr>
<tr><td>Cross-axis Motion: ASD measured with the same number of DOF as in the test axis, along the mutually orthogonal directions, in relation to the in-axis specified ASD.</td><td colspan="2">Less than 50% below 500 Hz
Less than 100% above 500 Hz
Less than the relevant specified ASD for the given cross-axis.</td></tr>
<tr><td>Frequency sweep rate</td><td colspan="2">± 10% of stated rate</td></tr>
<tr><td>Test time duration</td><td colspan="2">± 5% of stated duration</td></tr>
<tr><td>Amplitude distribution of the instantaneous values of the random vibration measured at the drive signal.</td><td colspan="2">Nominally Gaussian (Refer to paragraph 2.4 for amplitude distribution discussion)</td></tr>
</table>

[1] Composite Control is defined as: The ASD computed as either the average, maximum, or minimum (depending on control method) of all feedback channels deemed as control channels in a multi-point control scenario or the single control channel in a single-point control scenario. As discussed in paragraph 4.2.1.1 multi-point control is encouraged.

[2] If using minimum control, the negative tolerance will be that of the Composite Control.

The default assumption for all ASD references provided in this document is that the associated probability density function (pdf) is of Gaussian form. Generally, unless documentation from field data indicates otherwise, the drive-limiting option (often referred to as three-sigma clipping) should not be invoked. However, it is recognized that there are scenarios such as test equipment displacement limitations or power amplifier voltage or current limitations that could be resolved by invoking the drive limiting control parameter. When invoking the drive signal limiting feature on a Gaussian drive signal, the limiting threshold should never be set to less than three standard deviations (3-sigma). In addition, the test engineer or program engineer responsible for the test article should approve the operation and it should be properly documented within the test report.

When an ASD is being generated to serve as a reference for a vibration test, careful examination of field measured response probability density information should be performed. The probability density/distribution function should be estimated and compared with that of a theoretical Gaussian probability density/distribution. If there is strong evidence of departure from the Gaussian distribution then an accurate estimate of the higher moments – primarily kurtosis and skewness should be made, cognizant of the substantial increased amount of measurement information needed to estimate higher order moments accurately. Skewness and kurtosis are the third and fourth standardized moments about the mean computed as:

$$\text{Skewness} = E\left[\frac{(x-\mu)^3}{\sigma^3}\right] \quad \text{and} \quad \text{Kurtosis} = E\left[\frac{(x-\mu)^4}{\sigma^4}\right], \text{ where}$$

E = expectation operator
x = individual acceleration values
μ = mean acceleration value
σ = acceleration standard deviation

A Gaussian process has a skewness equal to 0 and a kurtosis equal to 3. Skewness is a measure of the asymmetry of the probability distribution of a random variable while kurtosis is a measure of "peakedness" or "flatness" of the distribution.

If analysis shows the data to be highly non-Gaussian, one may consider either of the following:

(1) Employing TWR techniques (that will generally preserve the measured pdf and the distribution in time of the time history characteristics e.g., peaks and valleys, that provide for kurtosis differing from the Gaussian theoretical value).

(2) Employing a control algorithm capable of drive signal synthesis per user defined kurtosis and "matching" the measurement pdf within some level of statistical confidence. All control systems do not necessarily assume the same model for generating non-Gaussian input and most control system software ignore the form of the pdf. Use of a control system that does not take account of the form of the pdf is discouraged unless it can be demonstrated that the pdf of the synthesized data is comparable (via statistical test) to that of the measured data upon which the test reference is based. This assumes a single measured test reference with non-Gaussian behavior. When several measured test references are present the overall non-Gaussian behavior may be due to "mixture distribution" effects, in which case an analyst must be consulted for recommendations as to a way to proceed.

In the event TWR or user defined kurtosis options as defined above are employed to address non-Gaussian scenarios, the time compression techniques outlined in Annex A paragraph 2.2 are not applicable.

The test engineer or program engineer responsible for the test article should approve any deviation from the standard Gaussian process and any deviations should be properly documented within the test report by time history plots, skewness/kurtosis estimates and probability density function estimate plots.

4.2.2.2 Peak sinusoidal acceleration.

The test facility should be able to excite the materiel as specified in the Test Plan. The motion should be sinusoidal and such that the fixing points of the test item move substantially in phase with and parallel to the excitation axis. The sinusoidal tolerances and related characteristics defined in Table 514.8-III should be used and checked with the test item installed. Only under exceptional circumstances should a Test Plan need to specify different tolerances. The complete test control system should not produce uncertainties exceeding one third of the tolerances listed in Table 514.8-III. The tolerances associated with the test severity parameters are not to be used to overtest or undertest the test item. If tolerances are not met, the difference observed should be noted in the test report.

Table 514.8-III. Sinusoidal Vibration Test Tolerances.

Specific Tolerances For All Sinusoidal Tests (including fixed, swept and stepped sine tests as well as the fixed and swept sinusoidal components of mixed random and sinusoidal tests)		
Parameter	**Tolerance**	
Frequency	± 0.1 %	
Composite Control: Maximum deviation of the composite control[1] tone level(s) in relation to the specified tone level(s).	± 10%	
Multi-point Control: Maximum deviation of the individual control channel tone levels in relation to the specified tone level(s).[2]	Average Control ± 25% below 500 Hz ± 50% above 500 Hz	Maxi Control +10% / -25% below 500 Hz +10% / -50% above 500Hz
Cross-axis Motion: Tone levels measured along the mutually orthogonal directions, in relation to the in-axis specified level(s).	Less than 50% below 500 Hz Less than 100% above 500 Hz Less than the relevant specified levels for the given cross-axis.	
Frequency sweep rate	± 10% of stated rate	
Test time duration	± 5% of stated duration	
Difference between the unfiltered signal and filtered acceleration signal[3]	± 5% on the grms values[4]	

1 Composite Control is defined as: The Line Spectrum computed as either the average, maximum, or minimum (depending on control method) of all feedback channels deemed as control channels in a multi-point control scenario or the single control channel in a single-point control scenario. As discussed in paragraph 4.2.1.1

2 If using minimum control, the negative tolerance will be that of the Composite Control.

3 Distortion of the sinusoidal signal can occur particularly when using hydraulic actuators. If distortion of the sinusoidal signal is suspected, the unfiltered signal and filtered acceleration signal should be compared. A signal tolerance of ±5 percent corresponds to a distortion of 32 percent by utilization of the formula:

$$d = \frac{\sqrt{a_{tot}^2 - a_1^2}}{a_1} \times 100$$

where: a_1 = grms value of acceleration at the driving frequency;
a_{tot}= total grms of the applied acceleration (including the value of a_1).

4 The grms of a sinusoid equals 0.707 times peak g. It is not related to grms 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 the values specified in Table 514.8-II 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 item is secured 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 transverse response to vertical axis test is excessive, the transverse response should be limited to some factor of the corresponding transverse 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 527.1 discusses the technical details associated with multi-axis vibration testing.

4.2.3 Instrumentation.

In general, acceleration will be the quantity measured to meet the vibration specification. On occasion, other devices may be employed, e.g., strain gage, linear displacement/voltage transducer, force gage, laser velocimeter, rate gyro, etc. In these cases, give special consideration to the instrument specification to satisfy the calibration, measurement, and analysis requirements. Calibrate all measurement instrumentation to traceable national calibration standards (see Part One, paragraph 5.3.2). The measurement device and its mounting will be compatible with the requirements and guidelines provided in paragraph 6.1, reference c.

a. Accelerometer. In the selection of any transducer, one should be familiar with all parameters provided on the associated specification sheet. Key performance parameters for an accelerometer follow:

(1) Frequency Response: A flat frequency response within ± 5 percent across the frequency range of interest is required.

(2) Transverse sensitivity should be less than or equal to 5 percent.

(3) Nearly all transducers are affected by high and low temperatures. Understand and compensate for temperature sensitivity deviation as required. Temperature sensitivity deviations at the test temperature of interest should be no more than ±5 percent relative to the temperature at which the transducer sensitivity was established.

(4) Base Strain sensitivity should be evaluated in the selection of any accelerometer. Establishing limitations on base strain sensitivity is often case specific based upon the ratio of base strain to anticipated translational acceleration.

b. Other measurement devices. Any other measurement devices used to collect data must be demonstrated to be consistent with the requirements of the test.

c. Signal conditioning. Use only signal conditioning that is compatible with the instrumentation requirements of the test, and is compatible with the requirements and guidelines provided in paragraph 6.1, reference c. In particular, filtering of the analog voltage signals will be consistent with the time history response requirements (in general, demonstrable linearity of phase throughout the frequency domain of response), and the filtering will be so configured that anomalous acceleration data caused by clipping will not be misinterpreted as response data.

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. Similarly, items mounted on rubber isolation systems may require monitoring of the isolator temperature with planned test interruptions to prevent overheating and unnatural failure of the isolator. 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, review the data leading up to the test interruption and assess the extent of over/under test, if any. If an over/under test condition is identified, document the incident and obtain approval from the organization responsible for the system under test to 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 by the organization responsible for the system under test. 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 vertical and longitudinal movement).

4.4.1 Procedure I - General vibration.

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

i. 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.

ii. 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.

b. Instrumentation. Installation and location of the control accelerometer(s) can significantly affect test outcome. It is recommended to mechanically attach (i.e., screw mount) control accelerometer(s) to the vibration test fixture near the test item interface(s) or at the location(s) used to derive the test specification. Additional control and/or response instrumentation may be attached with screws or adhesives to other locations on the vibration table or test item as specified in the test plan. All instrumentation 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 that 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 where the size of the item is such that more than three items in a typical cargo truck bed. Although the loose cargo transportation simulators are typically operated at fixed rates of rotation, it is recommended to monitor and record an accelerometer on the table surface in order to (1) provide measurable verification of the table motion and (2) detect any change in the test setup caused by degradation of the fencing or damage to the test article.

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 as defined in the vehicle OMS/MP.

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 (store) 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. 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 transverse axis is mutually perpendicular to longitudinal and vertical axes.

d. Vibration excitation. Store longitudinal vibration is typically less than vertical and transverse vibration. Vertical and transverse 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 transverse axes. In other cases, drive the store in the vertical, transverse, 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 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 527.1). 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 transverse directions. In other cases, transducers are required in vertical, transverse, 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 or resonance search, if required, 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 or resonance search, 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 identified peaks shall include at least the first 3 structural elastic modes of the store airframe, any local mode frequencies for subsystem structure of significant mass, and any frequencies which correspond with subassembly local modes which are critical for store performance. Additionally, the input spectra should be equalized at all frequencies up to the first flexible bending mode peak of the store to achieve the required test levels for ensuring the aircraft suspension equipment / store interface is adequately stressed. 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 response level
A_1 = Vertical axis requirement level
R_2 = Transverse axis response level
A_2 = Transverse axis requirement level
R_3 = Longitudinal axis response level
A_3 = Longitudinal axis requirement level.

For vibration being applied in either the transverse or longitudinal axis, repeat the above process.

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

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 4.3). 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 paragraph 6.1, references ll and mm, and Annex A, paragraph 2.5.)

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 either repair the test item or replace with a modified test item. Continue or repeat 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.

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Requests for other defense-related technical publications may be directed to the Defense Technical Information Center (DTIC), ATTN: DTIC-BR, Suite 0944, 8725 John J. Kingman Road, Fort Belvoir VA 22060-6218, 1-800-225-3842 (Assistance--selection 3, option 2), http://www.dtic.mil/dtic/; and the National Technical Information Service (NTIS), Springfield VA 22161, 1-800-553-NTIS (6847), http://www.ntis.gov/.

METHOD 514.8, 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 Method 514.8.

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 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 operational phases of the environmental life cycle. The endurance test is a fatigue test representing an entire life cycle. 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.

2.1.2.1 Functional test.

Functional testing is conducted to verify that the materiel functions as required while exposed to no less than the worst case operational vibration for a particular segment(s) of a mission profile. Functional vibration levels typically do not include time compression but may include some level of conservatism. Tailor the vibration level for each segment of the mission profile based on measured data, when available, or derived from the operational state of the vehicle platform.. This is the maximum vibration environment where the unit under test is expected to function. Fully verify function at the beginning, middle and end of each test segment. Monitor basic function at all times during each test run. 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 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 are 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 516.8). 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 an 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 effect 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 negative reciprocal of the slope of the S-N curve, known as the fatigue strength exponent and designated as "-1/*b*." Typical values of "*m*" are 80 percent of "-1/b" for random waveshapes, and 60 percent of "-1/*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 auto 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

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

$W(f)_2$ = ASD 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 ASDs, 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 2 (S_1/S_2) or 4 ($W(f)_1/W(f)_2$).

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.

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 (ASD) 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 525.1).

a. Frequency range. ASD 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 523.4).

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). 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 auto spectral 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 516.8; and Method 525.2 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. G-rms. 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.

2.3.6 Combination of test spectra

When combining test spectra to develop an envelope or weighted average of multiple vibration profiles, refer to the discussion and techniques presented in Annex F of this method.

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 514.8C-X 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.

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.

Experimental modal tests involve excitation of a structure with a measured force while measuring the acceleration response and computing the frequency response functions (FRF) at location(s) of interest for subsequent modal analysis. Excitation of the structure for modal test may be accomplished in various ways. The simplest method, a modal impact test, consists of excitation with a modally tuned impact hammer instrumented with a force gage to produce a low force impact on the structure that approximates an impulse function. This technique is commonly used as a quick check of resonant frequencies for fixtures and installed components. A more sophisticated approach would use burst random excitation with small vibration exciter(s) attached to a structure that is instrumented with an array of accelerometers. Modal tests with vibration exciters is more commonly used for high channel count modal tests of complex structures with more precise measurements required for the development of mode shapes and verification of analytical models. Sinusoidal and broadband random vibration excitation of a test fixture/item mounted on large vibration exciters are also options to check resonant frequencies for laboratory vibration test setups. 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. Modal parameters determined through modal test and analysis techniques are typically based on assumption of structural linearity. Linearity checks can be conducted during modal tests by collecting and analyzing data at various force levels and identifying frequency shifts, if any, in the resonant frequencies. For structures that exhibit highly non-linear behavior, additional analysis will be required to extrapolate modal test results to the expected life cycle vibration environments.

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 smooths 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 514.8D-IV are based on an average of this data. The following definitions and the values and the formulas of Annex D, Table 514.8D-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 kk.

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 that 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 514.8D-V. These are based on paragraph 6.1, references ff and kk.

a. <u>Calibrated airspeed</u>. 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 (K_{cas}). K_{cas} 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 (K_{ias}).

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 (K_{eas}).

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 (K_{tas}).

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 because 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 ASD 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 G-rms 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 ALL 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 paragraph 2.2 of this Annex. 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 514.8, 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 are 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.

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METHOD 514.8, 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. It 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.

It is recommended that 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 514.8-I in the front part of this Method contains an outline of the following paragraph with references to the paragraph numbers. For transportation vibration typical (default) missions are illustrated in Figure 514.8C-1.

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 516.8 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). Many of the profiles provided below include an enveloped profile for when the test item orientation relative to the vehicle is unknown or variable.

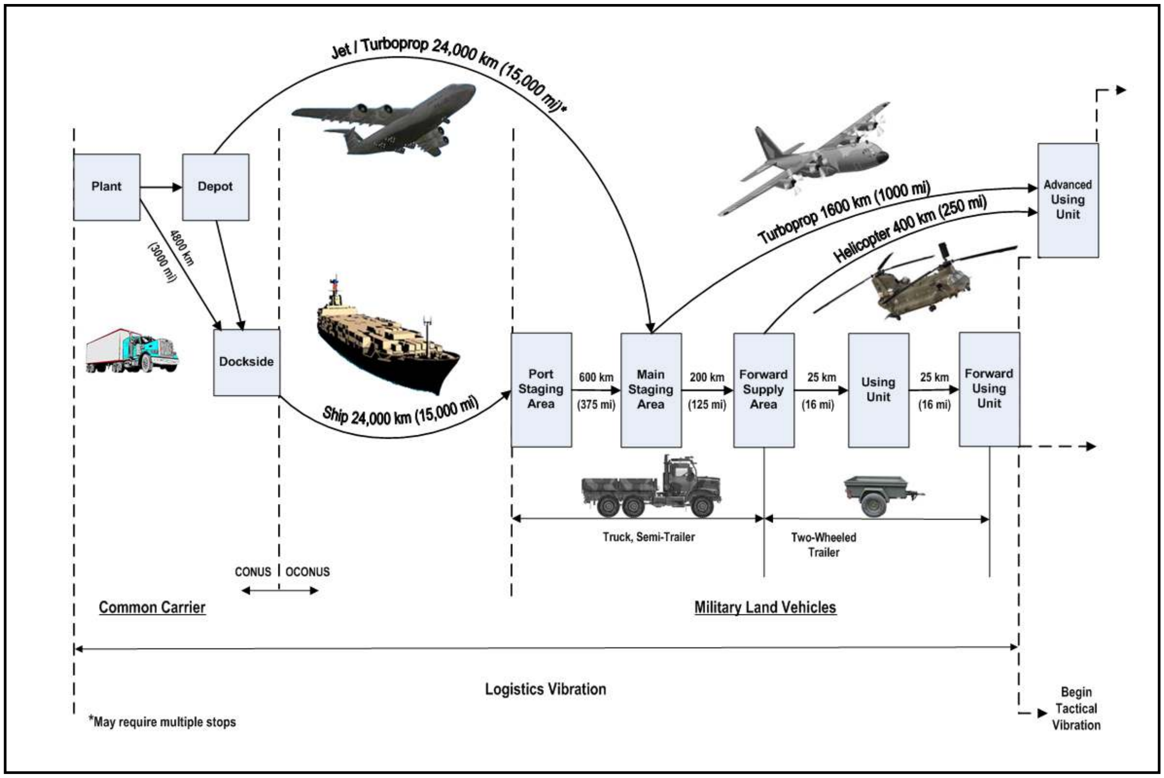

Figure 514.8C-1. Typical mission / field transportation scenario.[1, 2]

[1]See paragraph 6.1, reference nn.

[2]In the event that tracked vehicles are identified in LCEP, they should be considered in the typical mission/field transportation scenario. See paragraph 6.1, reference d.

NOTE: This Figure represents only one mission in the life cycle of materiel. Determine the number of missions in the life cycle of the materiel from the LCEP. See Part One Paragraph 4.1.2c for Whole Life Assessment (WLA) and In Service Surveillance (ISS) considerations.

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 in Part One, Figure 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 480 to 800 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 LCEP. Include realistic load configurations (approximately 75 percent of the vehicle load capacity by weight). Use these data to develop exposure levels per Annex F. Alternatively, derive exposure levels as discussed below.

a. Truck transportation over US highways. Derive exposure levels from Figure 514.8C-2 and Table 514.8C-I, or, if the test item orientation is unknown or variable see Figure 514.8C-3 and Table 514.8C-II for exposure levels. 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).

Test Schedule: Secured Cargo – Common Carrier (See paragraph 6.1, reference oo.)

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 (1000 mi) 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:[1,2] **(G-rms):** Vertical – 1.08;
Transverse – 0.21;
Longitudinal – 0.76;
Envelope – 1.17.

Velocity (in/sec) (peak single amplitude):[1,2]
Vertical – 9.68;
Transverse – 1.23;
Longitudinal – 6.11;
Envelope – 9.69.

Displacement (in) (peak double amplitude):[1,2]

Vertical – 0.37

Transverse – 0.04;

Longitudinal – 0.24;

Envelope – 0.37.

[1] Approximate values for a Gaussian random distribution which may vary based on the control system and spectral resolution. Peak velocity and displacement values are based on an acceleration maximum of three times the standard deviation (3σ) and a spectral resolution of 1 Hz.

[2] For test items for which the test item orientation is unknown or variable the Envelope profile should be run for all three axes (Figure 514.8C-3 and Table 514.8C-II).

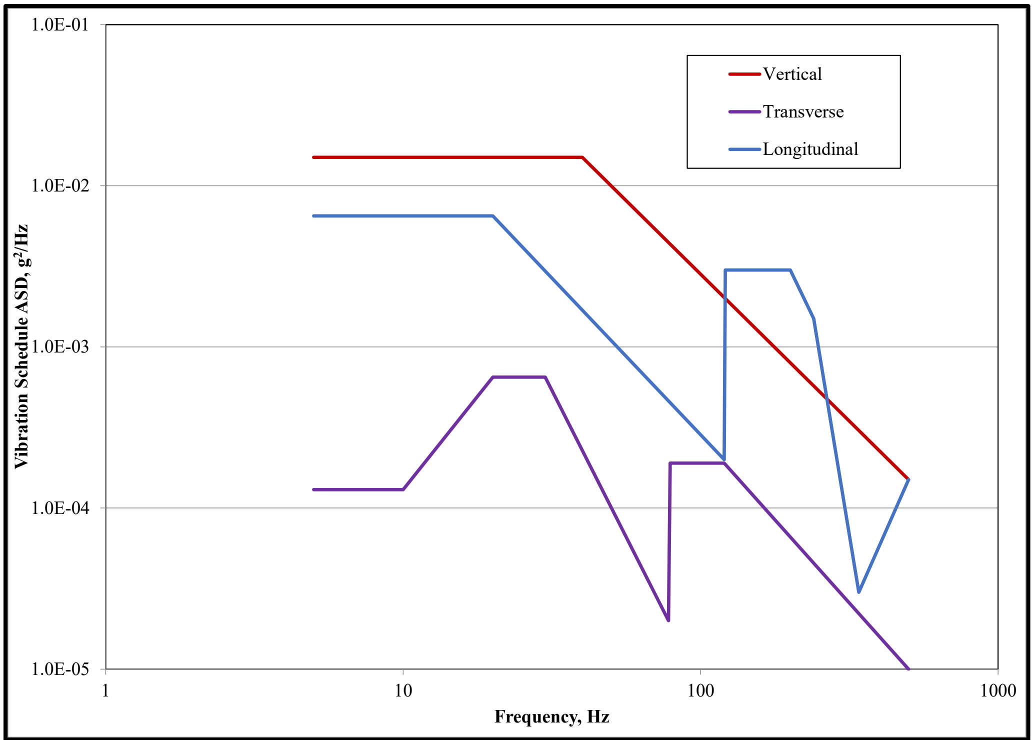

Figure 514.8C-2 – Category 4 – Common carrier (US highway truck vibration exposure).

Table 514.8C-I. Category 4 – Common carrier (Break points for curves of Figure 514.8C-2).

Vertical		Transverse		Longitudinal	
Frequency, Hz	**ASD, g^2/Hz**	**Frequency, Hz**	**ASD, g^2/Hz**	**Frequency, Hz**	**ASD, g^2/Hz**
5	0.015	5	0.00013	5	0.0065
40	0.015	10	0.00013	20	0.0065
500	0.00015	20	0.00065	120	0.0002
		30	0.00065	121	0.003
		78	0.00002	200	0.003
		79	0.00019	240	0.0015
		120	0.00019	340	0.00003
		500	0.00001	500	0.00015
rms = 1.08 g		rms = 0.21 g		rms = 0.76 g	

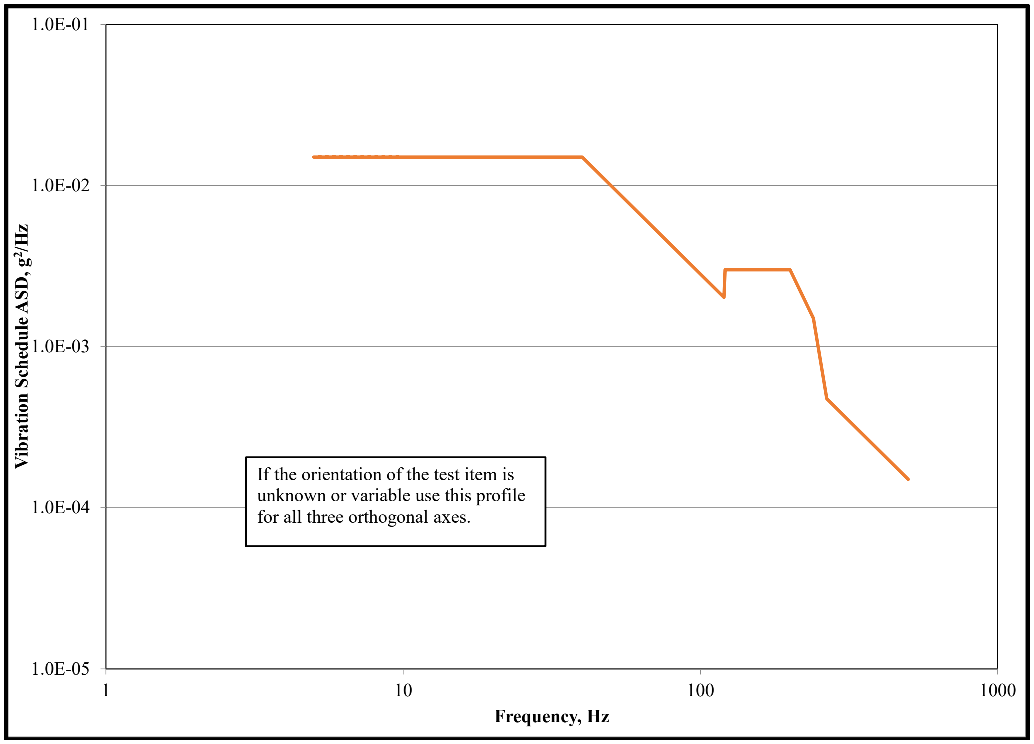

Figure 514.8C-3 – Category 4 – Common carrier for unknown orientation (US highway truck vibration exposure).

Table 514.8C-II. Category 4 – Common carrier for unknown orientation(Break points for curves of Figure 514.8C-3).

Envelope	
Frequency, Hz	**ASD, g^2/Hz**
5	0.015
40	0.015
120	0.002025
121	0.003
200	0.003
240	0.0015
266	0.000475
500	0.00015
rms = 1.17 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). When materiel is too large for the two-wheeled trailer, use the composite wheeled levels.

(1) **Two wheeled trailer (TWT)**. Exposures are shown in Figure 514.8C-4, and are followed by the respective data table (Table 514.8C-IV). If the orientation of the test item is unknown or variable see Figure 514.8C-5 and Table 514.8C-V for exposure levels. (See paragraph 6.1, references pp to vv.)

Test Schedule: Secured Cargo – Two-Wheeled Trailer

Vehicles Used for Composite: Measured vibration data from the following vehicles (Table 514.8C-III) were used to develop the Two-Wheeled Trailer Vehicle test schedule:

Table 514.8C-III. Vehicles used for TWT composite.

NOMENCLATURE	DESCRIPTION
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).

Type of Test Load: Sand filled ammo boxes (or other similar cargo) were secured to the cargo bed, and loaded to ¾ of vehicle rated load.

Scenario to be Simulated: 51.5 km (32 mi) 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 that 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 typical scenario has established that 51.5 km (32 mi) 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.):

Total Mission of 51.5 km (32 miles) is accounted for as follows:

- 15 percent of total mission, 7.7 km (5 miles), is on-road and considered benign compared to the off-road environment.
- 85 percent of total mission, 43.8 km (27 miles), is off-road:

  - One-third of the off-road environment, 14.6 km (9 miles), is rough terrain consistent with the Belgian Block, Two-Inch Washboard, Radial Washboard, and Three-Inch Space Bump courses used to collect data. Average Speed over these courses was 26 km/hr (16 mph).

  - Two-thirds of the off-road environment, 29.2 km (18 miles), is considered benign compared to the test conditions described above.

Failure mode: fatigue

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 Annex F, Appendix C, was used to create the spectra for the individual trailers in Table 514.8C-III. This method makes use of the spectral variance from different measurement locations and test conditions and produces a spectrum that is a very conservative estimate of the actual measured environments. This procedure produced an ASD for each trailer in each of the orthogonal axes. The composite two-wheeled trailer spectrum was created by enveloping the individual trailers. Ideally a statistical method would have been used (as was done for the Composite Wheeled Vehicle below) but because the number of samples was so low an enveloping method was employed.

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). Based on the field data characteristics and the conservatism associated with the composite vehicle VSD process, drive limiting to 3 sigma is recommended.

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

RMS Acceleration:[1,3] (G-rms): Vertical – 3.98;
Transverse – 1.22;
Longitudinal – 2.52;
Envelope – 4.03.

Velocity (in/sec) (peak single amplitude):[1,3]
Vertical – 33.29;
Transverse – 15.23;
Longitudinal – 18.18;
Envelope – 33.30.

Displacement (in) (peak double amplitude):[1,2,3]
Vertical – 1.51;
Transverse – 0.69;
Longitudinal – 0.79;
Envelope – 1.51.

[1] Approximate values for a Gaussian random distribution which may vary based on the control system and spectral resolution. Peak velocity and displacement values are based on an acceleration maximum of three times the standard deviation (3σ) and a spectral resolution of 1 Hz.

[2] For shaker systems that are incapable of the displacement requirements of this schedule, minor adjustments may be made to the low frequency within the tolerances specified in 4.2.2.1a (main body) to accommodate the shaker limitations. If any schedule needs to be modified, make sure that all parties involved (tester, customer, etc.) are 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.

[3] For test items for which the test item orientation is unknown or variable the Envelope profile should be run for all three axes (Figure 514.8C-5 and Table 514.8C-V).

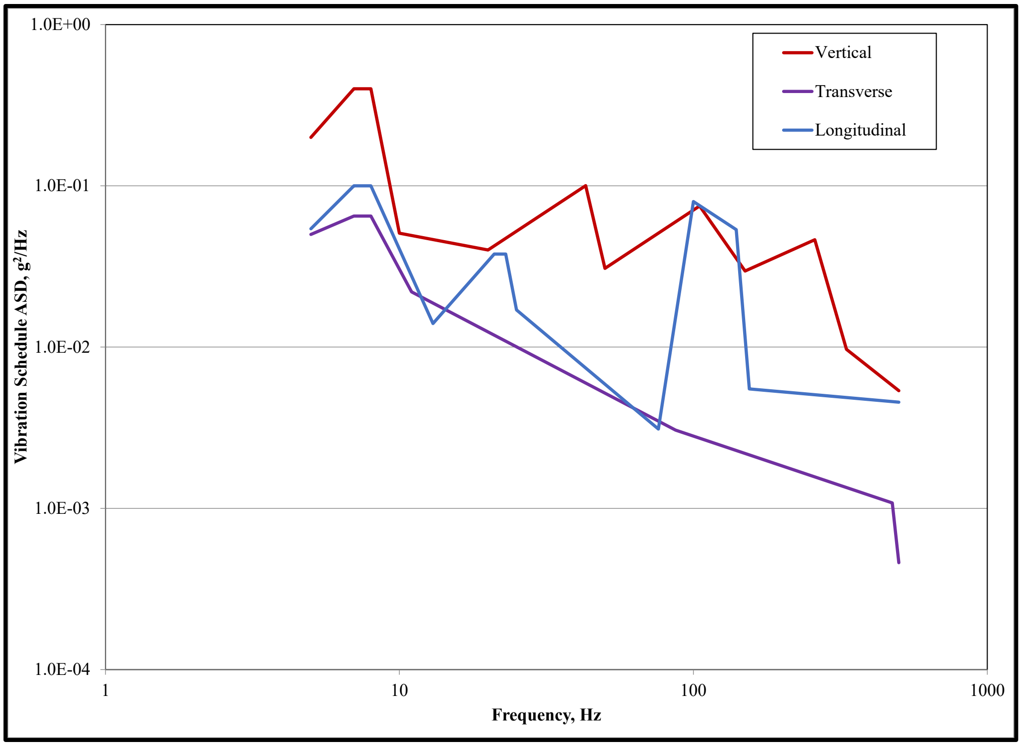

Figure 514.8C-4. – Category 4 – Composite two-wheeled trailer vibration exposure.

Table 514.8C-IV. Category 4 – Composite two-wheeled trailer vibration exposure. (Break points for curves of Figure 514.8C-4.)

Vertical		Transverse		Longitudinal	
Frequency, Hz	ASD, g^2/Hz	Frequency, Hz	ASD, g^2/Hz	Frequency, Hz	ASD, g^2/Hz
5	0.20000	5	0.05000	5	0.05418
7	0.40000	7	0.06500	7	0.10000
8	0.40000	8	0.06500	8	0.10000
10	0.05090	11	0.02200	13	0.01400
20	0.04000	87	0.00306	21	0.03780
43	0.10036	475	0.00108	23	0.03780
50	0.03079	500	0.00046	25	0.01700
105	0.07500			76	0.00310
150	0.02964			100	0.08000
259	0.04636			140	0.05354
332	0.00970			155	0.00551
500	0.00537			500	0.00456
rms = 3.98 g		rms = 1.22 g		rms = 2.52 g	

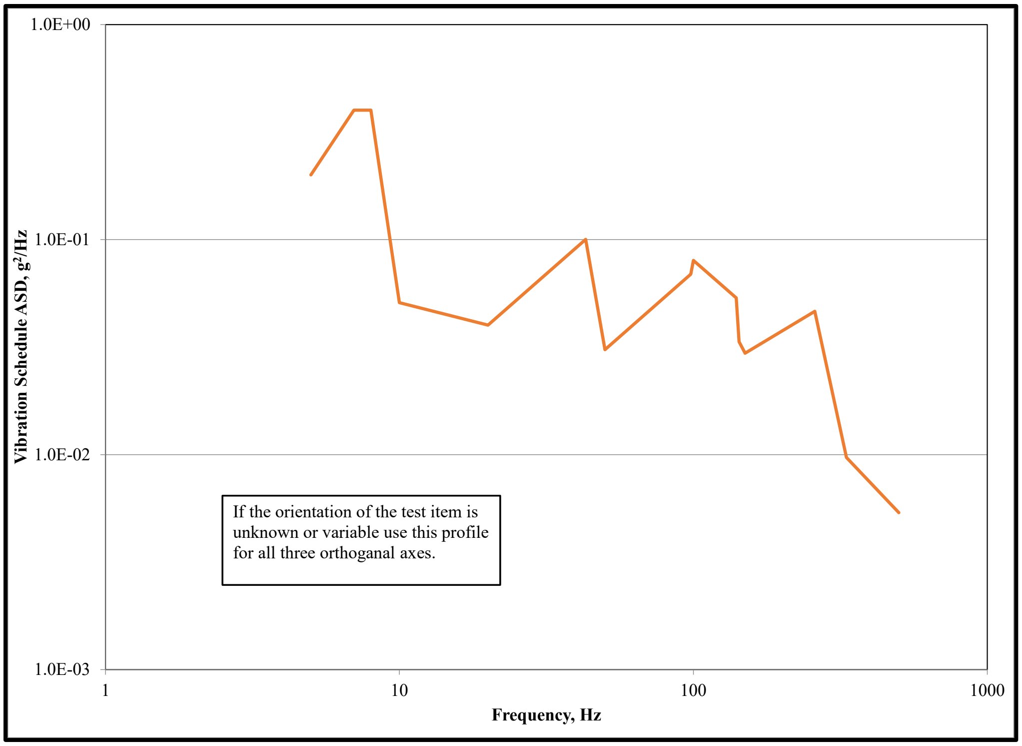

Figure 514.8C-5. – Category 4 – Composite two-wheeled trailer vibration exposure for unknown orientation.

Table 514.8C-V. Category 4 – Composite two-wheeled trailer vibration exposure for unknown orientation. (Break points for curves of Figure 514.8C-5.)

V, L&T Envelope	
Frequency, Hz	**ASD, g^2/Hz**
5	0.20000
7	0.40000
8	0.40000
10	0.05090
20	0.04000
43	0.10036
50	0.03079
98	0.06910
100	0.08000
140	0.05354
143	0.03350
150	0.02964
259	0.04636
332	0.00970
500	0.00537
rms = 4.03 g	

(2) **Composite wheeled vehicle (CWV)**. Exposures are shown in Figure 514.8C-6, and are followed by the respective data table (Table 514.8C-VII). If the orientation of the test item is unknown or variable, see exposure levels shown in Figure 514.8C-7 and Table 514.8C-VIII. (See paragraph 6.1, references pp to vv.)

Test Schedule: Secured Cargo – Composite Wheeled Vehicle

Vehicles Used for Composite: Measured vibration data from the following vehicles (Table 514.8C-VI) were used to develop the Composite Wheeled Vehicle test schedule:

Table 514.8C-VI. Vehicles used for CWV composite.

NOMENCLATURE	DESCRIPTION
M985	US Heavy Expanded Mobility Tactical Truck (HEMTT) 10-ton truck
MK27*	US Medium Tactical Vehicle Replacement (MTVR) 7-ton truck
M1083/M1084/M1085	US Medium Tactical Vehicle (MTV) 5-ton truck
M1151**/M1152/M1113	US High Mobility Multipurpose Wheeled Vehicle (HMMWV) 1-1/4-ton truck
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
Unimog	German 2-ton truck
Machine Fabrik Augsburg Nurnberg (MAN)	German 5-, 7-, 10-, 15-ton trucks

* 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 (or other similar cargo) were secured to the cargo bed, and loaded to ¾ of vehicle rated load.

Scenario to be Simulated: 805 km (500 mi) 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 that 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 typical scenario has established that 805 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.):

Total Mission of 805 km (500 miles) is accounted for as follows:

- 35 percent of total mission, 282 km (175 miles), is on-road and considered benign compared to the off-road environment.
- 65 percent of total mission, 523 km (325 miles), is off-road:
  - One-third of the off-road environment, 174 km (108 miles), is rough terrain consistent with the Belgian Block, Two-Inch Washboard, Radial Washboard, and Three-Inch Spaced Bump courses used to collect data. Average Speed over these courses was 26 km/hr (16 mph).
  - Two-thirds of the off-road environment, 349 km (217 miles), is considered benign compared to the test conditions described above.

Failure mode: fatigue

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

Test Time: 40 minutes per axis

Exaggeration Factor: $\left[\frac{W(f)_1}{W(f)_2}\right] = 1.85$

Method of Combination of Spectra: A statistical method, as described in Annex F, Appendix C, was used to create the spectra for the individual vehicles in Table 514.8C-VI. This method makes use of the spectral variance from different measurement locations and test conditions and produces a spectrum that is a very conservative estimate of the actual measured environments. This procedure produced an ASD for each vehicle in each of the orthogonal axes. The composite wheeled vehicle spectrum was created by applying the upper normal one-sided tolerance limit to the spectrum data. The upper normal one-sided tolerance limit is based on two values, β and γ. For these data β was set to 0.90 and γ was set to 0.50. This means that one is 50 percent confident that 90 percent of the vibration profiles of all wheeled cargo vehicles will fall below the composite wheeled vehicle vibration schedules presented below. The upper normal one-sided tolerance limit is described more fully in Annex F, Appendix B, paragraph 2.3.

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). Based on the field data characteristics and the conservatism associated with the composite vehicle VSD process, drive limiting to 3 sigma is recommended.

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

RMS Acceleration:[1,3] **(G-rms):** Vertical – 2.24;
Transverse – 1.45;
Longitudinal – 1.32;
Envelope – 2.24.

Velocity (in/sec) (peak single amplitude):[1,3]
Vertical – 28.76;
Transverse – 17.83;
Longitudinal – 12.75;
Envelope – 28.76.

Displacement (in) (peak double amplitude):[1,2,3]
Vertical – 1.22;
Transverse – 0.73;
Longitudinal – 0.51;
Envelope – 1.22.

[1] Approximate values for a Gaussian random distribution which may vary based on the control system and spectral resolution. Peak velocity and displacement values are based on an acceleration maximum of three times the standard deviation (3σ) and a spectral resolution of 1 Hz.

[2] For shaker systems that are incapable of the displacement requirements of this schedule, minor adjustments may be made to the low frequency ASD values within the tolerances specified in 4.2.2.1a (main body) to accommodate the shaker limitations. If any schedule needs to be modified, make sure that all parties involved (tester, customer, etc.) are 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.

[3] For test items for which the test item orientation is unknown or variable the Envelope profile should be run for all three axes (Figure 514.8C-7 and Table 514.8C-VIII).

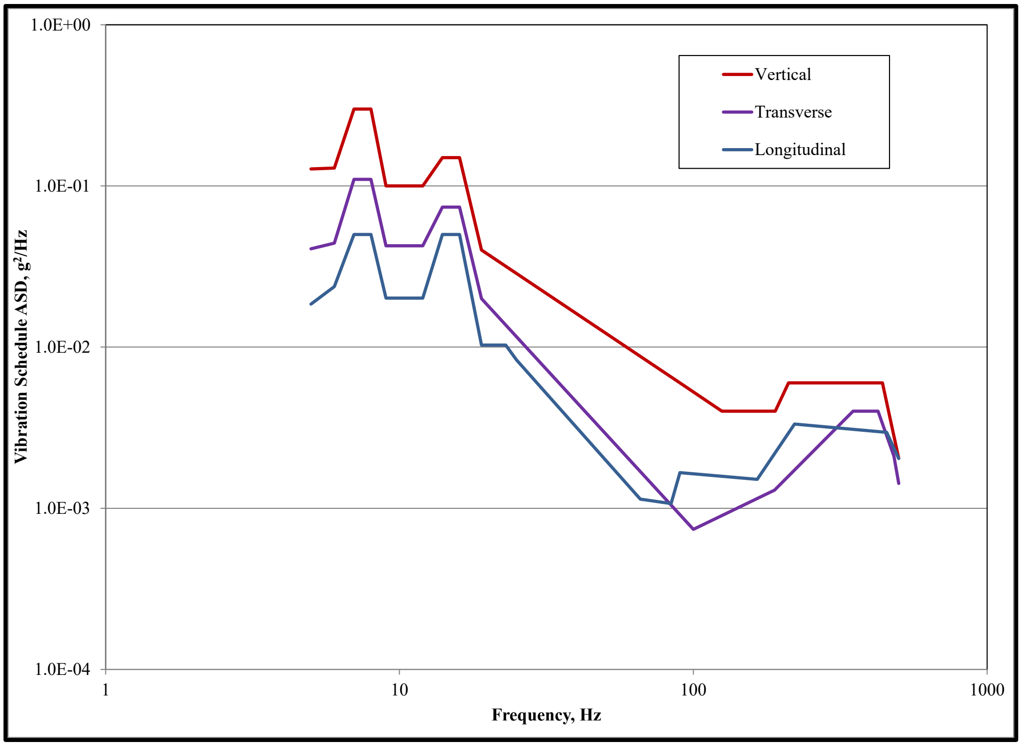

Figure 514.8C-6. – Category 4 – Composite wheeled vehicle vibration exposure.

Table 514.8C-VII. Category – 4 – Composite wheeled vehicle vibration exposure. (Break points for curves of Figure 514.8C-6.)

Vertical		Transverse		Longitudinal	
Frequency, Hz	ASD, g^2/Hz	Frequency, Hz	ASD, g^2/Hz	Frequency, Hz	ASD, g^2/Hz
5	0.12765	5	0.04070	5	0.01848
6	0.12926	6	0.04415	6	0.02373
7	0.30000	7	0.11000	7	0.05000
8	0.30000	8	0.11000	8	0.05000
9	0.10000	9	0.04250	9	0.02016
12	0.10000	12	0.04250	12	0.02016
14	0.15000	14	0.07400	14	0.05000
16	0.15000	16	0.07400	16	0.05000
19	0.04000	19	0.02000	19	0.01030
90	0.00600	100	0.00074	23	0.01030
125	0.00400	189	0.00130	25	0.00833
190	0.00400	350	0.00400	66	0.00114
211	0.00600	425	0.00400	84	0.00107
440	0.00600	482	0.00210	90	0.00167
500	0.00204	500	0.00142	165	0.00151
				221	0.00333
				455	0.00296
				500	0.00204
rms = 2.24 g		rms = 1.45 g		rms = 1.32 g	

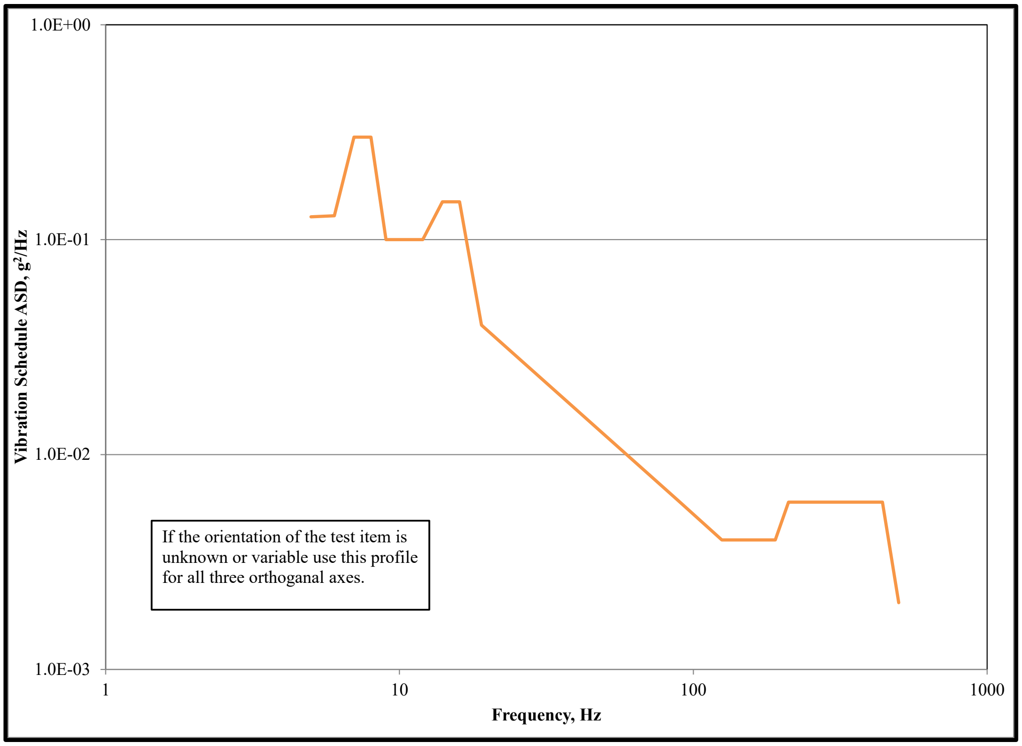

Figure 514.8C-7. – Category 4 – Composite wheeled vehicle vibration exposure for unknown orientation.

Table 514.8C-VIII. Category – 4 – Composite wheeled vehicle vibration exposure for unknown orientation. (Break points for curves of Figure 514.8C-7.)

Envelope	
Frequency, Hz	**ASD, g^2/Hz**
5	0.12765
6	0.12926
7	0.30000
8	0.30000
9	0.10000
12	0.10000
14	0.15000
16	0.15000
19	0.04000
90	0.00600
125	0.00400
190	0.00400
211	0.00600
440	0.00600
500	0.00204
rms = 2.24 g	

2.1.4 Exposure durations. Base durations on the materiel Life Cycle Environment Profile. Figure 514.8C-1 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).

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 40 minutes per 805 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 514.8C-8.) Cover the test bed of the package tester with a cold rolled steel plate (see note below), 5 to 10 mm (0.2 to 0.4 in) thick, and secure the plate with bolts. The tops of the heads should be 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. The default space around the perimeter of a test item or an item and a barrier wall is a minimum of one inch (25.4 cm) at the start of testing. The spacing varies during testing and is not controlled. 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 Figure 514.8C-8 package test equipment, operated in circular synchronous mode, provides a reasonable loose cargo simulation.

The equipment motion required is a 2.54 cm (1.0 inch) diameter orbital path at 5 Hz (300 RPM, approximately 1.3 g). Test equipment should have the capability to maintain the speed at 300 ±2 RPM. Tables operated near maximum load capacity or with an unbalanced test item(s) may require a larger RPM tolerance. The use of a package tester operating in non-synchronous, vertical linear motion, or a single axis vibration system, is not an acceptable substitute for the loose cargo test requirement.

(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 Figure 514.8C-1). Use ratio scenario times in the materiel Life Cycle Environment Profile to define exposure times.

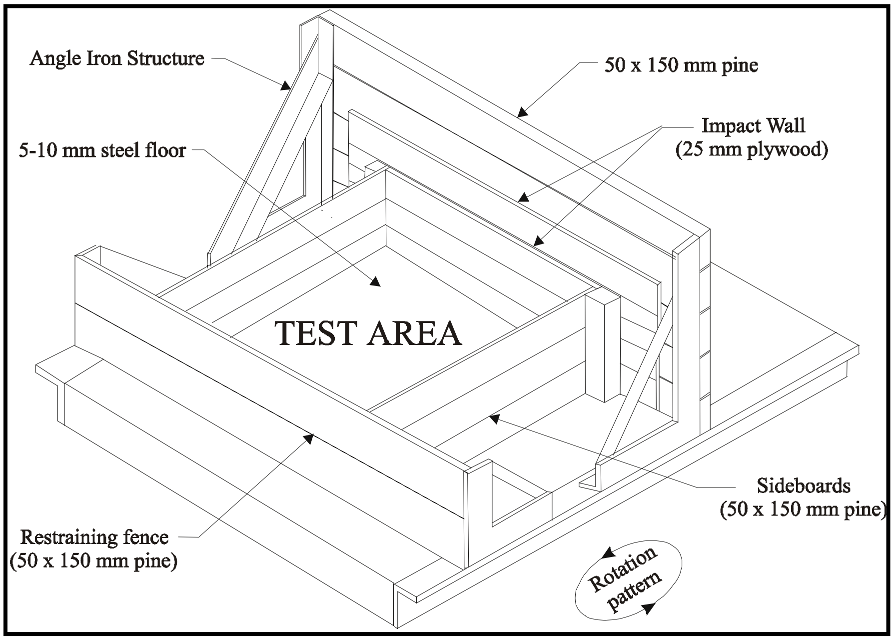

Figure 514.8C-8. Category 5 - Loose cargo test setup.

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 LCEP. 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 km/hr	(mph)	Course Length m	(ft)
(1) Coarse washboard [150 mm (6 in) waves; 1.8 m (6 ft) apart]	8	(5)	243	(798)
(2) Belgian block	32	(20)	1201	(3940)
(3) Radial washboard [50 mm (2 in) to 100 mm (4 in) waves]	24	(15)	74	(243)
(4) Two inch washboard [50 mm (2 in) waves, 0.6 m (2 ft) apart]	16	(10)	251	(822)
(5) Three inch spaced bump [75 mm (3 in) bumps]	32	(20)	233	(764)

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 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.) is experienced as steady inertial loads (acceleration). That part of the environment is included in Method 513.8.

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. The associated spectral shape and functional guidance from Annex D are repeated below for convenience as Figure 514.8C-10 and Table 514.8C-X.

(2) Figure 514.8C-9 shows the cargo compartment zone functional qualification levels of the C-5, C/KC-135, C-17, 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 514.8C-9 is used, select a duration of one minute per takeoff. Determine the number of takeoffs from the LCEP.

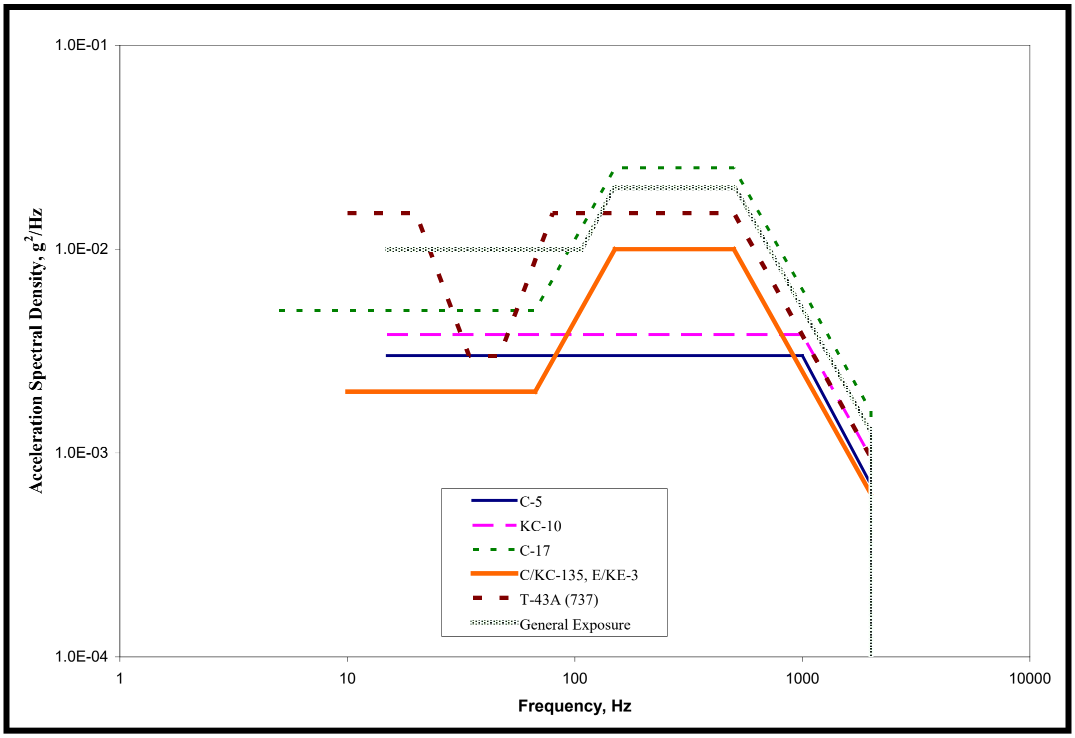

Figure 514.8C-9. Category 7 - Jet aircraft cargo vibration exposure.

Table 514.8C-IX. Category 7 - Jet aircraft cargo vibration exposure - Break points for Figure 514.8C-9.

C-5			KC-10			KC-135, E-3			C-17		
Hz	g^2/Hz	dB/Oct	Hz	g^2/Hz	dB/Oct	Hz	g^2/Hz	dB/Oct	Hz	g^2/Hz	dB/Oct
15	0.003		15	0.0038		10	0.002		5	0.005	
1000	0.003		1000	0.0038		67	0.002		67	0.005	
		-6			-6			6			6
2000	7.5E-4		2000	9.5E-4		150	0.01		150	0.025	
rms = 2.11 g			rms = 2.38 g			500	0.01		500	0.025	
								-6			-6
						2000	6.3E-4		2000	1.6E-3	
						rms = 2.80 g			rms = 4.43 g		

T-43A (737)			General Exposure		
Hz	g^2/Hz	dB/Oct	Hz	g^2/Hz	dB/Oct
10	0.015		15	0.01	
20	0.015		106	0.01	
		-9			6
34	0.003		150	0.02	
47	0.003		500	0.02	
		9			-6
80	0.015		2000	1.3E-3	
500	0.015		rms = 4.02 g		
		-6			
2000	9.5E-4				
rms = 3.54 g					

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

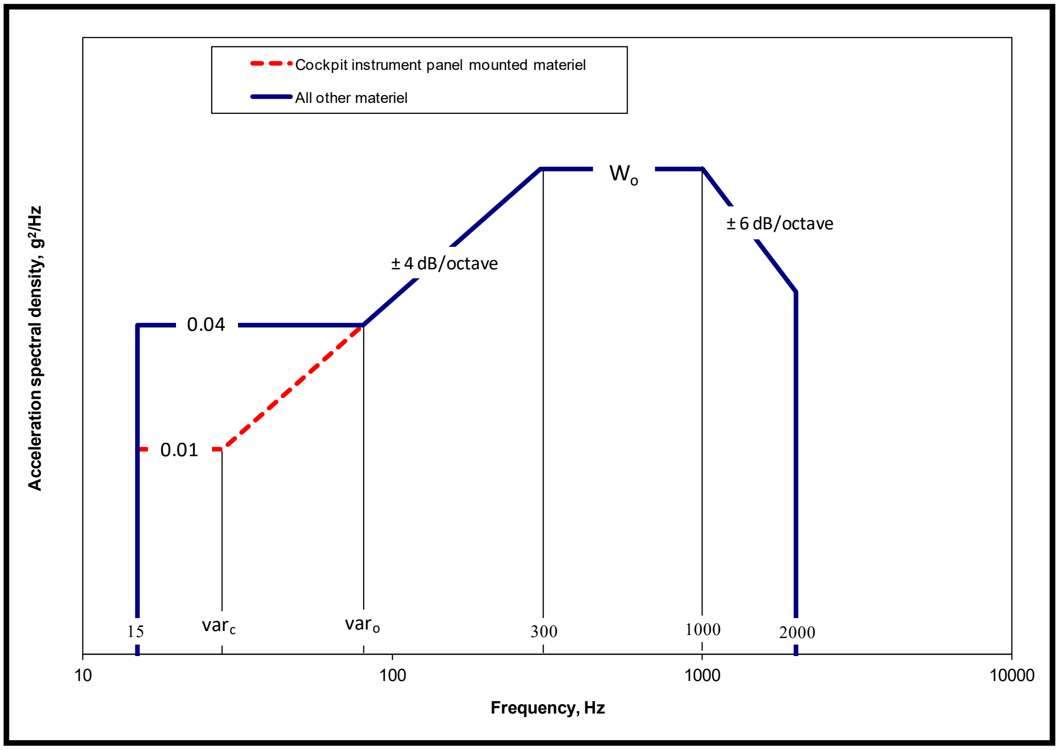

Figure 514.8C-10. Category 7 - Jet aircraft vibration exposure. (Same as Annex D, Figure 514.8D-1.)

Table 514.8C-X. Category 7 - Jet aircraft vibration exposure. (Same as Annex D, Table 514.8D-I.)

$W_0 = W_A + \sum_1^n (W_J)$					
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 514.8C-10.			
	=	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.
	=	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.	R	-	Vector distance from center of engine exhaust plane to materiel center of gravity, m (ft).
			θ	-	Angle between R vector and engine exhaust vector (aft along engine exhaust centerline), degrees For $70° < \theta \leq 180°$ use 70°.
c	=	Mach number correction. Note that this factor applies to W_0 and not to the low frequency portion (15 Hz to var_c or var_o) of Figure 514.8C-10.	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 $0 \leq Mach \leq 0.9$	V_c	-	Engine core exhaust velocity (without afterburner), m/sec (ft/sec).
	=	(-4.8M + 5.32) for $0.9 \leq Mach \leq 1.0$ (where M = Mach number)	V_f	-	Engine fan exhaust velocity (without afterburner), m/sec (ft/sec).
	=	0.52 for Mach number greater than 1.0			
q	-	Flight dynamic pressure, kN/m^2 (lb/ft^2).	var_c	-	intersection frequency for cockpit materiel based on 4dB/oct slope from W_0
		(See Annex A, para. 2.6.1 and Table 514.8D-V)	var_o	-	intersection frequency for all other materiel based on 4dB/oct slope from W_0
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. 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 10 Hz. At frequencies below 10 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 513.8.

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. Whenever possible, use flight vibration measurements to develop vibration criteria. In the absence of flight measurements: use the spectra of Figure 514.8C-11 and Table 514.8C-XI for the 4-blade C-130; use the spectra of Figure 514.8C-12 and Table 514.8C-XII for the 6-blade C-130; and use the spectra of Figure 514.8C-13 and Table 514.8C-XIII for fixed wing propeller aircraft other than C-130. Zones for propeller aircraft are shown in Figure 514.8C8-14. The C-130 spectra are based on measurements made on several versions of the C-130K (4 blade) and C-130J (6-blade) aircraft (paragraph 6.1, references yy and zz) and are fairly representative of the environments of these aircraft.

d. Exposure durations. Take durations from the Life Cycle Environment Profile. If LCEP data are not available for development of test durations, tests should be conducted for one hour per axis which is equivalent to a 20 hour flight. There are two versions of the C-130 vibration profile, the first represents the 4-bladed version and the second represents the 6-bladed version. For cargo that will be transported in various version of the C-130 aircraft, split the durations evenly between the 4-bladed version and the 6-bladed version.

e. Test Time Compression. For the C-130 spectra, test time was computed utilizing the guidance provided in Section 9.2.1.2 of Annex F with a slope (m) of 5.0.

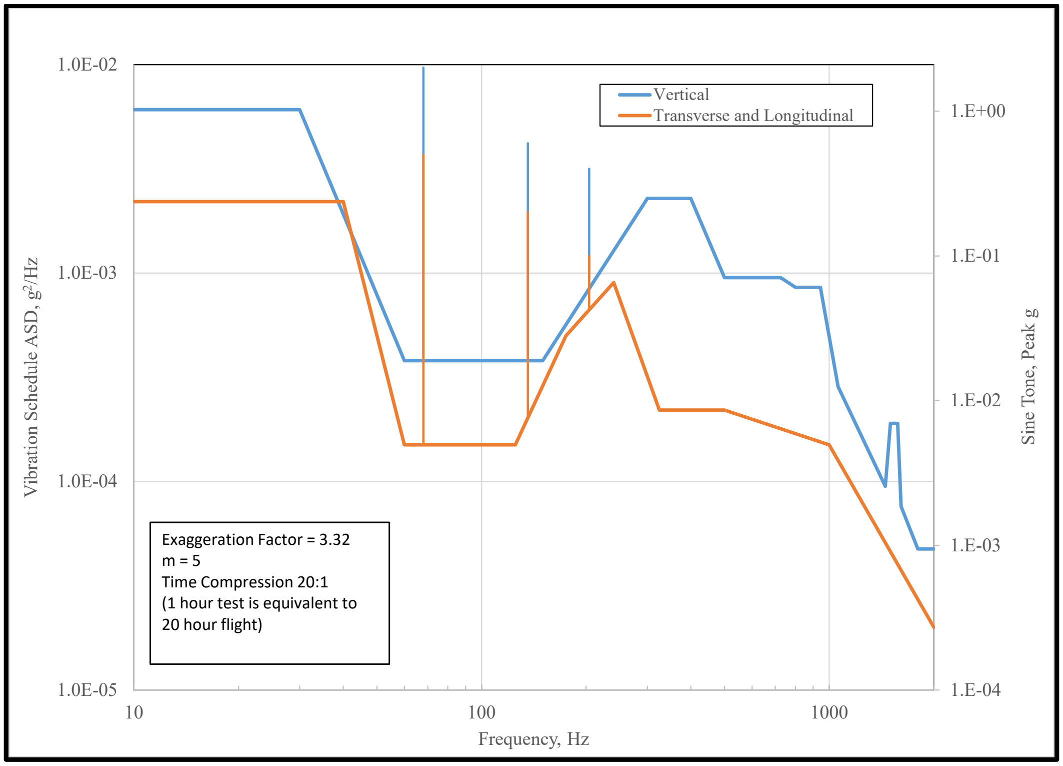

Figure 514.8C-11. Category 8 - Propeller aircraft vibration exposure, 4-bladed C-130.

Table 514.8C-XI. Category 8 - Propeller aircraft vibration exposure. 4-bladed C-130.

Vertical Axis Broadband Random		Vertical Axis Sinusoidal Components		Longitudinal and Transverse Broadband Random	
Frequency, Hz	ASD, g^2/Hz	Center Frequency, Hz (Blade Order)	Acceleration peak (g_{pk})	Frequency, Hz	ASD, g^2/Hz
10	0.0032	17 (R)	0.5	10	0.0022
30	0.0032	68 (nR)	2	40	0.0022
60	0.0002	136(2nR)	0.6	60	0.00015
150	0.0002	204 (3nR)	0.4	125	0.00015
300	0.0012	Overall rms, g	1.76	175	0.0005
400	0.0012			240	0.0009
500	0.0005			325	0.00022
725	0.0005			500	0.00022
800	0.00045			1000	0.00015
943	0.00045	Longitudinal and Transverse Sinusoidal Components		2000	0.00002
1061	0.00015			rms, g	0.61
1450	0.00005	Center Frequency, Hz (Blade Order)	Acceleration peak (gpk)		
1500	0.0001				
1575	0.0001	17 (R)	0.2		
1610	0.00004	68 (nR)	0.5		
1800	0.000025	136 (2nR)	0.2		
2000	0.000025	204 (3nR)	0.1		
rms, g	0.84	Overall rms, g	0.74		
Test Duration per axis: 1 hour for 20 hours of flight.					

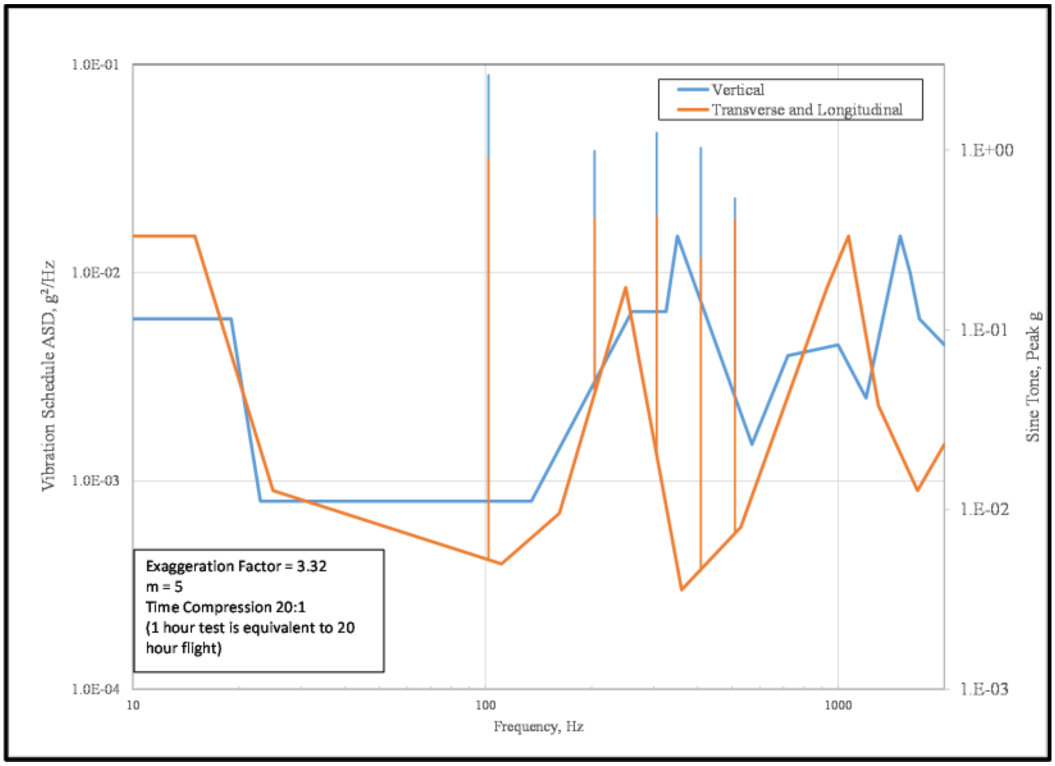

Figure 514.8C-12. Category 8 - Propeller aircraft vibration exposure. 6-bladed C-130

Table 514.8C-XII. Category 8 - Propeller aircraft vibration exposure. 6-bladed C-130.

Vertical Axis Broadband Random		Vertical Axis Sinusoidal Components		Longitudinal and Transverse Broadband Random	
Frequency, Hz	ASD, g^2/Hz	Center Frequency, Hz (Blade Order)	Acceleration peak (g_{pk})	Frequency, Hz	ASD, g^2/Hz
10	0.006	102 (nR)	2.62	10	0.015
19	0.006	204 (2nR)	0.99	15	0.015
23	0.0008	306 (3nR)	1.25	25	0.0009
135	0.0008	408 (4nR)	1.03	111	0.0004
260	0.0065	510 (5nR)	0.54	162	0.0007
325	0.0065	Overall rms, g	3.97	250	0.0085
350	0.015			360	0.0003
570	0.0015			530	0.0006
720	0.004	Longitudinal and Transverse Sinusoidal Components		930	0.0085
1000	0.0045			1070	0.015
1200	0.0025	Center Frequency, Hz (Blade Order)	Acceleration peak (gpk)	1300	0.0023
1500	0.015			1680	0.0009
1600	0.01	102 (nR)	0.9	2000	0.0015
1700	0.006	204 (2nR)	0.42	rms, g	2.49
2000	0.0045	306 (3nR)	0.43		
rms, g	3.22	408 (4nR)	0.25		
		510 (5nR)	0.41		
		Overall rms, g	2.63		
Test Duration per axis: 1 hour for 20 hours of flight.					

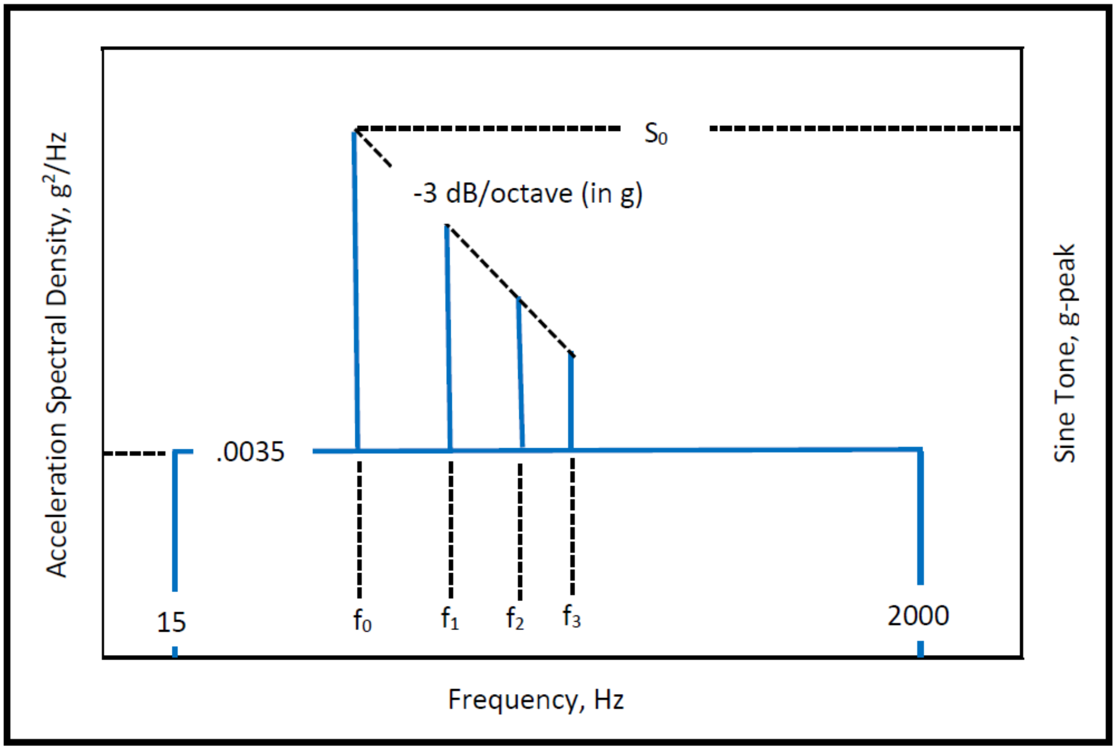

Figure 514.8C-13. Category 8 - Propeller aircraft vibration exposure. Other than C-130

Table 514.8C-XIII - Category 8 - Propeller aircraft vibration exposure. Other than C-130

TRANSPORTATION LOCATIONS (see Figure 514.8C-14)	**NARROWBAND LEVEL L_0 (g^2/Hz)**
In fuselage forward of propeller	0.035
In fuselage within one propeller blade radius of propeller passage plane	0.42
In fuselage or wing aft of propeller	0.11

1/ f_0 = blade passage frequency (propeller rpm times number of blades) (Hz).
$f_1 = 2 \times f_0$ $f_2 = 3 \times f_0$ $f_3 = 4 \times f_0$

2/ Test should be conducted as sine-on-random, with:

$$So = 1.414 * \sqrt{0.1 * fo * Lo}$$

3/ Sine tones may be swept to account for known variance in blade passing frequency.

4/ If transportation location is unknown test to highest S_0 level of the possible locations.

5/ Test duration per axis: 1 hour for 20 hours of flight.

6/ The broadband and narrowband levels were derived from previous versions of this standard by decompression from 1000 to 20 flight hours per hour runtime utilizing Equation 9.5 of Annex F with m = 7.5 (slope for acceleration spectral density).

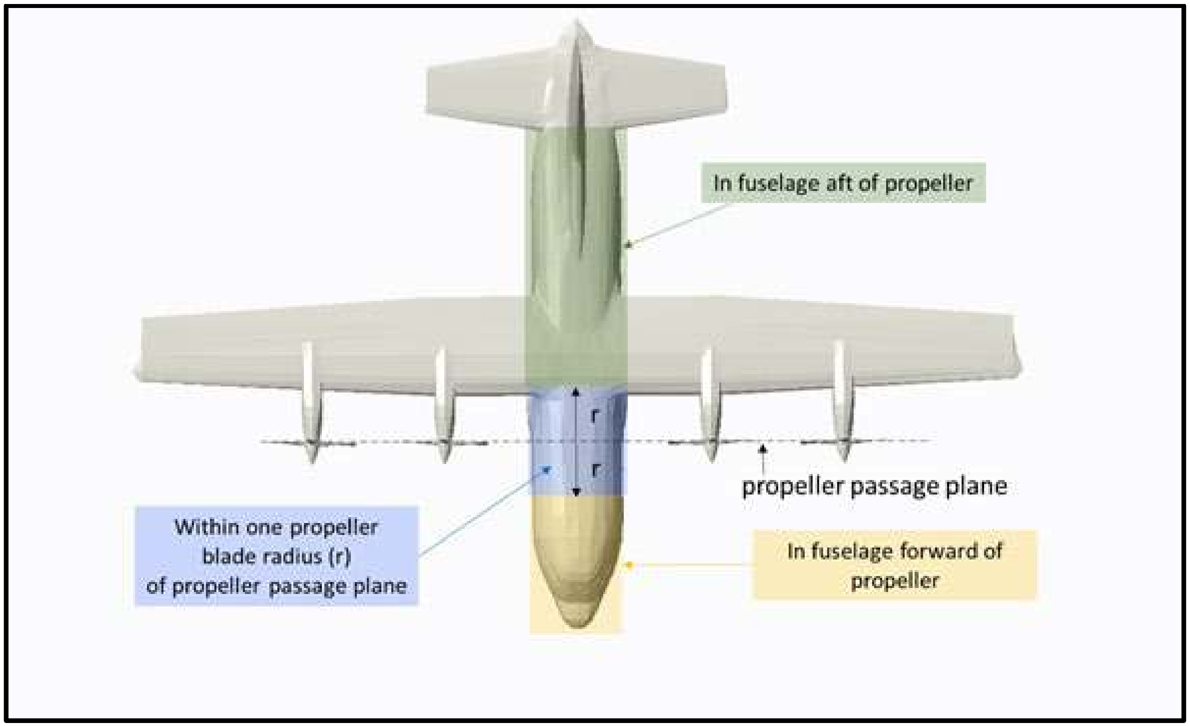

Figure 514.8C-14. Category 8 - Propeller aircraft transportation locations (other than C-130).

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.

Data acquired from variants of the rotorcraft listed in Table 514.8C-XIVa, were used to develop the random levels, source frequency relationships, and peak acceleration relationships reported in Table 514.8C-XIVb. Aircraft specific source frequencies are directly associated with rotor blade count and rotation speed. Tabulated source frequency ranges, peak acceleration amplitudes and associated random levels were empirically determined and encompass the vibration environments measured. The suitability of extrapolating these empirical peak acceleration relationships to aircraft not listed is unknown. Application of these empirical relationships to rotorcraft that are not included in the sample set should be applied with caution and only in the total absence of field data. Whenever possible, vehicle specific flight data should be acquired and employed in development of an aircraft specific vibration criterion.

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 514.8C-XIV. **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 TOP 01-2-603 paragraph 6.1, reference xx.

NOTE: These levels are intended to envelope potential worst-case environments, and have been aggressively compressed in time (paragraph 6.1, reference ww 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.

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

(3) Plans for development of updated vibration schedules representative of the modern rotorcraft fleet are in progress. As each aircraft's vibration schedule updates are completed, they will be provided as individual Annexes to TOP 01-2-603 (Rotorcraft Laboratory Vibration Test Schedules) along with vibration schedule development (VSD) technique details and all relevant descriptors such as mission scenario and instrumentation locations. The updated schedules will supersede the current defaults as listed in Table 514.8C-XIV. Currently there are only two rotorcraft in TOP 01-2-603, the UH-60 and the CH-47. These helicopters have therefore been removed from Table 514.8C-XIV.

d. Exposure durations. When measured data are used to establish exposure levels, take durations from the LCEP. Otherwise refer to the guidance provided in paragraph 2.3d in Annex D of this method.

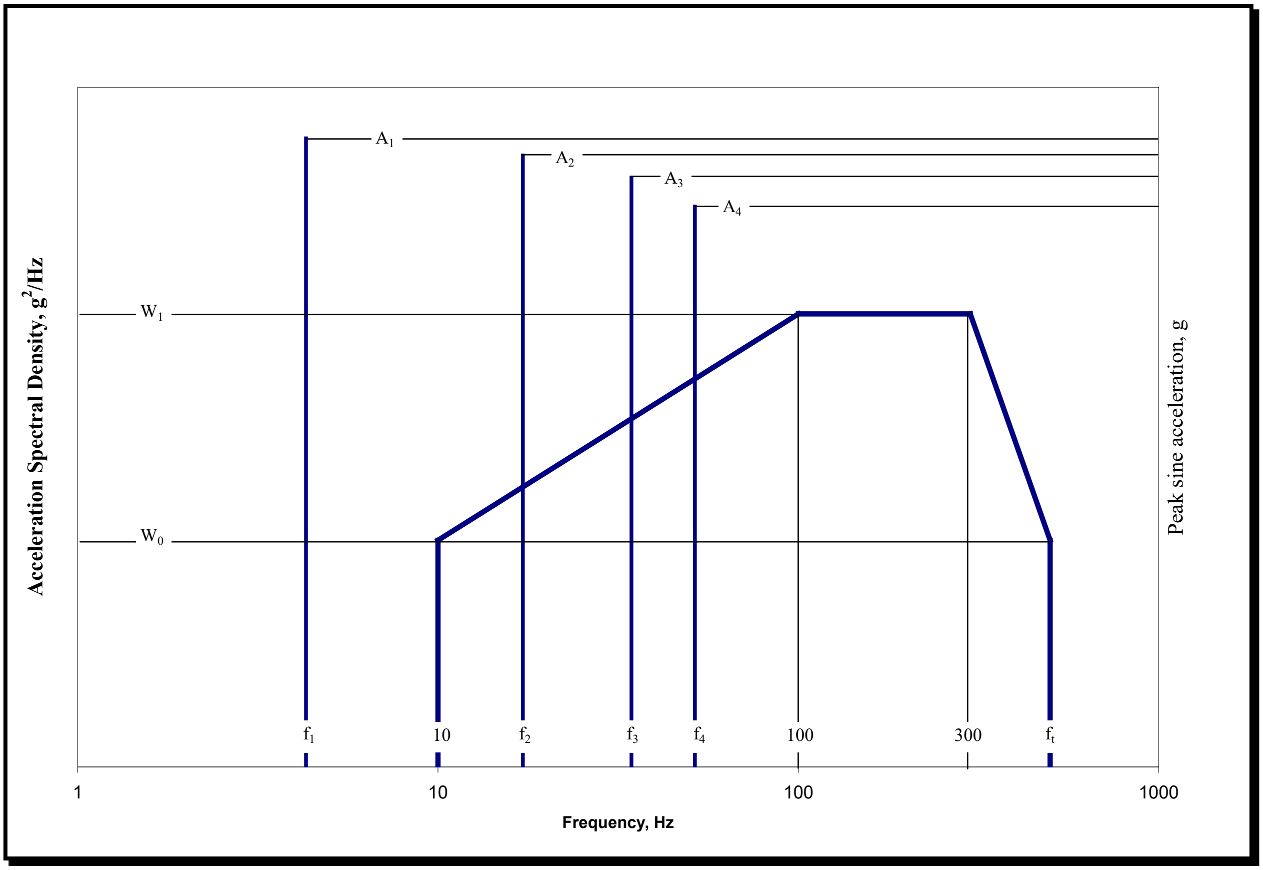

Figure 514.8C-15. Category 9 - Helicopter vibration exposure. (Same as Annex D, Figure 514.8D-4.)

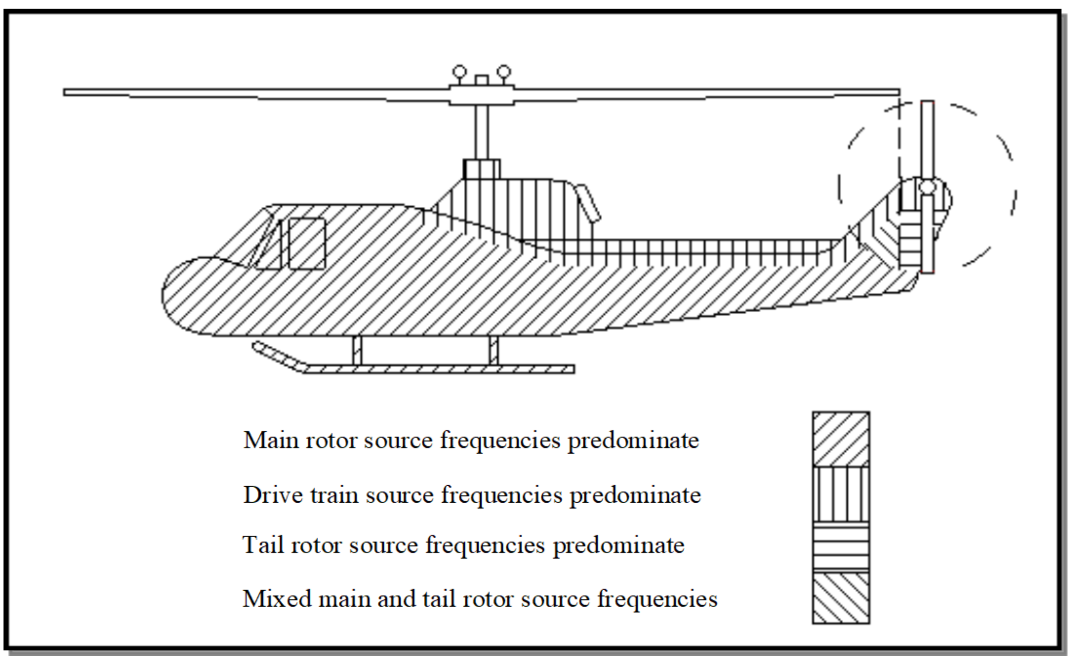

Figure 514.8C-16. Category 9 - Helicopter vibration zones. (Same as Annex D, Figure 514.8D-5.)

Table 514.8C-XIVa. Category 9 - Helicopter parameters. (Same as Annex D, Table 514.8D-IIIa.)

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	Refer to TOP 01-2-603 (Paragraph 6.1, reference xx)			
MH-6H	7.80	5	47.5	2
OH-6A	8.10	4	51.8	2
OH-58A/C	5.90	2	43.8	2
OH-58D	6.60	4	39.7	2
UH-1	5.40	2	27.7	2
UH-60	Refer to TOP 01-2-603 (Paragraph 6.1, reference xx)			

Table 514.8C-XIVb. Category 9 - Helicopter vibration exposure. (Same as Annex D, Table 514.8D-IIIb.)

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** 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 (BP)	$f_2 = 2 \times 1S$	2nd harmonic
$f_3 = 2 \times n \times 1P$	$f_3 = 2 \times m \times 1T$	2nd harmonic	$f_3 = 3 \times 1S$	3rd harmonic
$f_4 = 3 \times n \times 1P$	$f_4 = 3 \times m \times 1T$	3rd harmonic	$f_4 = 4 \times 1S$	4th harmonic

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 528.1.

2.8 Category 11 - Railroad - train.

Cargo vibration levels for rail transport are generally low amplitude and have a moderately wide frequency bandwidth. The vibration levels can vary significantly with position on the railcar, load capacity, and track quality. Vertical axis vibration is typically the most severe followed by transverse and longitudinal. See Method 526.2, Rail Impact, for the shock associated with railcar longitudinal axis shock during coupling.

a. Exposure levels. Transportation of non-isolated secured cargo on the railcar deck during cross country transportation is the typical environment. The ASD in Figure 514.8C-17 depicts the test severity at the railcar cargo deck. The vertical axis is up from the railcar deck, transverse is perpendicular across the rail tracks, and longitudinal is parallel to the rail tracks. The ASD is based on data measured at the cargo deck of different railcars including flat cars, box cars, and refrigerated cars on US rail track. The data were collected from typical rail lines with track sections across switch yards, bridges, and track crossings. The data include a varying percentage of partial cargo load to maximum capacity, and a range of railcar speeds. The typical railcar average speed for the measurements is 80 – 96 km/hr (50 to 60 mph). The ASD is a worst case envelope of the measured data, time compressed to a test time of 12 hours representing 4,800 km

(3000 miles) of rail transport. The ASD is not representative of high-speed magnetic levitation suspension systems. The ASD also does not represent low frequency, transient displacement and shock typical in the transverse and longitudinal axes. Additional information on the ASD background is available in reference f.

b. Exposure durations. Wheeled vehicle vibration amplitude is typically much higher than rail vibration and may eliminate the rail transportation test requirement. Rail vibration testing may be required for fragile or large mass equipment, or items shipped primarily by rail. Define the test duration based on the LCEP if the test is required. Measurements of the actual environment are recommended. If inadequate LCEP or field measurements are available use Figure 514.8C-17 to represent the worst case environment for each orthogonal axis. The default test duration is 12 hours/axis which represents 4,800 km (3,000 miles) of rail transport. An exaggeration factor of 1.5 using a value of m=7.5 (see paragraph 2.2 of Annex A for further explanation of exaggeration), is applied in Figure 514.8C-17.

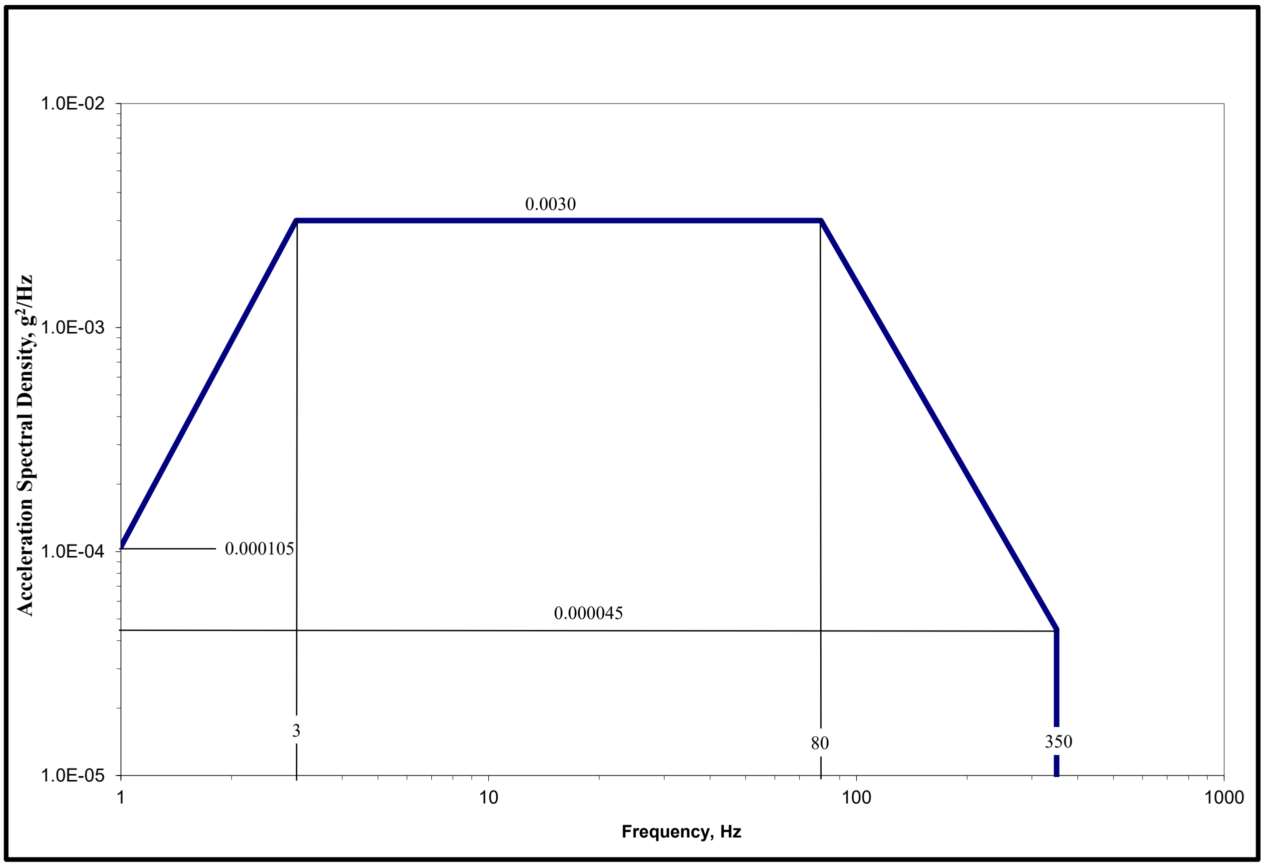

Figure 514.8C-17. Category 11 - Rail cargo vibration exposure.

METHOD 514.8, 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 514.8-I in the front part of this Method contains an outline of the following paragraphs with references to the paragraph numbers.

1.3 Limitations.

See paragraph 1.3 in the front part of this Method.

2. OPERATIONAL SERVICE.

This paragraph 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 519.8) 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 516.8 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 515.8 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 514.8D-1 and Table 514.8D-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 514.8D-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. Historically, the following defaults are employed in the absence of a well-defined LCEP. Note that the amplitudes computed from Table 514.8D-I are based on empirical data and time compression information is unknown.

(1) Environmental Worthiness test 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).

(2) Endurance Test default durations are 1 hour/axis.

(3) Functional testing (when required) is recommended to be split such that one-half is conducted prior to endurance testing and one-half after endurance testing. The duration of each half of the functional test should be sufficient to fully verify equipment functionality or one-half hour per axis, whichever is greater.

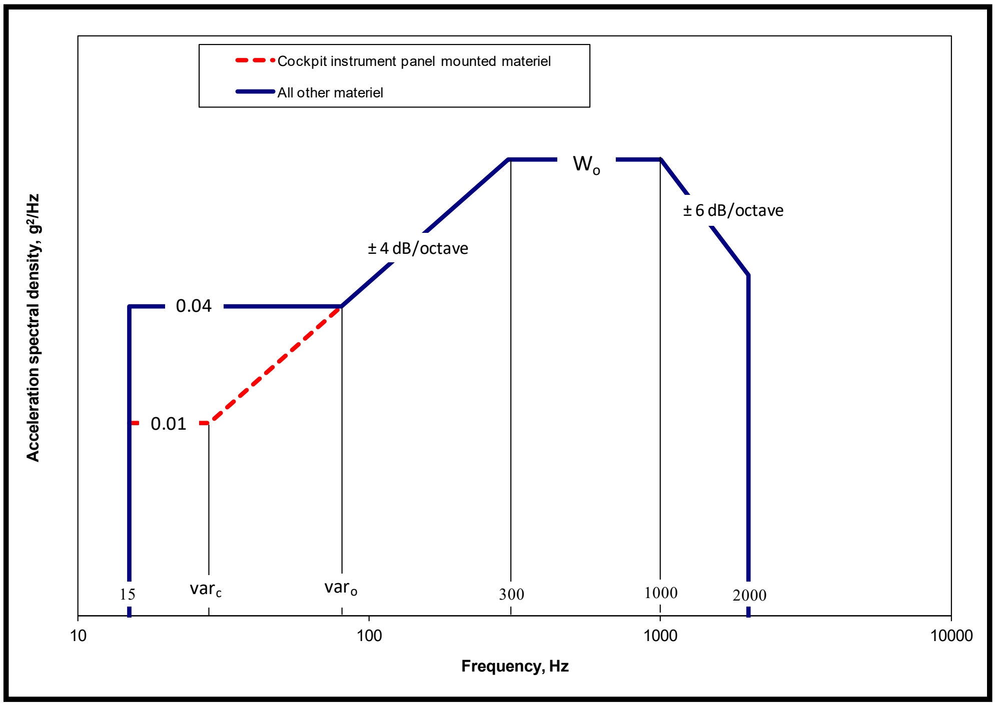

Figure 514.8D-1 - Category 12 - Fixed wing aircraft - jet aircraft. (Same as Annex C, Figure 514.8C-10.)

Table 514.8D-I – Category 12 - Jet aircraft vibration exposure. (Same as Annex C, Table 514.8C-X.)

<table>
<tr><td colspan="6">$W_0 = W_A + \sum_1^n (W_J)$
W_0, W_A, W_J - Exposure levels in acceleration spectral density (g^2/Hz).</td></tr>
<tr><td colspan="6">Aerodynamically induced vibration
$W_A = a \times b \times c \times (q)^2$</td></tr>
<tr><td colspan="6">Jet engine noise induced vibration
$W_J = \{[0.48 \times a \times d \times \cos^2(\theta)/R] \times [D_c \times (V_c / V_r)^3 + D_f \times (V_f / V_r)^3]\}$</td></tr>
<tr><td>a</td><td>-</td><td colspan="4">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 514.8D-1.
= 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.</td></tr>
<tr><td>b</td><td>=</td><td>Proportionality factor between vibration level and dynamic pressure (SI units).</td><td>$\sum_1^n$</td><td>-</td><td>Jet noise contribution is the sum of the W_J values for each engine.</td></tr>
<tr><td></td><td>=
=

=</td><td>2.96×10^{-6} for materiel mounted on cockpit instrument panels.
1.17×10^{-5} for cockpit materiel and materiel in compartments adjacent to external surfaces that are smooth and free from discontinuities.
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.</td><td>d

R

θ</td><td>-
=
=
-

-</td><td>Afterburner factor.
1. 0 for conditions where afterburner is not used or is not present.
4. 0 for conditions where afterburner is used.
Vector distance from center of engine exhaust plane to materiel center of gravity, m (ft).
Angle between R vector and engine exhaust vector (aft along engine exhaust centerline), degrees For $70° < \theta \le 180°$ use 70°.</td></tr>
<tr><td>c</td><td>-

=
=

=</td><td>Mach number correction. Note that this factor applies to W_0 and not to the low frequency portion (15 Hz to var_c or var_o) of Figure 514.8D-1.
1. 0 for $0 \le$ Mach ≤ 0.9
(-4.8M + 5.32) for $0.9 \le$ Mach ≤ 1.0 (where M = Mach number)
0.52 for Mach number greater than 1.0</td><td>D_c
D_f
V_r

V_c
V_f</td><td>-
-
-
=
-
-</td><td>Engine core exhaust diameter, m (ft).
Engine fan exhaust diameter, m (ft).
Reference exhaust velocity, m/sec (ft/sec).
564 m /sec (1850 ft/sec)
Engine core exhaust velocity (without afterburner, m/sec (ft/sec))
Engine fan exhaust velocity (without afterburner, m/sec (ft/sec))</td></tr>
<tr><td>q</td><td>-</td><td>Flight dynamic pressure, kN / m^2 (lb/ft^2).</td><td>var_c

var_o</td><td>-

-</td><td>intersection frequency for cockpit materiel based on 4dB/oct slope from W_0
intersection frequency for all other materiel based on 4dB/oct slope from W_0</td></tr>
<tr><td colspan="6">**If Dimensions are in feet and pounds then**:</td></tr>
<tr><td>a</td><td>=
=
=</td><td colspan="4">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.</td></tr>
<tr><td>b</td><td>=</td><td colspan="4">6.78×10^{-9}, 2.70×10^{-8}, or 1.40×10^{-7} in the order listed above.</td></tr>
<tr><td>V_r</td><td>=</td><td colspan="4">1850 feet / second</td></tr>
</table>

2.2 Category 13 - Propeller aircraft.

The vibration environment for materiel installed in propeller aircraft (except engine-mounted, see paragraph 2.11, and gunfire induced (see Method 519.8)) is primarily propeller induced. The vibration frequency spectra consists of a broadband background with superimposed spikes (see paragraph 6.1, references n through t). The spikes are more nearly sinusoidal than narrowband and are best represented utilizing sine-on-random vibration. 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 fixed frequency spikes like those of Figures 514.8D-2 at the blade passing frequency and harmonics.

b. Varying propeller speed. When propeller speed varies during operation, the frequency of the spikes change. This can be represented by swept sine tests with the sweep 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. When measured data are not available, endurance levels can be derived from Table 514.8D-II, and Figures 514.8D-2 and 514.8D-3. Functional test levels can be derived by scaling the endurance ASD levels (broadband and L_0) by a factor of 0.35. Reliability test levels can be derived by scaling the endurance levels by a factor of 0.22. Once scaled L_0 can be converted to an equivalent sine tone (S_0) using the formula provided in Table 514.8D-II. Subsequent harmonics (S_1, S_2, and S_3, corresponding to f_1, f_2, and f_3) are calculated from S_0 dropping 3 dB in amplitude per octave. Tests should be conducted as sine-on-random vibration, with sine levels calculated as defined in Table 514.8D-II and Figure 514.8D-2.

e. Exposure durations. Take durations from the Life Cycle Environment Profile. If LCEP data are not available for development of the test durations, endurance tests should be conducted for one hour per axis which equivalent to 1000 hours of flight. Test durations associated with functional testing should be kept to a minimum and it is generally not considered part of the endurance test duration. Test duration for reliability testing should be set to the total flight hours required, divided equally among the three test axes, and can be considered as part of the endurance test. For equipment that will be installed on multiple fixed wing propeller aircraft the test can be divided equally between all aircraft types.

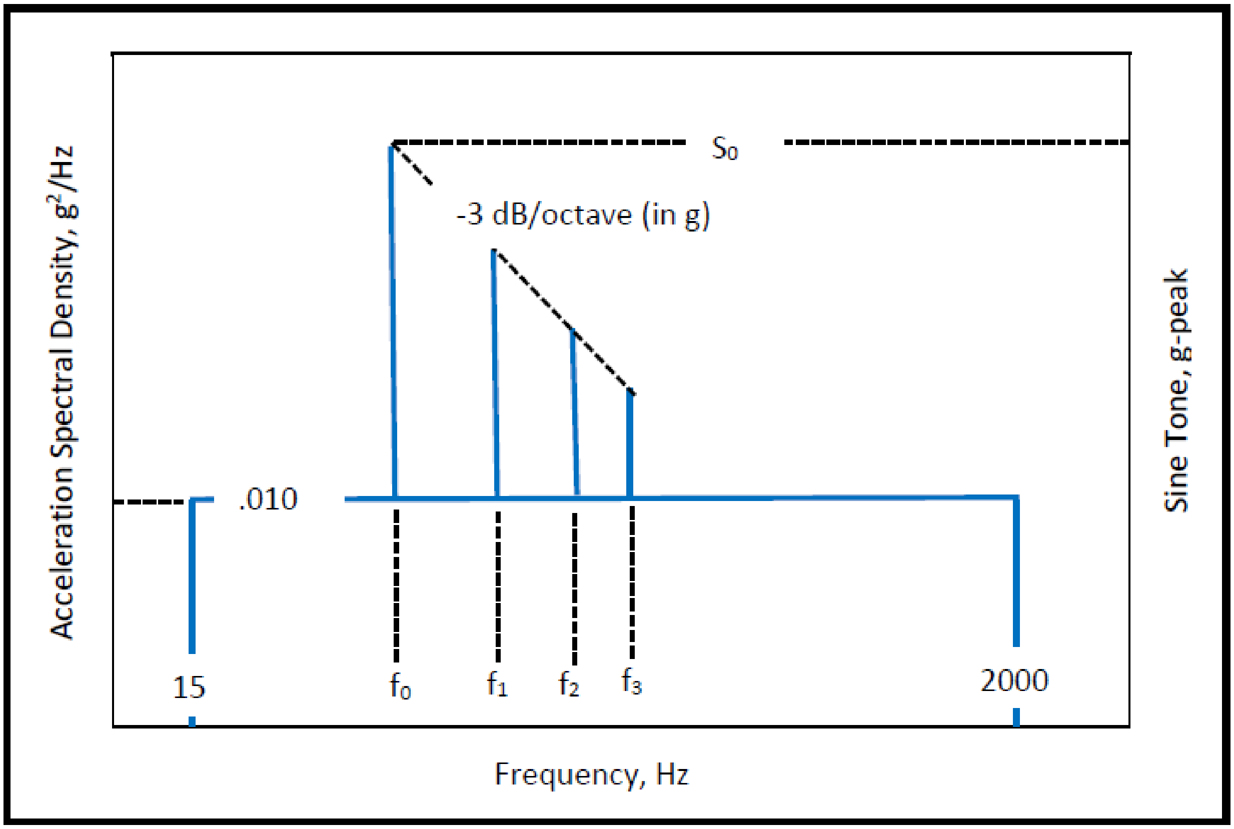

Figure 514.8D-2. Category 13 - Propeller aircraft vibration exposure.

Table 514.8D-II - Category 13 - Propeller aircraft vibration exposure.

TRANSPORTATION LOCATIONS (see Figure 514.8D-3)	NARROWBAND LEVEL L_0 (g^2/Hz)
In fuselage or wing forward of propeller	0.1
Within one propeller blade radius of propeller passage plane	1.2
In fuselage or wing aft of propeller	0.3
In engine compartment, empennage, or pylons	0.6

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/ Test should be conducted as sine-on-random, with:

$$So = 1.414 * \sqrt{0.1 * fo * Lo}$$

4/ Sine tones may be swept to account for known variance in blade passing frequency.

5/ C-130 Aircraft: 4 blade propeller - f_0 = 68 Hz (C-130K); 6 blade propeller - f_0 = 102 Hz (C-130J)

6/ Endurance test duration per axis: 1 hour for 1000 hours of flight.

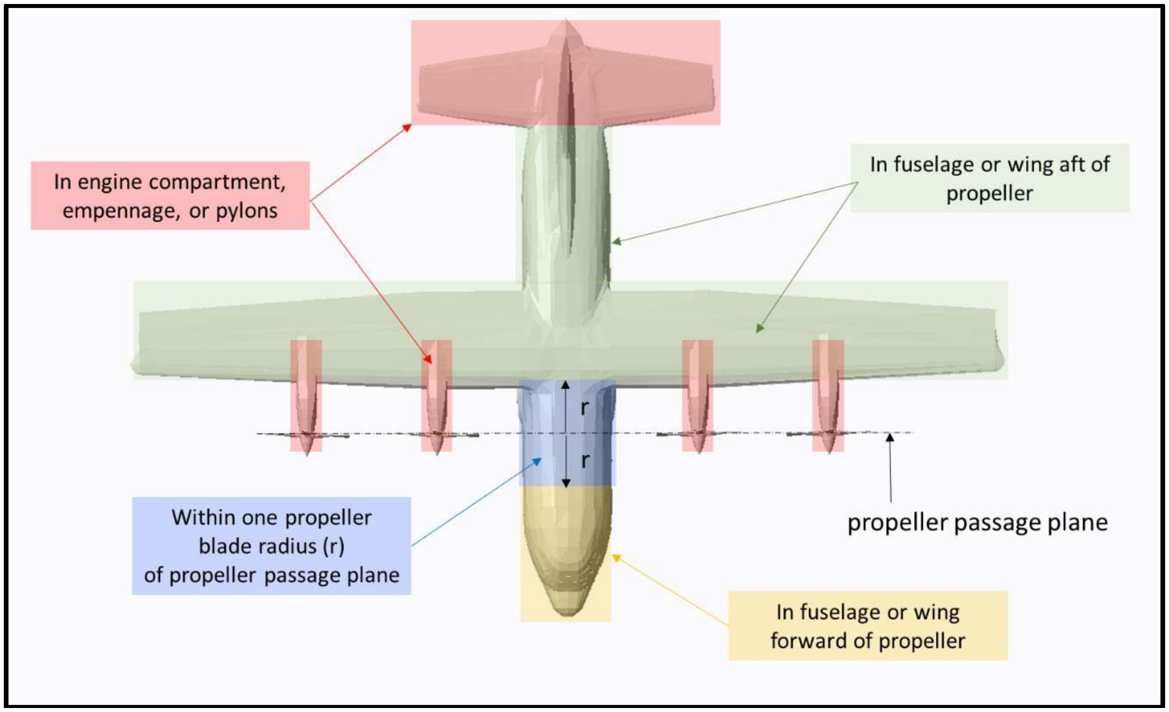

Figure 514.8D-3. Category 13 - Propeller aircraft installed equipment locations.

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 519.8) is characterized by dominant peaks superimposed on a broadband background, as depicted in Figure 514.8D-4. 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 percent 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 xx). When measured data are not available, levels can be derived from Table 514.8D-III, and Figures 514.8D-4 and 514.8D-5.

> NOTE: These levels are intended to envelope potential worst-case environments, and have been aggressively compressed in time (paragraph 6.1, reference ww 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. Functional test levels can be derived as discussed below in paragraph 2.3e (4).

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.

Data acquired from variants of the rotorcraft listed in Table 514.8D-IIIa, were used to develop the random levels, source frequency relationships, and peak acceleration relationships reported in Table 514.8D-IIIb. Aircraft specific source frequencies are directly associated with rotor blade count and rotation speed. Tabulated source frequency ranges, peak acceleration amplitudes and associated random levels were empirically determined and encompass the vibration environments measured. The suitability of extrapolating these empirical peak acceleration relationships to aircraft not listed is unknown. Application of these empirical relationships to rotorcraft that are not included in the sample set should be applied with caution and only in the total absence of field data. Whenever possible, vehicle specific flight data should be acquired and employed in development of an aircraft specific vibration criterion.

(2) To determine levels, divide the aircraft into zones as shown in Figure 514.8D-5. Use the source frequencies of the main rotor in determining the values of A_1, A_2, A_3, and A_4 (Table 514.8D-III) 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 Table 514.8D-III. 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.

(3) Plans for development of updated vibration schedules representative of the modern rotorcraft fleet are in progress. As each aircraft's vibration schedule updates are completed, they will be provided as individual Annexes to TOP 01-2-603, Rotorcraft Laboratory Vibration Test Schedules, (paragraph 6.1, reference xx) along with vibration schedule development (VSD) technique details and all relevant descriptors such as mission scenario and instrumentation locations. The updated schedules will supersede the current defaults as listed in Table 514.8D-III. Currently there are only two rotorcraft in TOP 01-2-603, the UH-60 and the CH-47. These helicopters have therefore been removed from Table 514.8D-III.

(4) In the event that Functional Testing is to be considered it is permissible to reduce the test levels derived from Table 514.8D-IIIb by an amount which will yield levels representative of the maximum measured field levels. This is achieved by scaling the derived random levels (in g^2/Hz) by a factor of 0.18 and the peak acceleration levels (A_x in g) by a factor of 0.34. Test durations associated with Functional Testing should be kept to a minimum and it is generally not considered part of the Endurance Test duration.

(5) In the event that Reliability Testing is to be considered it is permissible to reduce the test levels derived from Table 514.8D-IIIb by an amount which will yield a one-to-one equivalency in total test hours

and flight hours. This is achieved by scaling the derived random levels (in g^2/Hz) by a factor of 0.24 and the peak acceleration levels (A_x in g) by a factor of 0.41. Test duration should be set to the total flight hours required for Reliability Testing, divided equally among the three test axes and can considered as part of the Endurance Test duration.

f. Exposure durations. When measured data are used to establish exposure levels, take durations from the LCEP.

g. Environment Profile. Default test duration of four (4) hours in each of three (3) orthogonal axes for a total test time of twelve (12) hours is recommended, when levels are derived from Tables 514.8D-IIIa and 514.8D-IIIb, and Figures 514.8D-4 and 514.8D-5. This test duration represents a 2500-hour operational life. If the LCEP of the UUT is other than the 2500 Hr default, modify the test duration as appropriate (i.e., a 1250 Hr LCEP would yield a 2 hour test at the default amplitudes of Table III). Such linear scaling of duration is acceptable to a minimum test duration of 0.5 Hrs. (which represents 312.5 Flight Hrs.). In the general case, it is acceptable to adjust the test durations and test levels per the guidance provided in Section 9.2.1.2 of Annex F, provided the test duration is not less than 30 minutes per axis, the test levels do not exceed the defaults derived from the tables, and the test levels are not less than the Functional Test levels defined in paragraph 2.3e(4). Seek assistance from specialist with expertise in vibration specification development as required.

Example: Consider a situation in which the 50 flight hours are required and the default amplitude for f_1 is 1.944 g-Pk. Applying linear scaling as described above yields a .08 hour test. Scale the default amplitude to yield the default minimum duration of 0.5 hours per the guidance provided in Section 9.2.1.2 of Annex F. In this example t_1 = 0.08 hours, t_2 = 0.5 hours and $W(f)_1$ = 1.944 g-Pk. Using the default slope of 6 for a sine tone yields a revised amplitude for f_1 of 1.432 g-Pk for a 0.5 hour test. (Scale the remaining tones in a similar manner). The broadband random portion of the spectrum should be scaled using a value of m = 7.5.

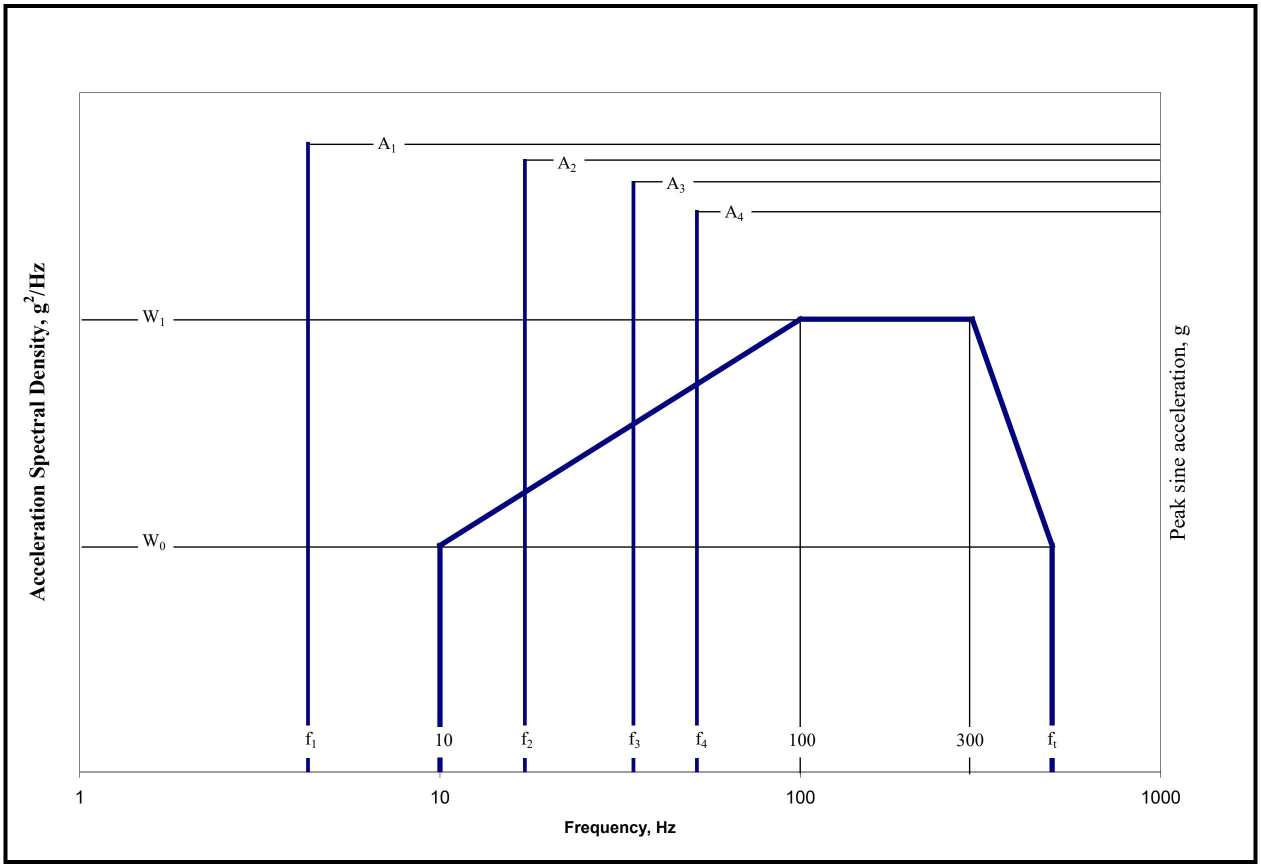

Figure 514.8D-4 Category 14 – Helicopter vibration (Same as Annex C, Figure 514.8C-15).

Table 514.8D-IIIa – Category 14 - Helicopter parameters. (Same as Annex C, Table 514.8C-XIVa.)

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	Refer to TOP 01-2-603 (Paragraph 6.1, reference xx)			
MH-6H	7.80	5	47.5	2
OH-6A	8.10	4	51.8	2
OH-58A/C	5.90	2	43.8	2
OH-58D	6.60	4	39.7	2
UH-1	5.40	2	27.7	2
UH-60	Refer to TOP 01-2-603 (Paragraph 6.1, reference xx)			

Table 514.8D-IIIb – Category 14 - Helicopter vibration exposure. (Same as Annex C, Table 514.8C-XIVb.)

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 (BP)	f_2 = 2 x 1S	2nd harmonic
f_3 = 2 x n x 1P	f_3 = 2 x m x 1T	2nd harmonic	f_3 = 3 x 1S	3rd harmonic
f_4 = 3 x n x 1P	f_4 = 3 x m x 1T	3rd harmonic	f_4 = 4 x 1S	4th harmonic

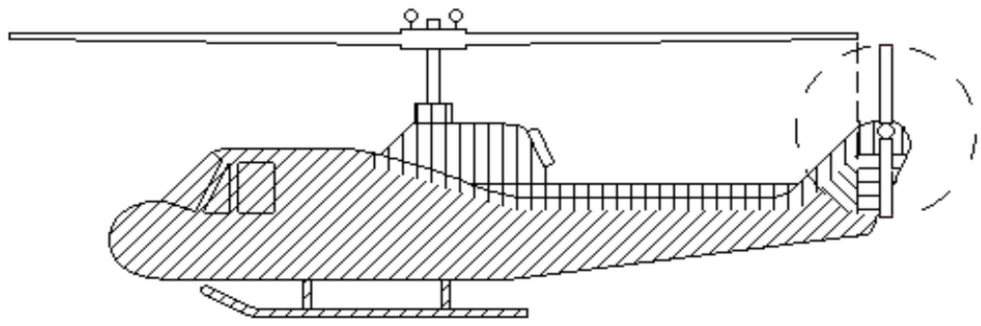

Figure 514.8D-5 – Category 14 - Helicopter vibration zones (Same as Annex C, Figure 514.8C-16).

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 (above 1000 Hz) cannot be practically transmitted to a store mechanically. Combine store vibration and acoustic testing (Method 523.4). 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 519.7) 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 affect overall store vibration. However, 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 523.4. 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

515.8). 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 with very high spikes across the spectrum, unless suppression devices are installed in the bay. 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 515.8.

   (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 open bay 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 516.8) 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 514.8D-IV and Figures 514.8D-6 and 514.8D-7. Buffet test spectra and levels are provided in Figure 514.8D-7. 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.

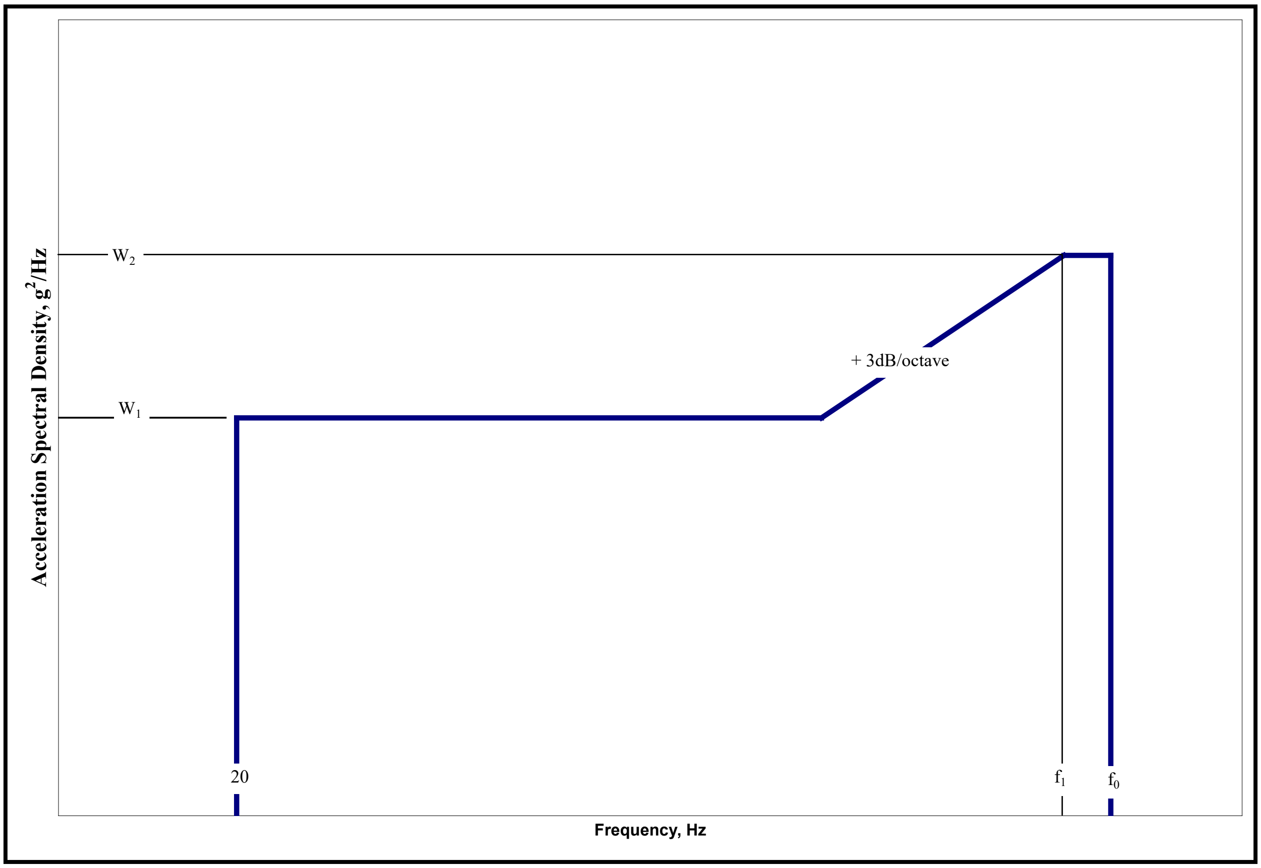

Figure 514.8D-6. Category 15 - Jet aircraft store vibration response.

Table 514.8D-IV. Category 15 - Jet aircraft external store vibration exposure.

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

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

$M \leq 0.90$, $K = 1.0$; $0.90 \leq M \leq 1.0$, $K = -4.8 \times M + 5.32$; $M \geq 1.0$, $K = 0.52$ 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 514.8D-V) – kN/m^2 (lb/ft^2).
ρ – Store weight density (weight/volume) - kg/m^3 (lb/ft^3).
Limit values of ρ to $641 \leq \rho \leq 2403$ kg/m^3 $(40 \leq \rho \leq 150$ $lb/ft^3)$.
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 $100 \leq f_1 \leq 2000$ Hz
4/ – Free fall stores with tail fins, $f_1 = 125$ Hz
5/ – Limit length ratio to: $0.0010 \leq C(t/R^2) \leq 0.020$
6/ – $f_o = 500$ Hz for cross sections not circular or elliptical
7/ – If $f_0 \geq 1200$ 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)	500	1500
Missile, air to air	76.61	(1600)	1602	(100)	500	1500
Instrument pod	86.19	(1800)	801	(50)	500	1500
Dispenser (reusable)	57.46	(1200)	801	(50)	200	1200
Demolition bomb	57.46	(1200)	1922	(120)	125	1100
Fire bomb	57.46	(1200)	641	(40)	100	1100

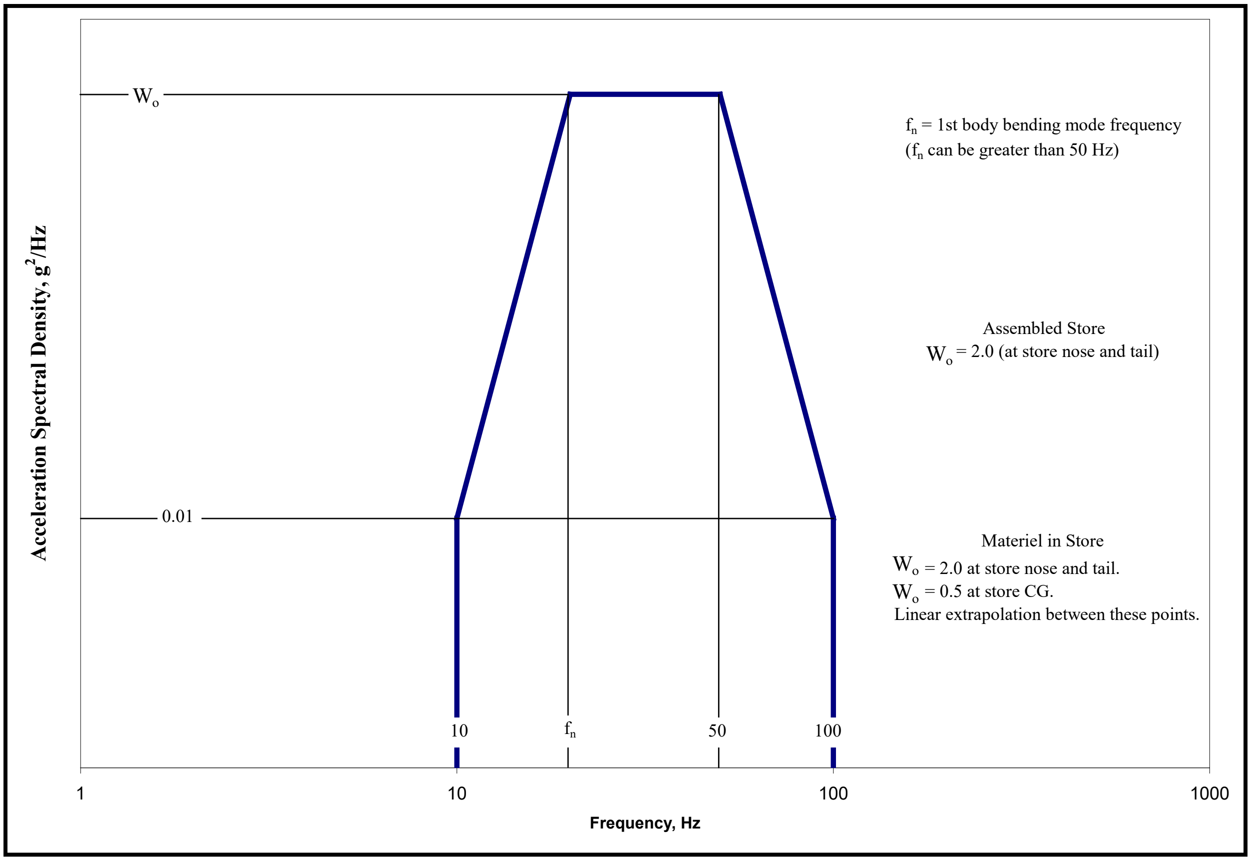

Figure 514.8D-7. Category 15 - Jet aircraft store buffet response.

Table 514.8D-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.

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

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

	$h \le 11000$ 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)		
V_{ao}	– Sea level speed of sound, m/sec (ft/sec)	σ	– Ratio of local atmospheric density to sea level atmospheric density (standard atmosphere)
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

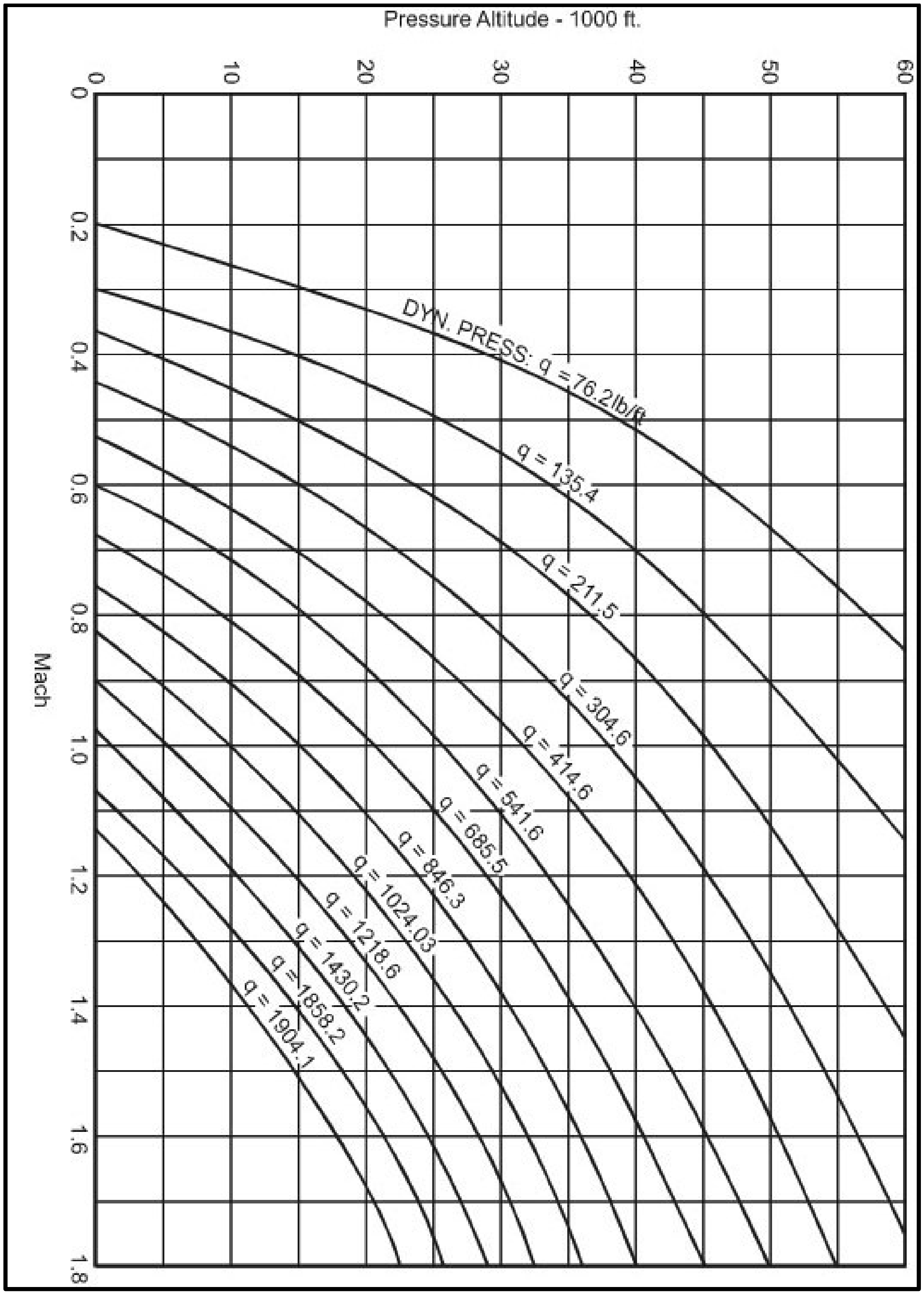

Figure 514.8D-8. Dynamic pressure as a function of Mach number and altitude.

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 514.8D-IV and Figure 514.8D-9.

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.

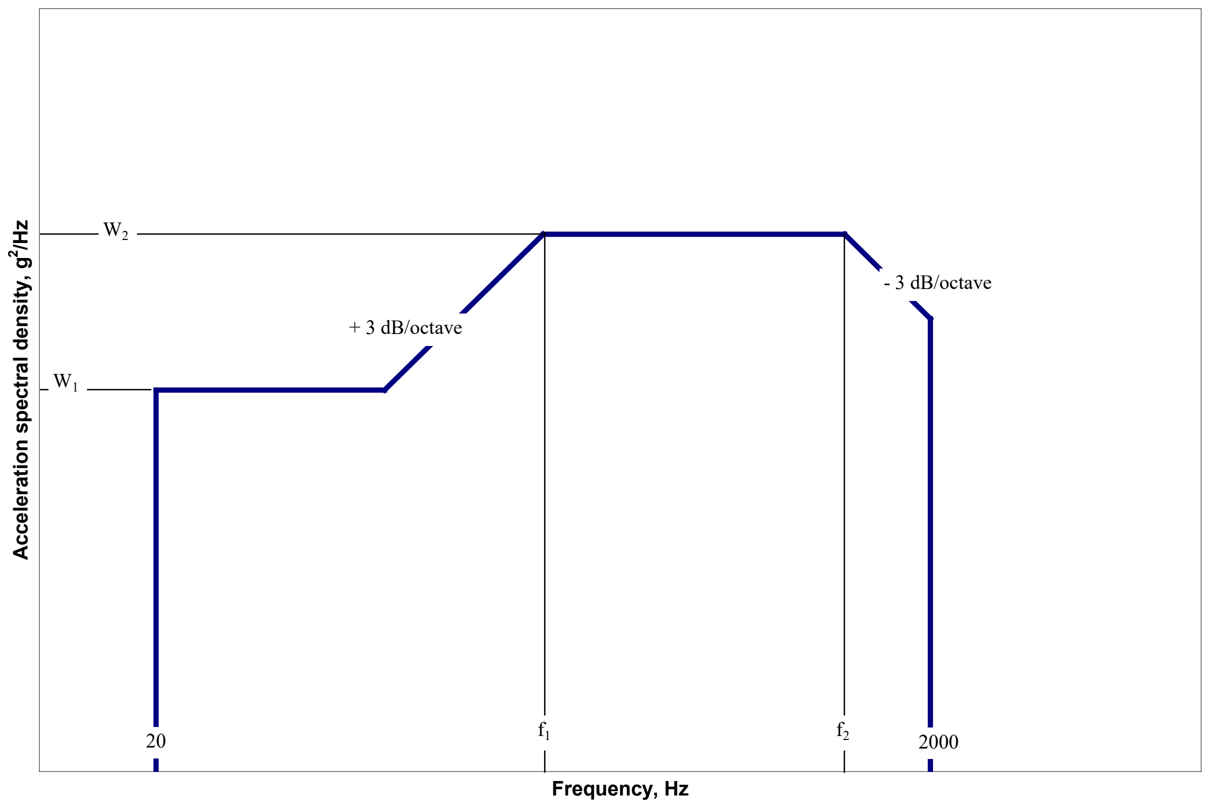

Figure 514.8D-9. Category 16 - Jet aircraft store equipment vibration exposure.

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 519.8). 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 514.8D-II and Figure 514.8D-2 may be used to develop preliminary estimates of general vibration. The criteria of Figure 514.8D-7 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 519.8.

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 514.8D-III, and Figures 514.8D-4 and 514.8D-5, 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 514.8D-5. 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 Table 514.8D-III). Also in Table 514.8D-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 LCEP. When levels are derived from Table 514.8D-III, and Figures 514.8D-4 and 514.8D-5, 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 2.4.3 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 free flight vibration, measurement of the actual environment is essential. The aircraft store criteria of Table 514.8D-IV and Figures 514.8D-6 and 514.8D-9 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 pp to vv.)

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 519.8) 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 514.8C-2 will be overly conservative at notches in the frequency spectrum. The spectra of Annex C, Figures 514.8C-4 through 514.8C-7 are typical of cargo bed responses in two-wheeled trailers and tactical wheeled vehicles (including four-wheeled trailers), respectively. 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 that 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 514.8D-10. Test execution requires sweeping across the narrow band regions (rectangular shapes in Figure 514.8D-10) 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 d contains criteria that may be used directly or adapted as necessary.

d. Exposure durations. Take durations from the LCEP. Guidance is given in paragraph 6.1, reference d, relating durations to exposure levels for various tracked vehicles.

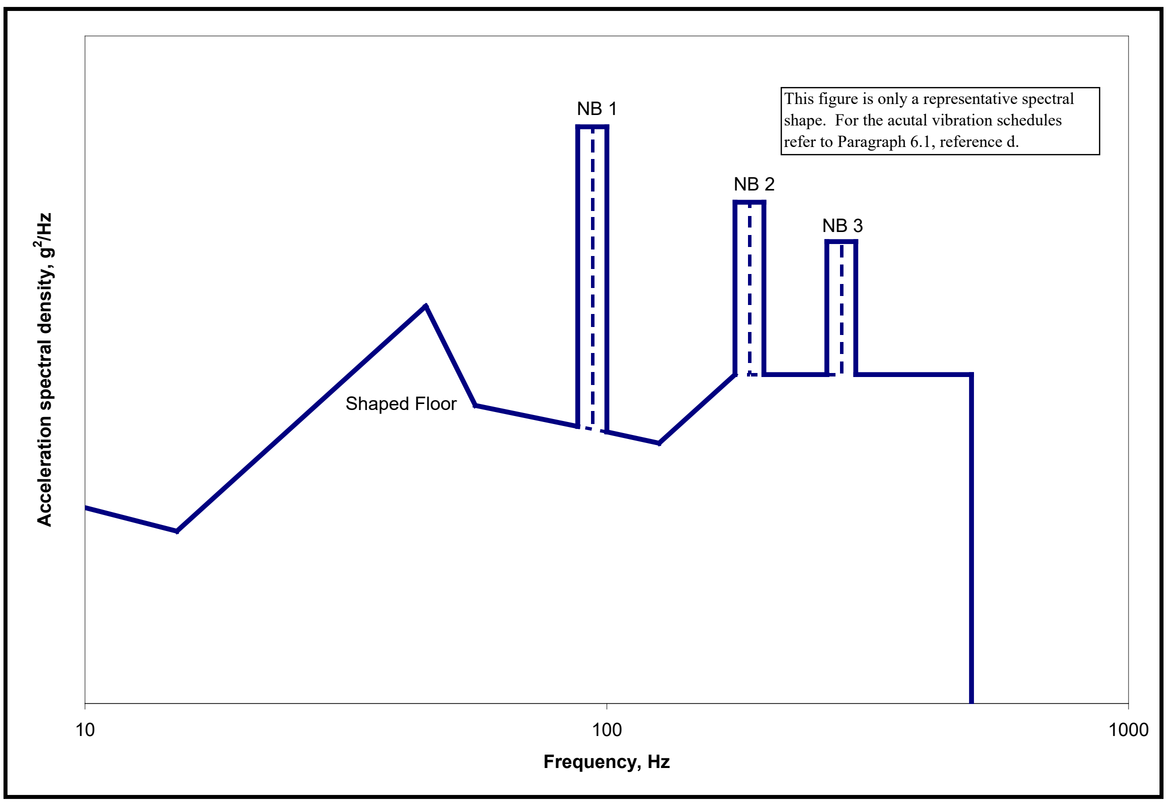

Figure 514.8D-10. Category 20 - Tracked vehicle representative spectral shape.

2.10 Category 21 - Watercraft - marine vehicles.

Note: For US Navy applications refer to Method 528.1.

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 shock criteria per Method 519.8 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 514.8D-11 for a duration of two hours along each of three orthogonal axes, and the sinusoidal requirements of Method 528 Procedure I. In the event that actual shipboard vibration data recorded on candidate vessels show levels or frequency ranges different from those for Method 528, Procedure I, the test levels should be tailored to envelope the highest values for each frequency, with appropriate consideration given to the fatigue life of the equipment. For material to be installed in a US Navy ship any deviation from the defaults of Method 528 requires the approval of the responsible US Navy Warrant. 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.

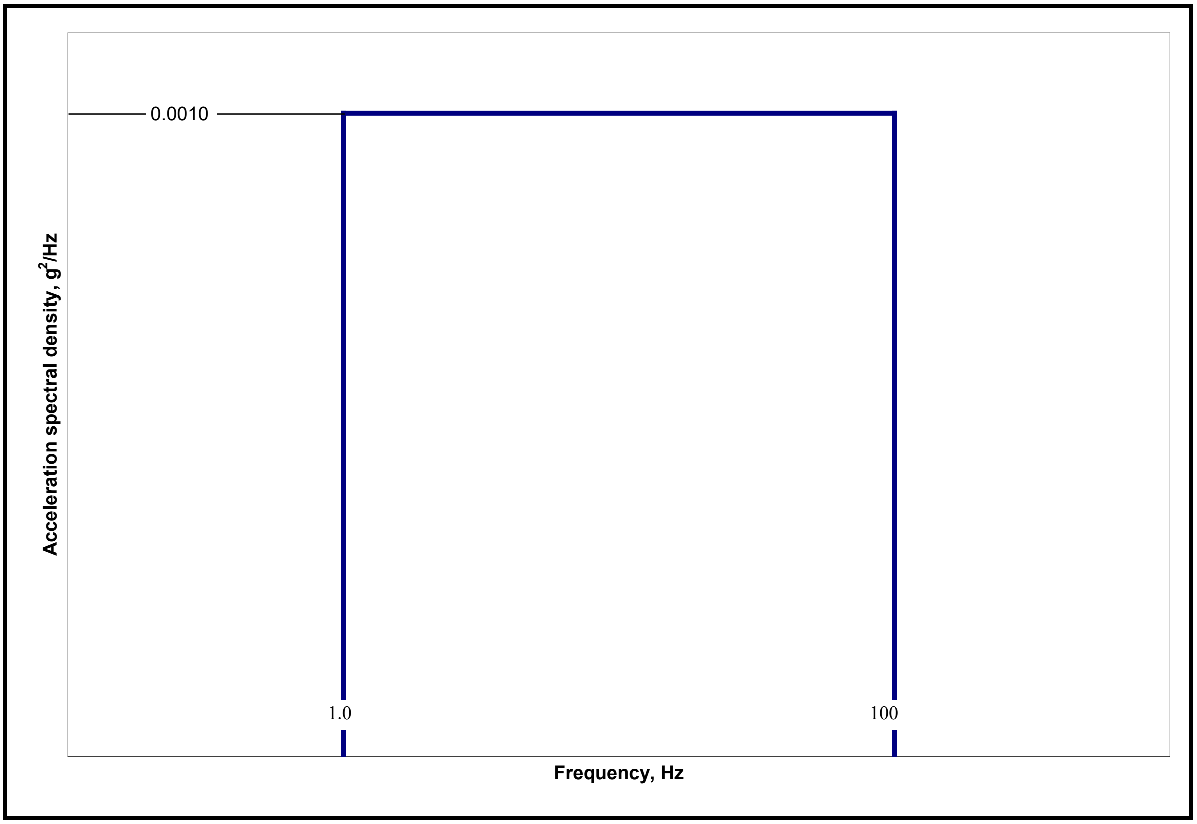

Figure 514.8D-11. Category 21 - Shipboard random vibration exposure.

2.11 Category 22 - Engines - turbine engines.

Vibration spectra for materiel mounted directly on or in close proximity to 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 514.8D-12. 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 514.8D-12 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 514.8D-12 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 514.8D-12 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, paragraph 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 514.8D-12 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.

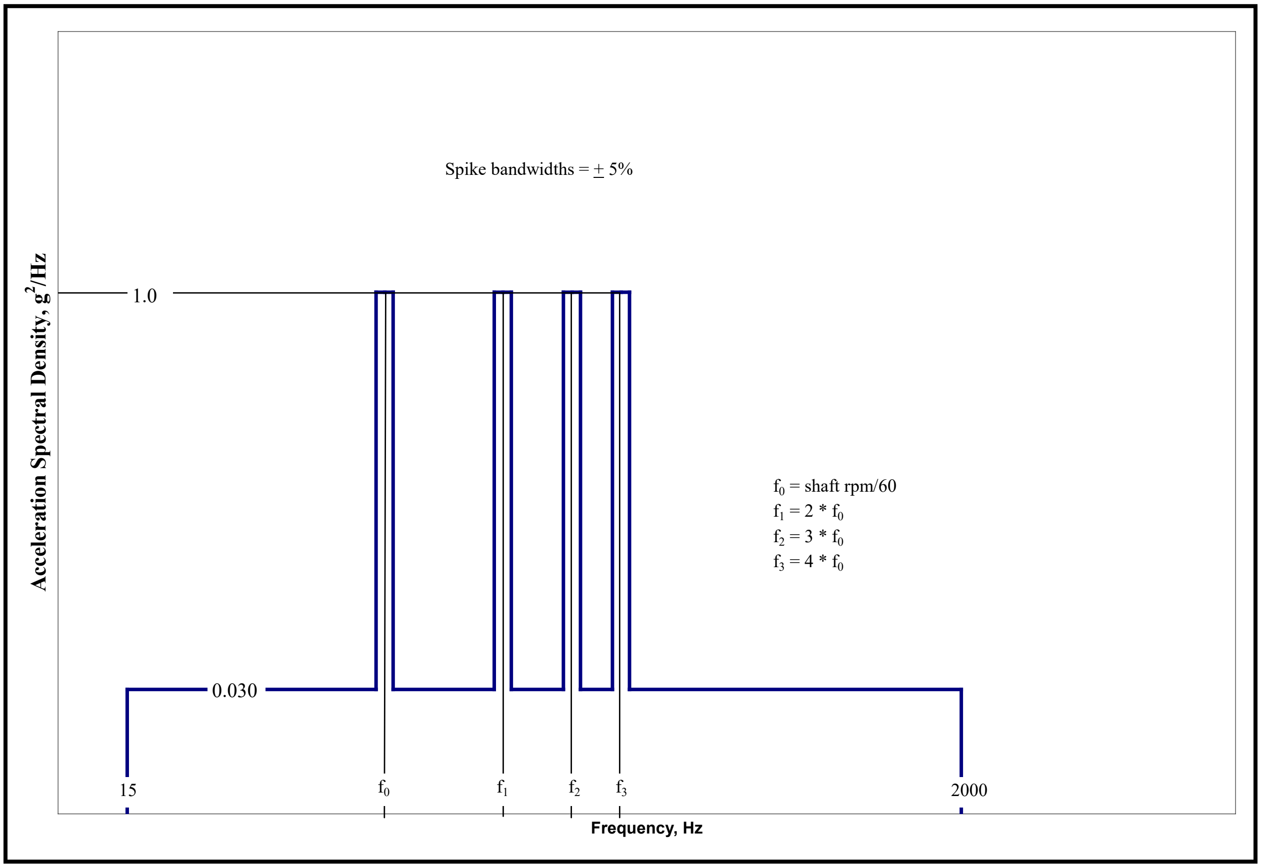

Figure 514.8D-12. Category 22 - Turbine engine vibration exposure.

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.

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METHOD 514.8, 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 514.8-I in the front part of this Method contains an outline of the following paragraph 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 that 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 cannot 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 514.8E-1 and 514.8E-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 514.8E-1 and 514.8E-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 preserved). 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 514.8E-1 for general use, and in Figure 514.8E-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 514.8E-1 for general use, and in Figure 514.8E-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.

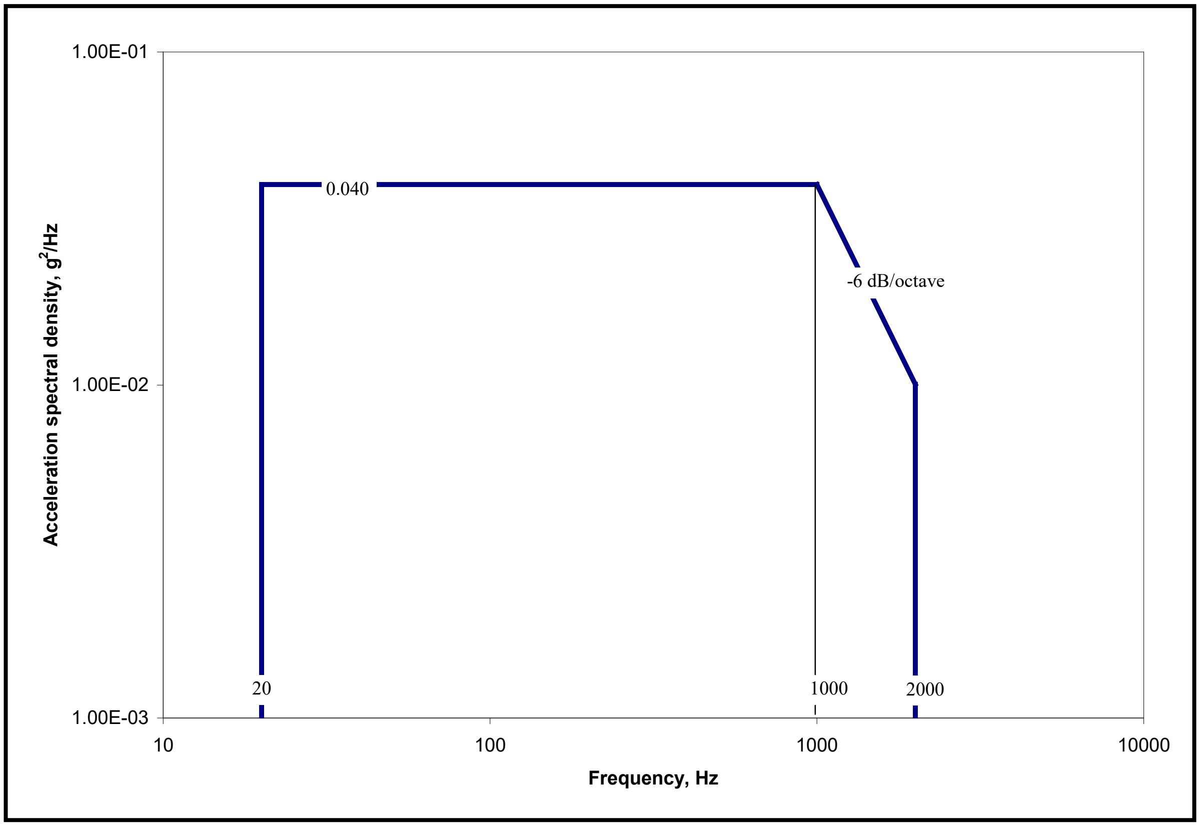


Figure 514.8E-1. Category 24 - General minimum integrity exposure.
(Test duration: One hour per axis; rms = 7.7 g's)

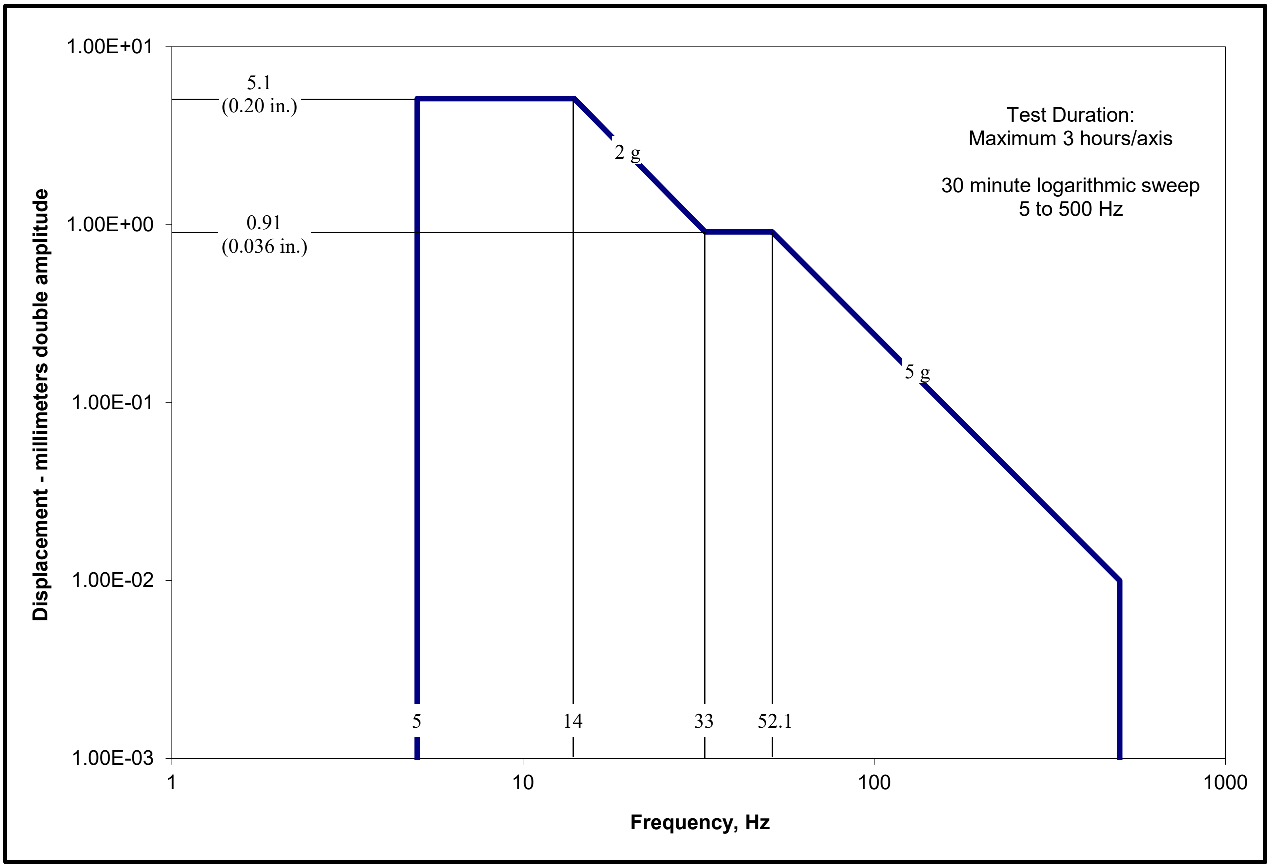


Figure 514.8E-2. Category 24 - Helicopter minimum integrity exposure. (Test duration: Maximum three hours per axis – 30 minute logarithmic sweep 5 to 500 Hz.)

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, paragraph 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, paragraph 7.10 or paragraph 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:

$$f = 0.22\ V/D$$

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

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. Platform environments.

(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 downstream 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, paragraph 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 LCEP. 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.

METHOD 514.8, ANNEX F

Development of Laboratory Vibration Test Schedules

NOTE: Unless specifically noted, all document references refer to Annex F, Appendix F of this Method.

1. GENERAL.

The purpose of this annex is to present considerations and techniques for developing Laboratory Vibration Test Schedules (LVTS) that can be utilized to simulate field vibration environments on a vibration table. Laboratory vibration tests are used extensively in lieu of more time-consuming and less cost effective field exposure tests. This annex specifically addresses vibration testing controlled to frequency-domain vibration spectra and is currently limited to single mechanical degree-of-freedom scenarios.

Analysis considerations and techniques depend somewhat on the intended use of the LVTS. An LVTS developed solely for functional testing will differ from one developed to induce a full lifetime of vibration exposure. This annex primarily addresses development for the purpose of inducing a lifetime of vibration exposure, but also discusses development for other purposes.

The primary function of Vibration Schedule Development (VSD) is to combine vibration measurements of numerous events that collectively represent an item's lifetime vibration exposure into a manageable set of LVTS representing the equivalent exposure. The most dynamically accurate method to reproduce the full exposure would be to sequentially vibrate the system to all the individual, uncompressed events representing its full lifecycle. However, such an approach is generally not feasible from both schedule and economic perspectives and some compromises must be made to realize the benefits of testing in the laboratory. Time compression techniques based on fatigue equivalency are typically employed such that vibration testing can be performed in a timely and economic manner. This annex presents guidance for developing accurate representations, and issues that should be considered during the VSD process.

There is no single "best method" for VSD. Several methods have evolved at different organizations. Those methods were influenced by project specific issues, the nature of the vibration exposures, and the concerns of the given organization. This annex presents one VSD method plus two methods of combining spectra which can be useful for validation of test schedules, comparing one test schedule with another and comparing one test schedule with measured data. Critical issues are also presented that should be addressed by all methods to ensure accurate representations. Which methods are adopted may depend on the item being tested, the exposure to be replicated, the concerns of the parties involved, or other project specific factors. Ultimately, the VSD method selected must yield a set of vibration definitions and durations that collectively replicates the actual field exposure and/or induces the equivalent fatigue.

This annex addresses vibration issues only and does not address fatigue or damage potential of shock events. Shock concerns and respective test development issues are discussed in Method 516.8. Note that conditions that produce vibration may also produce shock (a pothole during road transport). Shock events should be identified, removed and addressed separately for analysis and testing.

2. REQUIREMENTS.

VSD requires a thorough knowledge of the dynamic environment in which the test hardware will be exposed when fielded. This knowledge must include characterization of the exposure levels and durations for all relevant conditions. Annex F, Appendix A presents guidelines and cautionary notes related to data acquisition.

Vibration of an item may be induced by transportation on a given platform, co-location near other vibrating equipment, self-induced, or a result of other sources. This annex is relevant as long as the expected exposure conditions and durations are understood, and the vibration levels can be measured and/or characterized.

To characterize the exposure levels, the test hardware and deployment vehicle (if applicable) are often instrumented at points of interest. The hardware is then exposed to the environments of concern and vibration data is acquired. In the event that the test items, prototypes, or carrier vehicles are not available, predictions of the vibration environment may be developed per simulation techniques provided the model fidelity is understood and has been properly verified and validated.

The duration of the vibration environments can be derived from the item's Life Cycle Environment Profile (LCEP).

The life cycle will include many different types of induced mechanical environments which may occur while the materiel is being handled, transported, deployed and operated. Although all the induced mechanical environments are not critical in terms of generating potential damaging response amplitudes, they contribute in varying degrees to the materiel's fatigue damage. All expected exposure conditions should be tabulated, along with corresponding durations, to form the items lifetime "scenario". The scenario is a key parameter in the development of any vibration schedule. Methods for deriving an LCEP are discussed in Part 1 of this standard and in AECTP-100 (reference a). Methods for refining a scenario for VSD are presented in this annex.

3. DEFINITIONS.

For clarity of discussion, the following definitions are provided. The definitions are not intended to be general in nature, but rather specific to the discussions in this annex.

Laboratory Vibration Test Schedule (LVTS) – All information required to perform a vibration test on a vibration exciter. Information typically includes: a broadband spectra (or profile), sine or narrowband information (if used), test run time, control accelerometer locations, control methods and tolerances, and any test specific information required.

Event – A unique exposure condition that represents some portion of the full lifecycle of a given item. Examples include flight maneuvers (i.e., forward flight at 80 percent VH) or ground vehicle conditions (i.e., paved road at 30 mph). Many events may be required to fully characterize the vibration exposure of an item.

Group – A set of events with similar vibration characteristics that are grouped together for processing.

Scenario – A tabulation of expected exposure events and the corresponding durations.

Profile – A broadband spectra that a vibration system can use as a control reference. The profile is typically provided in Auto Spectral Density (ASD) format and defined by a series of frequency and amplitude breakpoints.

Power Spectral Density (PSD) – The PSD describes how the power of a signal is distributed with respect to frequency. Vibration control systems typically use PSDs as the control reference; therefore, vibration profiles are generally developed in a PSD format. The PSD is also referred to as the auto spectral density (ASD). See Annex F, Appendix B for a description of ASD/PSD calculation methods often used. For consistency the term ASD will be used for the remainder of this Annex.

Windowing – Multiplication of a time history by a function which is zero valued outside of a given interval. Windowing is necessary for proper ASD calculation, with the Hann or Hamming windows commonly applied.

Leakage – An undesired result of windowing in which energy at one frequency leaks into adjacent frequencies. This can affect the spectral shape of the ASD and is dependent on the frequency resolution of the ASD calculations. Although the energy leaks into adjacent frequencies, the total amount of energy is preserved and the total g-rms of the ASD is unaffected.

Breakpoint – A point on the broadband profile, defined by a frequency (Hz) and a power level (g^2/Hz). Breakpoints allow the multi-point profile to be represented by a reduced set of points without overly compromising the spectral information.

Miner-Palmgren Hypothesis (Miner's Rule) – A set of mathematical equations used to scale vibration spectra and their associated test times while maintaining fatigue equivalency. A more detailed description of the Miner-Palmgren Hypothesis can be found below in paragraph 9.2.1.

Spectral Spike – Any narrowband, high-level vibration content in a vibration spectrum. The energy associated with the narrowband may be either narrowband random or sinusoidal in nature, depending upon the nature of the forcing function of the test platform. This energy is often removed from the broadband information and processed separately during analysis.

4. NATURE OF VIBRATION.

For VSD purposes, vibration can generally be classified in one of three categories. The category of vibration can affect the analysis techniques or test methods.

Sinusoidal – Vibration at a single frequency, typically of constant amplitude. Depending on the source of the vibration, the frequency might remain constant (dwell) or change (sweep) over a pre-defined bandwidth.

Broadband Random – Vibration is simultaneously present at all frequencies over a wide bandwidth. The amplitude may vary significantly over the full bandwidth.

Narrowband Random – Vibration is simultaneously present over a narrow bandwidth of frequencies. Narrowband vibration is typically defined by a center frequency, a bandwidth, and amplitude. As with sinusoidal vibration, the frequency of the narrowbands is sometimes constant and sometimes swept.

An item will often undergo more than one category of vibration simultaneously. Most modern vibration test systems can produce broadband random, pure sinusoidal, sine-on-random (SOR), and narrowband random-on-random (NBROR) vibration. The sinusoids and narrowbands can either dwell or sweep.

In the field, narrowband energy is rarely pure sinusoidal or pure narrow-band random, but is more commonly a combination of the two. Unfortunately, most vibration control systems can produce either narrowband random or sine vibration at a given frequency, but not both. For that reason it is necessary to determine if the vibration of interest is more nearly sinusoidal or narrowband random in nature. This can be difficult as the leakage in ASD calculation often makes sinusoidal vibration appear to be narrowband random. One method of differentiating between sinusoidal and narrowband random data is the width of harmonically related spectral spikes. If the vibration is sinusoidal the width is a result of ASD leakage and will remain nearly constant in the harmonics. However, if the vibration is narrowband the widths will be harmonically related. Histograms and band-pass filter time histories are also helpful in determining the nature of spectral spikes.

5. PLATFORM SPECIFIC CONSIDERATIONS.

5.1 Road Transport - Wheeled Vehicle.

Equipment secured for transport in a wheeled vehicle will primarily be exposed to broadband random vibration, with the majority of the energy at low frequencies (relative to a tracked vehicle). It is often argued that items transported on both tracked and wheeled vehicle need only be tested to the tracked vehicle exposure under the assumption that tracked vehicle transport is more severe. However, this is not the case for items that may be sensitive to high-level low-frequency vibration, or the resultant high velocities and displacements characteristic of a wheeled vehicle.

Sinusoidal washboard courses are sometimes used to replicate real world exposure when road testing vehicles. Vibration data on these courses are often recorded and utilized for VSD. The vibration induced by these courses will include harmonically related spectral spikes superimposed over broadband random. Employing standard analysis techniques such as histograms, bandpass filters, and harmonic relationships between spectral spikes, one may deduce that the time histories yielding the dominant spectral spikes to be more nearly sinusoidal than narrowband in nature, with the frequencies being speed dependent. A swept SOR test is typically used to replicate washboard exposure. However, an assessment of the project specific data should be made to determine the nature of the vibration.

The terrain and severity of the vibration environment changes from relatively smooth asphalt/concrete roads through secondary roads to trails and virgin cross-country. Trails and cross-country terrains provide the most severe vibration environment for a given speed, and paved road produce the least severe. Many test tracks have been built to allow vehicle testing and data acquisition in a controlled test environment. Some of these tracks were designed specifically to replicate real world worst case environments and can be beneficial for VSD development. Other test tracks were developed to investigate aspects of vehicle handling and reliability and may not be appropriate for VSD. Courses often used for wheeled vehicle VSD include paved road, gravel road, Belgian block, radial washboard, embedded rock, two-inch washboard, and cross-country. Embedded rock and the washboard courses replicate the worst case exposure. Typically transport over asphalt/concrete roads produces vibration levels that are insignificant in comparison; therefore, that portion of a scenario is often ignored for VSD purposes. Additional wheeled vehicle transport vibration issues are discussed in AECTP 240, Leaflets 242/1, 242/5, and 245/2 (reference m).

5.2 Road Transport - Tracked Vehicle.

The vibration induced into secured equipment by tracked vehicles will include harmonically related spectral spikes superimposed over broadband random. The frequency of these narrowbands created by the interaction between the tracks and hard road surface and is proportional to vehicle speed. This proportion can be described as follows:

$$f = .28\frac{v}{p}$$

in which: f = frequency (Hz), p = track pitch (m), and v = velocity (km/h)

Employing standard analysis techniques such as histograms, bandpass filters, and harmonic relationships between spectral spikes, one may deduce that the time histories yielding the dominant spectral spikes to be more nearly narrowband random in nature than sinusoidal, with the frequencies being speed dependent. A swept NBROR test is typically used to replicate tracked vehicle exposure. However, an assessment of the project specific data should be made to determine the nature of the vibration.

Road courses typically used for tracked vehicle VSD include paved road, gravel road, and cross-country. Asphalt/concrete roads provide the most severe vibration levels in a tracked vehicle because of the relatively constant impact of the track blocks on the hard surface. Hard packed gravel or dirt secondary roads will produce levels nearly equivalent to asphalt/concrete roads and should be considered in the development of vibration schedules as well. Additional tracked vehicle transport vibration issues are discussed in TOP 01-2-601 (reference c) and AECTP 240, Leaflet 245/1 (reference m).

5.3 Air Transport - Rotor Wing.

The vibration induced into equipment transported by rotor wing platforms (whether captive carry, mounted internally, or secured in the cargo area) will include harmonically related spectral spikes superimposed over broadband random. Employing standard analysis techniques such as histograms, bandpass filters, and harmonic relationships between spectral spikes, one may deduce that the time histories yielding the dominant spectral spikes to be more nearly sinusoidal in nature than narrowband random, with the frequencies being dependent upon the number of rotor blades and the main rotor rate. Predominate frequencies are determined by the normally constant blade passing frequency and are independent of vehicle speed. Vibration of equipment mounted near the tail rotor may be dominated by the tail rotor blade passing frequency. A SOR test is typically used to replicate rotor wing platform exposure, with the sine tone frequencies held constant. However, an assessment of the project specific data should be made to determine the nature of the vibration.

Vibration severity is related to flight conditions. The vibration environment at a given location in or on a helicopter is affected by the power output of the engine, the aerodynamic buffeting of the rotor(s), and atmospheric conditions. VSD should include analysis of all aircraft maneuvers that constitute a significant portion of the expected flight time and that produce significant vibration amplitudes. Additional rotor wing transport vibration issues are discussed in TOP 01-2-603 (reference q) and AECTP 240, Leaflet 242/3 (reference m).

5.4 Air Transport - Fixed Wing.

Vibration environments on jet aircraft are broadband random in nature. The maximum vibrations are usually engine exhaust noise generated during takeoff. Levels drop off rapidly after takeoff to lower level cruise levels that are boundary layer noise generated.

Vibration environments on propeller aircraft are dominated by relatively high amplitude, approximately sinusoidal spectral spikes at propeller passage frequency and harmonics. Some aircraft have fixed-pitch, variable-speed rotor blades and in these cases the rotor speed and hence rotor related spectral spikes vary with engine speed over a wide frequency band. In this case a swept SOR test is likely to be appropriate. Other aircraft have variable-pitch, constant-speed rotor blades and in these cases the rotor speed is designed to be constant and therefore the rotor related spectral spikes should remain constant. However even in this later case minor rotor speed variation is likely resulting in rotor related spectral spikes varying in frequency by up to 1 percent of nominal frequency. These minor variations can usually be ignored. In addition to the sinusoidal spectral spikes 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. Additional fixed wing air transport vibration issues are discussed in AECTP 240, Leaflet 242/3 (reference m).

5.5 Sea Transport.

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, hull resonance and local equipment tones often related to main power. 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. VSD for shipboard materiel should address both the levels of environmental inputs and the coincidence of materiel/mounting resonances and input frequencies although in the transport by sea case, the vibration amplitudes are relatively benign and can often be considered as if they were wideband in nature. It is often not necessary to test for sea transport if an item is tested to other more severe transport, such as ground or jet aircraft transport. Additional sea transport vibration issues are discussed in AECTP 240, Leaflet 242/4 (reference m). For US Navy vessels refer to Method 528.1.

5.6 Rail Transport.

Vibration levels for rail transport are generally low in level and moderately wideband. Vertical axis vibration is typically more severe than transverse and longitudinal. It is often not necessary to test for rail transport if an item is tested to other more severe transport, such as ground transport. Additional rail transport vibration issues are discussed in AECTP 240, Leaflet 242/2 (Annex F, Appendix F reference m).

6. DATA COLLECTION, REVIEW AND SELECTION.

The data set for a typical VSD project is usually quite large. Data may have been acquired for multiple loading configurations or multiple platforms. For each configuration, many events are generally required to completely characterize the system's vibration exposure. Data is often acquired for multiple repetitions of each event. Some data acquisition issues are discussed in Annex F, Appendix A. The first step of any VSD project is to thoroughly review the data set for validity, accuracy, and content.

Various commercially available data analysis software tools are utilized for the data review. A review for accuracy may include a study of the time histories for possible erroneous data, comparison of channels at similar locations, comparison to historic data of similar vehicles, a search for outliers, and various test specific interests. Any erroneous data should be noted and identified. Once data integrity is assured, the selection of data for the VSD process can begin.

Data selection will include a study of the relative severity of multiple configurations and a determination of how the configurations will be weighted during development. The multiple events are studied to determine how they should be grouped. Due to several factors, it is often unwise to combine all events into a single vibration schedule. Consideration should be given to the linearity of the system. The events are compared, and those with similar ASD shape and level are grouped and processed together. This often results in two or more LVTS to reproduce a system's equivalent fatigue, but produces a more accurate representation of the vibration exposure.

Studies are also conducted to answer questions as to the nature of the data. What bandwidth is required to include the majority of the vibration energy? Is the vibration characterized as Gaussian, or how well can it be replicated by a control system that generates a Gaussian drive signal? Is the energy broadband, or does it contain narrowband energy (e.g., tonal energy induced by a helicopter main rotor)? If narrowband energy is present, is it more sinusoidal or more narrowband random in nature? Often, project specific studies must be conducted before the VSD procedure can begin.

7. SCENARIO DEVELOPMENT.

The expected duration of vibration exposure is derived from the system's mission or lifetime scenario, often provided in the LCEP. A system's mission or lifecycle scenario is a key parameter for a VSD effort. In some cases a number of mission types are required, each with differing proportions of terrain or maneuvers utilized. These must all be weighted appropriately depending upon the user requirement/LCEP and used in the generation of the vibration schedule. As a minimum, the scenario for a ground vehicle must provide terrain type, average and maximum speeds associated with each terrain type, and total distance traveled on each terrain type. For an aircraft, the scenario must provide a detailed description of all flight conditions, including hover, forward level flight, take-off/ landing and other and relevant maneuvers. The description should include the percentage of flight duration represented by each condition and the number of repetitions for each maneuver.

7.1 Ground Vehicle.

Often, scenario information in the form required for the VSD process is not available. This is particularly true for vehicles not yet in the DoD inventory. If no information is available the scenario information may be inferred by the intended usage. For cargo items, the ground distance is determined based upon transport distance between each of the designated supply points that extend from the depot through the Port Staging Area (PSA) to the user of the item. For installed equipment items, the ground distance is determined on the basis of the maintenance schedule for the vehicle on which the equipment is mounted or on the basis of designer/user agreed upon repair/replacement schedule for the particular installed equipment item.

Often, limited scenario information can be found in the vehicles LCEP or other documentation. This information typically includes overall terrain type distance percentages and sometimes includes total distance and maximum and/or average speed information. Extensive manipulation is often required to distribute the total distance into the various road surfaces and speeds that characterize the vehicles usage. This process is illustrated in Table 514.8F-I.

The Level 1 breakout of Table 514.8F-I contains the minimum scenario information required for a VSD. The Level 2 breakout is a distribution of the general terrain type mileage into the various test surfaces for which data is typically acquired. All surfaces likely to be encountered for a given terrain type should be included in the Level 2 breakout. Surfaces used for Department of Defense (DoD) projects should be similar to those listed in Table 514.8F-I and described in reference r. Level 2 breakout information is rarely available and is typically derived through discussion between the analyst, the user, and other interested parties.

Table 514.8F-I: Lifetime Scenario Breakout – Example Only

LEVEL 1 BREAKOUT					LEVEL 2 BREAKOUT				
TOTAL MILES:	**1000**								
Terrain Type	**Percent**	**Miles**	**Max Speed**	**Avg Speed**	**Surface[1]**	**Percent**	**Miles**	**Max Speed**	**Avg Speed**
PRIMARY ROAD	**70%**	**700**	**55**	**35**	Paved	100%	700	55	35
						100%	700		
SECONDARY ROAD	**20%**	**200**	**40**	**22**	Secondary Road	60%	120	40	25
					Gravel Road	23%	46	45	22
					Belgian Block	10%	20	25	15
					Embedded Rock	1%	2	10	7
					Radial Washboard	3%	6	15	9
					2" Washboard	3%	6	10	7
						100%	200		
*** Off Road**	**10%**	**100**	**25**	**14**	Cross Country	85%	85	25	16.3
* A combination of trails and cross country					Embedded Rock	5%	5	10	7
					Radial Washboard	5%	5	15	9
					2" Washboard	5%	5	10	7
						100%	100		

LEVEL 1	This information should be provided by the program manager and is required before LVTS development can begin. This information can sometimes be found in the LCEP or other system documentation.
LEVEL 2	This breakout has a significant impact on the test durations of the final LVTS and should therefore be given serious consideration. This information, too, should be provided but is seldom available. Development cannot begin without this breakout. Often the analyst is forced to recommend a breakout for the concurrence of user.

[1] Surfaces are described in Annex F, Appendix F, reference r

7.1.1 Beta Distribution.

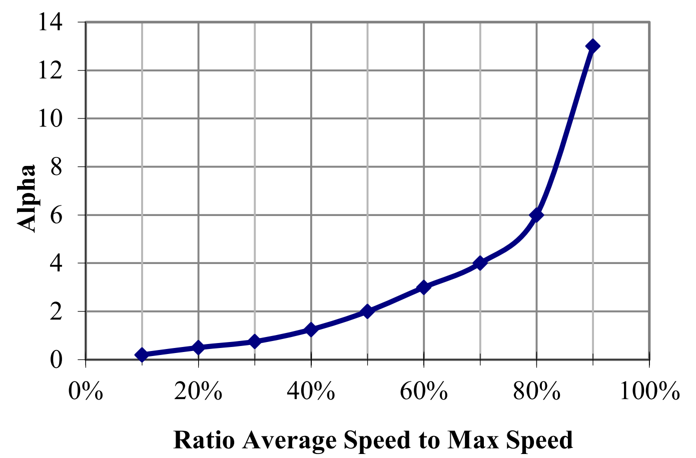
Once consensus is reached on the Level 2 breakout, the distance must be further distributed into the various speeds for which data was acquired. This additional level of fidelity is rarely provided. One option is to utilize the Beta distribution to distribute surface distance into the speed events for that surface. The Beta is a probability distribution with two shaping parameters, α and β, calculated as defined in equation 7.1 where x is the normalized distribution range.

$$f(x) = \frac{(\alpha+\beta-1)!}{(\alpha-1)!(\beta-1)!} x^{\alpha-1}(1-x)^{\beta-1} \tag{7.1}$$

Guidelines have been established to allow consistent selection of α and β, based on the ratio of the average to maximum speed. Alpha can be selected from Table 514.8F-II. Beta is iteratively calculated to yield a calculated average speed from the Beta distribution results to match the average speed provided in the scenario. The Beta distribution should be utilized to distribute the distance into a set of speed ranges, rather than into a set of discreet speeds. An alternative to distributing the total distance is to distribute the total time, based on the total distance and average speed. A Beta distribution is produced for each road surface utilizing a spreadsheet. An example Beta distribution spreadsheet is provided in Figure 514.8F-1.

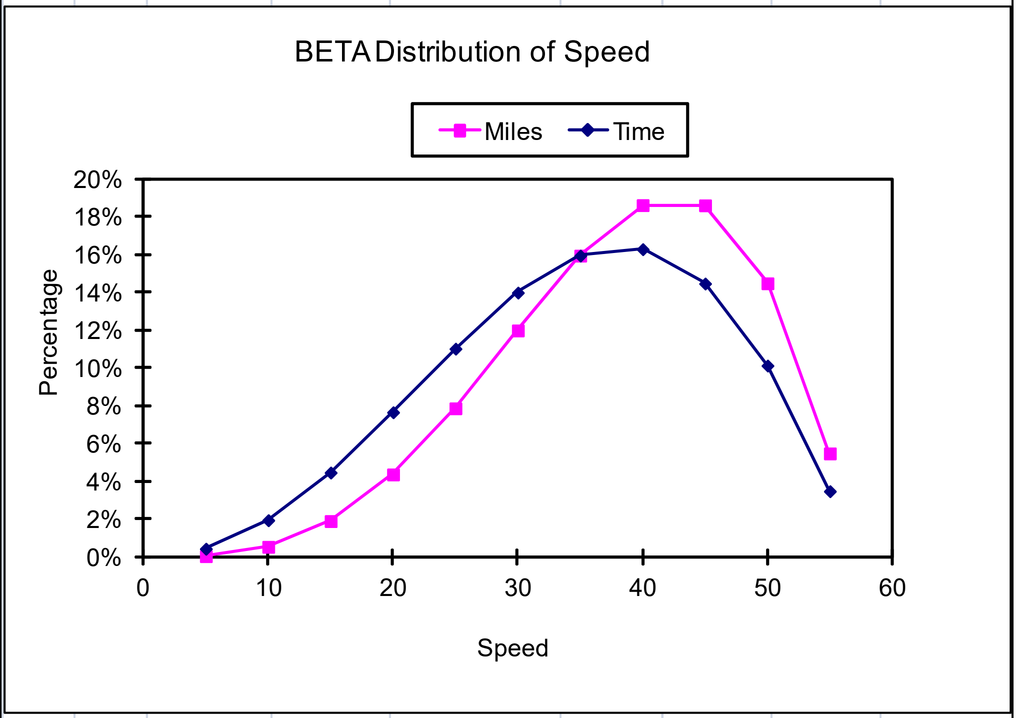
Table 514.8F-II: Selection of Alpha for Beta Distribution

Ratio of Avg to Max Speed	Alpha
10%	0.2
20%	0.5
30%	0.75
40%	1.25
50%	2
60%	3
70%	4
80%	6
90%	13



BETA DISTRIBUTION INPUTS	
SURFACE	Paved Road
MIN SPEED OF DATA SET	5
MAX SPEED OF DATA SET	55
AVG SPEED FROM SCENARIO	35
SPEED INCREMENT OF DATA SET	5
TOTAL MILES FROM SCENARIO	700.00
TOTAL HOURS	20.000
Ratio Avg/Max Speed	64%

CALCULATED RESULTS	
Dist Min Speed	0
Dist Max Speed	57.5
ALPHA	3.40
BETA	2.19
Average Speed	35.00
Total Miles	699.982
Total Hours	20.000
Error	**0.00%**



BETA DISTRIBUTION OF SPEED								
Repr Speed	Start Speed	End Speed	Range Avg	Percentage Time	Time in Hours	Time in Min.	Miles	Percentage Miles
n/a	0	2.5	1.25	0.012%	0.002	0.15	0.0031	0.00%
5	2.5	7.5	5	0.458%	0.092	5.50	0.46	0.07%
10	7.5	12.5	10	1.966%	0.393	23.59	3.93	0.56%
15	12.5	17.5	15	4.487%	0.897	53.84	13.46	1.92%
20	17.5	22.5	20	7.673%	1.535	92.08	30.69	4.38%
25	22.5	27.5	25	11.035%	2.207	132.42	55.18	7.88%
30	27.5	32.5	30	13.999%	2.800	167.99	84.00	12.00%
35	32.5	37.5	35	15.955%	3.191	191.46	111.68	15.95%
40	37.5	42.5	40	16.295%	3.259	195.54	130.36	18.62%
45	42.5	47.5	45	14.478%	2.896	173.74	130.31	18.62%
50	47.5	52.5	50	10.142%	2.028	121.71	101.42	14.49%
55	52.5	57.5	55	3.499%	0.700	41.99	38.49	5.50%
TOTAL				100.0%	20.000	1200.00	699.982	100.0%
TOTAL USED				100.0%	19.998	1199.85	699.979	100.0%

Figure 514.8F-1. Sample beta distribution (wheeled vehicle).

The Beta distribution calculations are performed in the "BETA DISTRIBUTION OF SPEED" table of Figure 514.8F-1. A description of the fields follows.

a. Repr Speed - The representative speed for this entry. This is the speed for which vibration data were acquired.

b. Start Speed – The beginning of the speed range for this entry.

c. End Speed – The ending of the speed range for this entry.

d. Range Average – The average of the speed range for this entry. This number should be equal to the representative speed for the entry.

e. Percentage Time – This is the actual Beta distribution as a percentage of the total drive time. This column, along with the Percentage Miles column, is plotted on the graph of Figure 514.8F-1.

f. Time in Hours – The time in hours represented by this data entry, calculated by multiplying the total hours by the percentages of the previous column. The total hours is calculated from the total miles and the average speed.

g. Time in Min. – The time in minutes represented by this data entry. This is the final output of the Beta distribution and is passed forward to the VSD process.

h. Miles – The miles represented by this data entry, calculated by multiplying the Time in Hours by the Range Average.

i. Percentage Miles – The percentage of the total miles represented by this entry. This column, along with the Percentage Time column, is plotted on the graph of Figure 514.8F-1.

Note that the widths (in units of speed) of each speed range in the table of Figure 514.8F-1 are equal to the speed increment for which data was acquired and are centered around the acquired speeds. This results in two slight inconsistencies at the endpoints of the Beta distribution. First, the percentage of the miles at very low speeds (below 2.5 mph in this example) is not included in the VSD process. It is expected that the vibration at these speeds will be quite low and have no effect on the resultant LVTS, even if included. Second, the maximum speed of the Beta distribution is one-half speed increment higher than the highest speed for which data was acquired. This too should have little effect on the VSD process since very little time is spent at this speed.

The endpoints of the Beta distribution technique are treated slightly different for NBROR or SOR LVTS. In those cases, the endpoints for Beta distribution are set to exactly the minimum and maximum speeds acquired. If the example presented here were for a tracked vehicle the range of the first entry would be from 5 to 7.5 mph instead of 2.5 to 7.5 mph. Likewise, the last entry would be from 42.5 to 45 mph instead of 42.5 to 47.5 mph. For a tracked vehicle the narrowband random sweeps dominate the fatigue exposure represented by an LVTS. The same is true for the swept sine LVTS. Therefore, more emphasis is placed on the sweep ranges when calculating the Beta distribution. The sweep ranges are bound by the frequencies associated with the minimum and maximum speeds acquired, and the Beta distribution ranges are selected to account for that. Note that the speed ranges of the endpoints are then one-half as wide as the intermediate points. This is accounted for in the VSD process when calculating the actual run time represented by each speed event. The run times of the first and last speeds are set to one half of the intermediate speeds. Note also that during testing on the shaker, the swept narrow bands are in the range of the endpoint speeds for one-half the time of the other speeds.

7.2 Aircraft.

The scenario for cargo and installed equipment transported by aircraft is generally measured in time rather than distance. The time begins with the standby-engine running phase and progresses through ascent, level flight, maneuvers, and ends with descent and landing. It is imperative that the scenario information for a given aircraft provides sufficient flight conditions to adequately describe the most severe vibration environment. For example, level flight should include a range of speeds between minimum and maximum in order to determine the most severe level flight condition. In addition, the number of flights must be known so that the laboratory test time can be determined.

Detailed scenario information is generally more readily available for aircraft than for ground vehicles in the form of usage spectrums. A usage spectrum is a tabulation of the percentage of flight time associated with all maneuvers relevant for the aircraft. This information feeds directly into the tables required for VSD. Generally, the only manipulation required is to combine the usage of the extensive list of maneuvers included in an aircraft's usage spectrum into the relatively few maneuvers for which data is typically acquired. During the data acquisition phase, it is typically not feasible to acquire data for all the maneuvers in an aircraft's usage spectrum. Engineering judgment is exercised when selecting a representative set of maneuvers for which data is acquired, although it is common practice to explore the limits of the allowable aircraft flight envelope (altitude, speed, angle of attack, throttle variations, acceleration etc.) plus enough information to allow extrapolation/interpolation to cover other events. Likewise, the flight time percentages of all maneuvers in the usage spectrum must be distributed into the maneuvers for which data was acquired. This analysis should rely on sources knowledgeable of aircraft usage to assist in scenario development.

7.3 Sea Vehicle.

Materiel installed aboard naval ships is subjected to varying frequencies and amplitudes of environmental vibration for extended periods of time, during which they are required to perform their normal function. Principal causes of steady state shipboard vibration are propeller blade excitation and unbalanced forces of the propeller and shafting. Vibrations are also experienced by shipboard mounted equipment caused by mounting system resonances, changes in ship speed and heading, and changes in sea state.

Equipment integrated onto a ship will generally have a much longer service life than that of cargo. For either case, one would expect the LCEP to consist of the number of hours at sea subdivided into various sea states. If an exact breakdown of sea states is not provided, an experienced analyst may take advantage of the Beta distribution techniques discussed in the previous section as a method of refining the LCEP.

7.4 Rail Transport.

Material installed on railcars is primarily subjected to low level broadband vibration affected primarily by the railcar speed. There are no surface considerations. If an exact breakdown of speeds is not provided, an experienced analyst may take advantage of the Beta distribution techniques discussed in the previous section as a method of refining the LCEP.

8. VSD ALTERNATIVES.

As discussed in Annex F, paragraph 4, data classifications for a VSD effort will be either sinusoidal, random, or a combination thereof. In the case of random data, there is an underlying assumption of stationarity and Gaussian probability density function characteristics. For cases in which the field data is clearly not stationary or not Gaussian, alternatives to the VSD techniques discussed in this document should be investigated. Techniques such as Time Waveform Replication (TWR), consists of the replication of either measured or analytically specified time trace(s) in the laboratory. TWR is a statistically non-parametric technique in which both spectral and temporal characteristics are preserved. For more information about TWR refer to Method 525.2.

9. VSD PROCEDURES.

9.1 VSD Considerations.

The VSD process will depend on several factors, including the vibration environment, system goals, value of the hardware, system fragility, test schedule constraints, test lab capabilities, and other considerations. Independent of the methods utilized, the results must define the vibration in laboratory testable terms and include a definition of the vibration levels and test exposure times.

The objective in the VSD effort outlined in Annex F, Appendix D, as opposed to a simple statistical combination of spectra exercise, is development of both a spectral reference and associated test time. As stated above in Annex F, paragraph 1, time compression techniques based on fatigue equivalency are typically employed such that vibration testing can be performed in a timely and economic manner. However, regardless of the VSD technique employed, one would expect the spectral shape of the final product to be similar to that of the field data used as the basis for the development. As a sanity check, one may wish to compare the spectral shape resulting from a VSD development to a basic statistical summary of the uncompressed reference data. Annex F, Appendix B provides a basic discussion on the topic of statistical combination of data that often proves useful in reviewing VSD spectral results. Annex F, Appendix C provides a discussion of combination of data from a Fatigue Damage Spectrum (FDS) perspective.

9.2 Engineering Data Common Across VSD Methods.

The Handbook for Dynamic Data Acquisition and Analysis (reference l) provides a wealth of signal analysis techniques and overall data acquisition guidance and is recommended as a key reference in the VSD process. A few of the most common analysis definitions utilized in VSD efforts are provided in Annex F, Appendix B.

9.2.1 Miner-Palmgren Hypothesis.

In the simplest terms, the Miner-Palmgren Hypothesis (Miner's rule) is a set of mathematical equations used to scale vibration spectra levels and their associated test times. It provides a convenient means to analyze fatigue damage resulting from cyclical stressing. Miner's rule, originally based on empirical data, establishes a relationship between the ratio of the number of cycles at a given stress level to the number of cycles at another stress level.

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 further increasing the 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. Conversely, overly extending test durations in order to excessively reduce the amplitude may result in the test article passing vibration testing in the laboratory but experience vibration related failures in the field.

While the use of Miner's rule is based upon fatigue damage being the principal failure mechanism, it has been found historically that test durations calculated by this means tend to be somewhat conservative when considering other failure mechanisms such as fretting and other types of wear. However, when considering the wide range of dynamic forcing functions considered over the life cycle of most hardware, test durations calculated using Miner's rule have proven to be generally acceptable regardless of the failure mechanism under consideration.

9.2.1.1 S/N Curve.

Graphically, the relationship of stress to number of cycles can be depicted as shown in Figure 514.8F-2. Figure 514.8F-2 relates stress (S) to the number of cycles (N) and is an example of a plot commonly referred to as the S/N curve. The black curve of Figure 514.8F-2 is the theoretical relationship of stress and the number of cycles. The red curve is a linearized representation of the black curve. Note that the number of cycles increases as the stress level decreases. At point A on the curve the stress level is so high that fatigue failure will result from any number of cycles. At point B on the curve, commonly referred to as the endurance limit, the stress level is so low that an infinite number of cycles will induce no fatigue damage. Between points A and B is the region of interest for Miner's rule calculations.

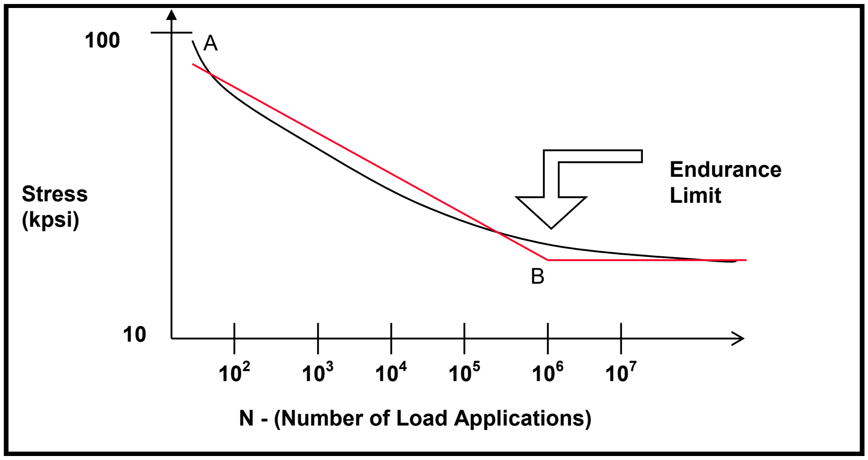


Figure 514.8F-2. S/N curve.

9.2.1.2 Miner-Palmgren Equations.

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 (9.1) and (9.5).

$$\frac{t_2}{t_1} = \left[\frac{S_1}{S_2}\right]^m \quad (9.1)$$

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.

In practice, vibration test amplitudes and durations need to be rescaled without knowledge of the original in-service condition (S_2). Equation 9.2 is the generalized relationship for rescaling sine tone test amplitudes based on the original time compression and new time compression.

$$S_{1new} = S_1\left(\frac{t_1 t_{2new}}{t_2 t_{1new}}\right)^{\frac{1}{m_S}} \quad (9.2)$$

where:

t_1= original test time

t_2= original in-service time used to develop test

S_1= original test levels

m_S = 6 (Historical materiel exponent for sinusoidal vibration, see Annex A, paragraph 2.2. The same material exponent value should be used when rescaling as used during the initial compression.)

t_{1new}= new test time

t_{2new}= new in-service time on LCEP

S_{1new}= rescaled test levels based on LCEP

Fatigue damage can be calculated using either a stress life or strain life process. Although most engineering structures are designed such that the nominal loads remain elastic, it is important to acknowledge that stress concentrations often cause plastic strains to develop in the vicinity of notches. Figure 514.8F-3 illustrates the total strain as a sum of plastic and elastic components of strain (reference o).

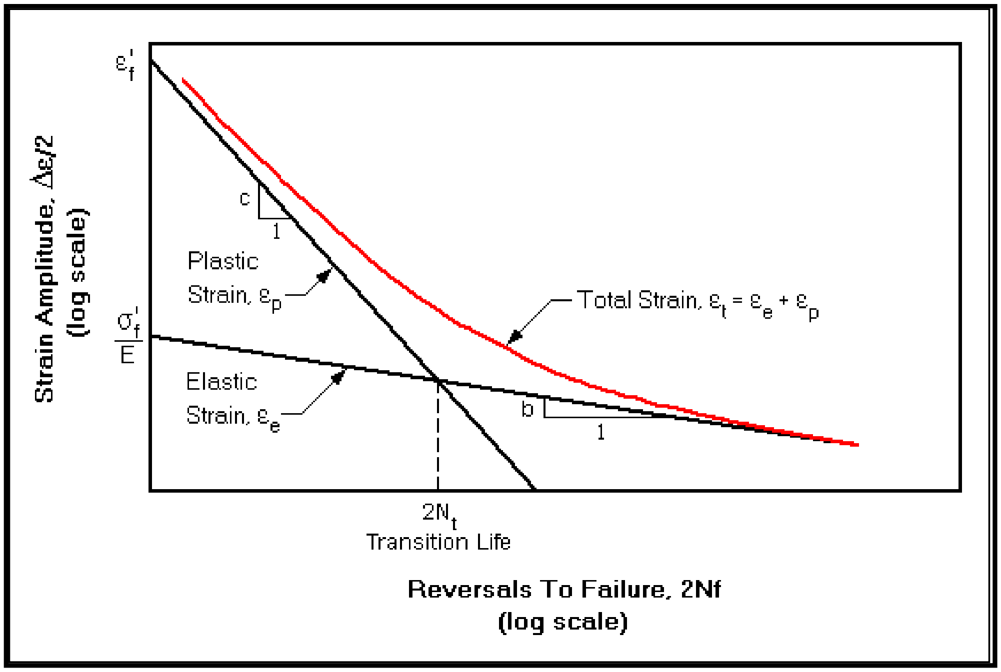


Figure 514.8F-3. Typical strain life curve.

For the strain life technique (assuming zero static load), the number of cycles to failure, N_f, is computed from:

$$\varepsilon_a = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \qquad (9.3)$$

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)

In equation 9.3, $\frac{\sigma'_f}{E}\left(2N_f\right)^b$, represents elastic components on the strain-life, while $\varepsilon'_f\left(2N_f\right)^c$, represents the plastic components. In the event a static load is present, Equation 9.3 may need to be compensated using techniques such as the Smith-Topper-Watson mean stress correction (reference n).

The transition life, $2N_t$, represents the life at which the elastic and plastic strain ranges are equivalent. The transition point of the two components of strain can be computed as:

$$2N_t = \left[\varepsilon'_f E / \sigma'_f\right]^{1/(b-c)} \tag{9.4}$$

As shown in Figure 514.8F-3, the transition life provides a convenient delineation between low and high-cycle fatigue. Plastic strains have greater influence below the transition life and Elastic strains have a greater influence above the transition life. For long fatigue lives, the strain-life approach will essentially approach the stress-life approach.

The value of m in Equation 9.1 is strongly influenced by the material S/N curve, but fatigue life is also influenced by the surface finish, the treatment, the effect of mean stress correction. Figure 514.8F-4 graphically depicts the effects of finishing options on SAE-8630 steel to illustrate influence of surface finish on parameter m.

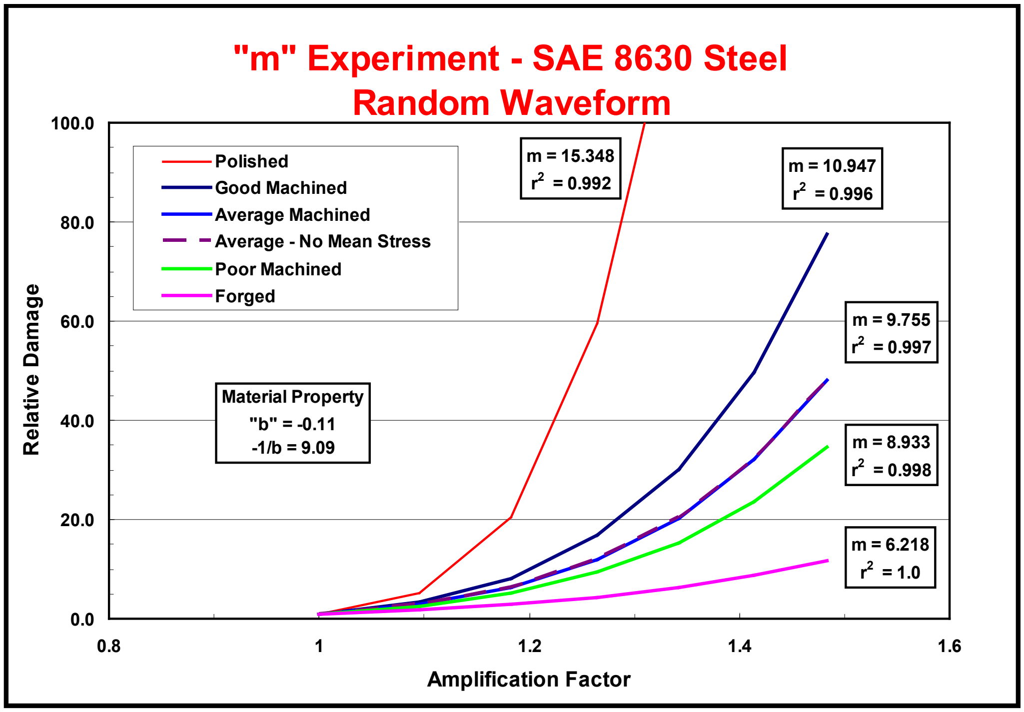


Figure 514.8F-4. Relative damage as a function of surface finish – SAE-8630 steel.

The combined contributions of elastic and plastic strain, and the waveshape of the strain time history, will also influence the value of m. Using SAE-8630 steel as an example, Figure 514.8F-5 graphically depicts the influence of the plastic component of strain on parameter m as strain levels approach the transition point.

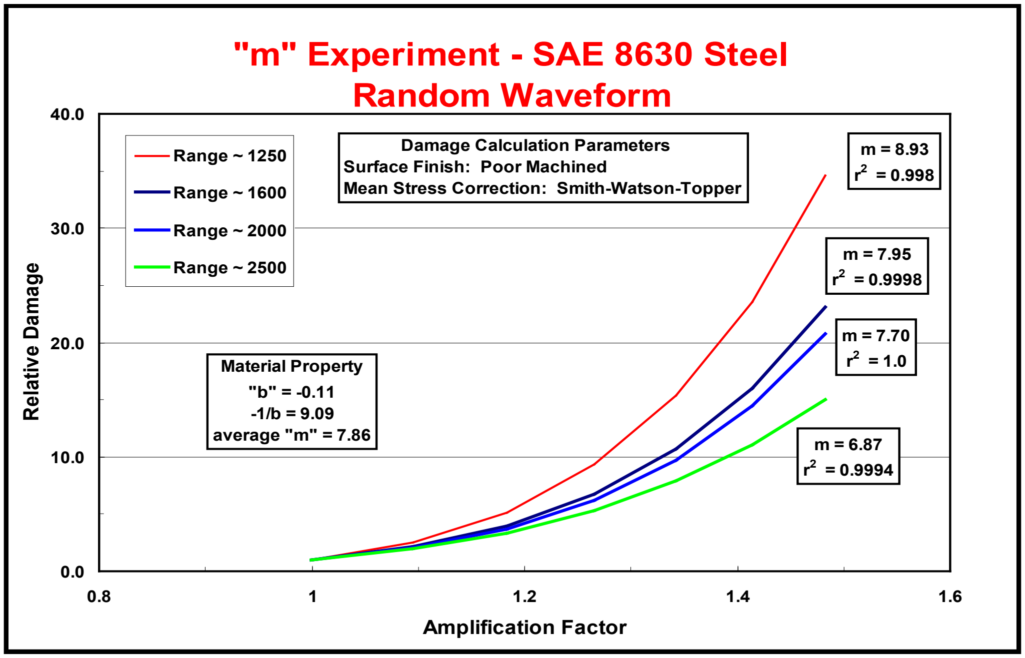


Figure 514.8F-5. Relative damage as a function of strain range – SAE-8630 steel.

As a result of multiple factors such as finishing and actual strain levels, 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 $1/b$ for random waveshapes, and 70 percent of $1/b$ for sinusoidal waveshapes.

Historically, values of *m* between 5 and 8 are commonly used when addressing random environments. A value in the range of 6 is commonly used for sinusoidal environments (references b, h and p).

The basis for the default recommendations in Table 514.8F-III may be traced to historical success of *m* selections within the range suggested in Table 514.8F-III, combined with investigating the properties of a wide range of steel and aluminum alloys as discussed in reference n. Reference n summarizes a strain analysis that was conducted on an ensemble of commonly used steels and aluminum alloys in which strain levels approaching the transition life were considered. Strain levels in the analytical investigation of reference n were controlled such that the minimum number of cycles to failure was generally greater than 10,000. Multiple finishing processes were considered as well. The default values in Table 514.8F-III have been separated into families of steel and aluminum alloys to add some fidelity in the selection of *m*. Observe that historical values of 5-8 fall within the range of *m* defined in Table 514.8F-III, providing an additional level of confidence between the historical values used for *m* and the recent analytical study of reference n.

Table 514.8F-III. Default Values for *m*

Excitation Type	*m* – (Default Value) (Steels)	*m* – (Default Value) (Aluminum Alloys)
Sinusoidal	**5.75**	**8.5**
Random	**7**	**9**

When addressing a LVTS for a simple test article whose design consists of a single material, one could simply look up the value of b directly, and compute *m* as a percentage (70-80 percent) of the inverse of b as discussed above. The difficulty common to most LVTS development efforts of complex systems is that more than one material comprises the system design. In such cases, default values for parameter *m* are recommended per Table 514.8F-III. If the exact composition of a complex structure is not known, it is recommended that the more conservative selections for *m* based on steel are selected.

The cumulative damage assumption is based on the fatigue properties of metals. The Shock and Vibration Handbook, chapter 35 (reference d), 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 (9.1) 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 auto spectral density function, Equation (9.1) can also be formulated as:

$$\frac{t_2}{t_1} = \left[\frac{W(f)_1}{W(f)_2}\right]^{\frac{m}{2}} \tag{9.5}$$

where:

t_1 = equivalent test time

t_2 = in-service time for specified condition

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

$W(f)_2$ = ASD 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 (9.1)

The ratio of $W(f)_2$ to $W(f)_1$ becomes the exaggeration factor. For factors greater than 1, the laboratory test time is reduced and conversely, for factors less than 1, the test time is increased.

In practice, vibration test amplitudes and durations need to be rescaled without knowledge of the original in-service condition $W(f)_2$. Equation 9.6 is the generalized relationship for rescaling the random broadband background based on the original time compression and the new time compression.

$$W(f)_{1new} = W(f)_1 \left(\frac{t_1 t_{2new}}{t_2 t_{1new}}\right)^{\frac{2}{m_R}} \tag{9.6}$$

where:

t_1= original test time

t_2= original in-service time

$W(f)_1$= original test levels

m_R = 7.5 (Historical materiel exponent for random vibration, see Annex A, paragraph 2.2. The same material exponent value should be used when rescaling as used during the initial compression.)

t_{1new}= new test time

t_{2new}= new in-service time

$W(f)_{1new}$= rescaled test levels based on LCEP

Selection of exponent *m* does not give complete freedom to the use of equations (9.1) and (9.5) in compressing test times! Caution must be exercised in using the exaggeration factor. It appears foolish to attempt to compress test time so that increased amplitude will exceed the yield or ultimate strength of the material. Reference h, suggests limiting the exaggeration of test levels so as not to exceed the ratio of ultimate strength to endurance strength of the material being tested. In an attempt to determine a value for the maximum exaggeration factor, a search was conducted of the mechanical properties of 25 metals that have been used most often in a large variety of test items (reference i).

The ratios of ultimate stress (U) to the elastic limit (Y) and ultimate stress (U) to the endurance limit (EN) were calculated for each of the metals and averaged, producing values of U/Y = 1.37 and U/EN = 2.78. These ratios were then averaged, producing a value of 2.08 (see Table 514.8F-IV). The value of 2 is therefore suggested as the maximum limit for exaggeration factors.

Table 514.8F-IV. Metals and Material Properties.

	ELASTIC LIMIT (Y)	ENDURANCE LIMIT (EN)	ULTIMATE (U)	RATIO (U/Y)	RATIO (U/EN)
Steel, 0.4% C, h. rolled	53	38	84	1.59	2.21
Steel, stainless (18-8) annealed	36	40	85	2.36	2.13
Steel, stainless (18-8) cold rolled	165	90	190	1.15	2.11
Alum, cast, 195T-6	24	7	36	1.33	5.14
Alum, wrought, 2014-T4	41	18	62	1.51	3.44
Alum, wrought, 2024-T4	48	18	68	1.42	3.78
Alum, wrought, 6061-T6	40	13.5	45	1.13	3.33
Magnesium, extrusion, AZ80X	35	19	49	1.40	2.58
Magnesium, sand cast, AZ63-HT	14	14	40	1.00	2.86
Monel, wrought, hot rolled	50	40	90	1.80	2.25
Steel, 1040	60	43	90	1.50	2.09
Steel, 1340	63	59	102	1.62	1.73
Steel, 4130	63	47	97	1.54	2.06
Steel, 4140	143	66	165	1.15	2.50
Steel, 4340	200	68	222	1.11	3.27
Steel, 5140	169	82	190	1.12	2.32
Steel, HY140	142	70	149	1.05	2.13
Steel, Marage 200	215	100	225	1.05	2.25
Steel, Marage 350	345	110	352	1.02	3.20
Alum, cast, 113	15	9	24	1.60	2.67
Alum, cast, 335, T61	35	10	39	1.11	3.90
Alum, cast, 224, T7	48	12	61	1.27	1.27
Alum, cast, A249, T7	50	11	60	1.20	5.46
Cast iron, malleable	33	28	58	1.76	2.07
Cast iron, ductile	55	30.5	80	1.46	2.62

Average U/Y = 1.37
Average U/EN = 2.78
Average $\frac{U/Y + U/EN}{2} = 2.08$

This approach is based upon a combination of experience and some valid assumptions. Experience has shown that equipment is designed so that its structural integrity lies above the endurance limit of the material because fatigue failures occur in the field. Items are not designed at the ultimate limit of the material, however, because these failures do not occur on the first vibration cycle.

Assuming that equipment is designed so that its structural characteristics lie somewhere in the midpoint region between the endurance and elastic limits (see Figure 514.8F-6), splitting the approximate difference would produce a value of 2 which thus lends credence to the use of 2 as the maximum exaggeration factor. The value of 2 as a maximum exaggeration factor applies to the definition of exaggeration factor of equation 9.1 above (S_1/S_2). It would follow that because the values in equation 9.5 (W_1/W_2) are squared values with respect the equation 9.1 that the maximum exaggeration factor of equation 9.5 would be 4. However in some cases large exaggeration factors can lead to controllability issues on vibration exciters.

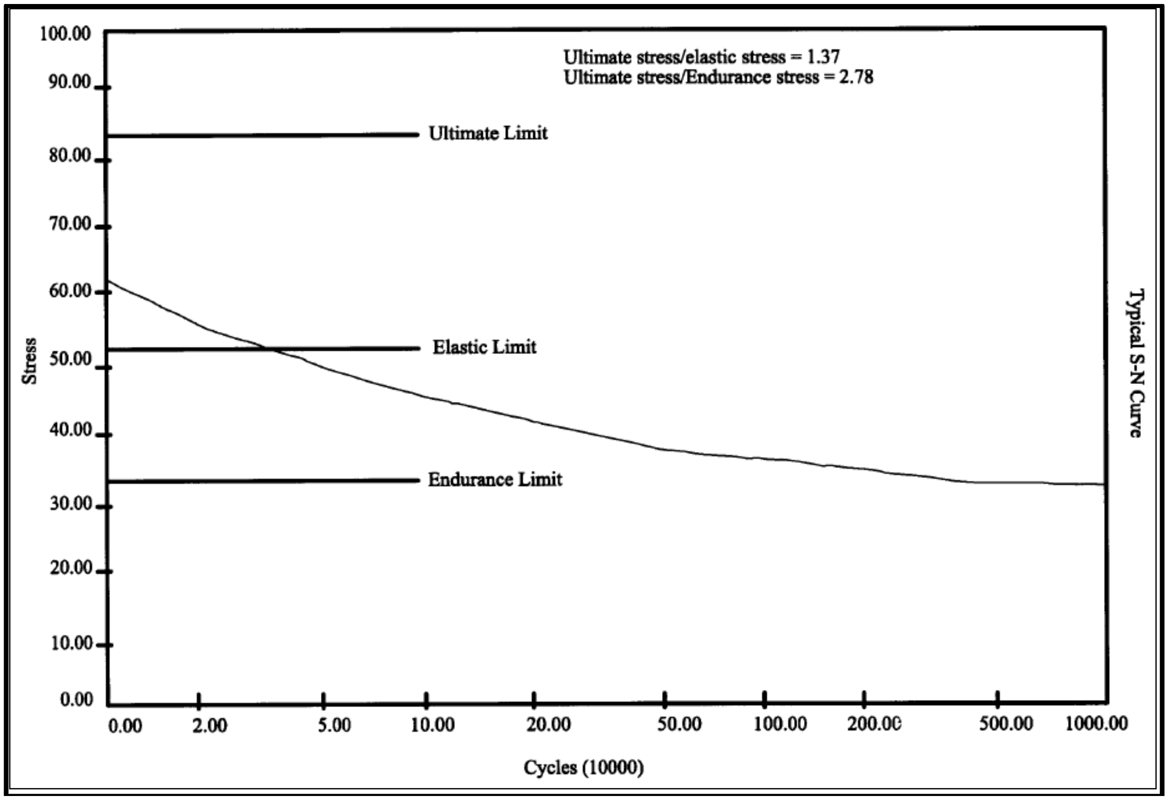


Figure 515.8F-6. Typical S/N curve.

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. However, when considering the wide range of dynamic forcing functions considered over the life cycle of most hardware, test durations calculated using Miner's rule have proven to be generally acceptable regardless of the failure mechanism under consideration.

Miner's rule, as with any analysis method, is not without its shortcomings. The text "Shock and Vibration Handbook", fourth Edition, C Harris, 1996, identifies two shortcomings. In reference to Miner's rule the text states, "… it does not consider the sequence of loading and assumes that damage in any individual stress cycle is independent of what has preceded it. Furthermore, it assumes that damage accumulation is independent of stress amplitude." However, the same text refers to Miner's rule as "the most commonly applied linear damage rule". Its acceptance in the vibration community certainly supports Harris's assertion. The use of Miner's rule for VSD is recommended by many national and international documents. However, care should be taken to assure that Miner's rule is applied properly and with an understanding of its limitations.

10. PREDICTIONS OF MAXIMUM RESPONSE.

Subsequent to development of the LVTS, it is generally of interest to analyze response dynamics of the unit under test (UUT) prior to conducting a laboratory test. In the absence of a detailed mechanical model of the UUT, one might consider use of the Maximum Response Spectrum (MRS) model. The basic concept of MRS analysis and defining mathematics are detailed in Annex F, Appendix E. In the event maximum response levels exceed design targets, it is recommended that a thorough review of both the LVTS variables and details of the design targets be conducted prior to initiating the laboratory test.

11. SUMMARY AND CONCLUSION.

LVTS development methods will continue to evolve. This evolution could result from improvements in vibration control systems, or from the results of on-going analysis studies. For example, the ability to simultaneously test in multiple axes, and the ability of modern control systems to account for non-Gaussian skewness and kurtosis will eventually affect LVTS development. The methods and procedures presented in this document are intended as guidelines, with the understanding that project specific tailoring may be required, and that new methods may be incorporated as they become available. Information on the development of multiple axis LVTS can be found in Method 527.2.

METHOD 514.8, ANNEX F, APPENDIX A
Preparation for VSD - Data Acquisition

1. INTRODUCTION.

VSD requires full characterization of system vibration exposure. The characterization typically includes a collection of vibration time histories of all relevant exposure conditions, and a table of exposure times for those conditions. This Appendix presents general information relative to the acquisition and preparation of the time histories, and the generation of the exposure time table (system scenario).

2. VEHICLE PREPARATION FOR DATA ACQUISITION - CARGO.

2.1 Specified Load: If the load and tie-down method are specified, no further instructions are necessary.

2.2 General Cargo Simulated Load: For general applications when loads and tie-down methods are not specified, choose typical cargo packages such as boxes, drums or cartons, designed to provide a simulated load that covers as much of the cargo bed as possible, consistent with the tie-down method. The cargo weight should be approximately 75 percent of the rated payload. This weight limitation is an arbitrary figure based on a study (reference j) in, which load weights were found to vary in the field enough to be unpredictable but tended toward full load. Another study revealed that the severity of the cargo bed vibration environment was minimal at full load and increased dramatically as the load decreased (reference k). The value of 75 percent of rated payload was chosen to provide a degree of conservatism. The analyst should consider the mission scenario carefully to establish the likelihood of lighter loads being carried. If unable to be reasonably sure that light loads will not be carried, some data capture should also be conducted using additional light load conditions and the VSD should utilize data from all load conditions considered.

Large rigid items such as steel plates, beams, concrete blocks, should not be used as simulated loads because their monolithic nature inhibits the flexibility of the cargo bed. In addition loose material such as sand or soil should not be placed directly on to the load bed as this will tend to dampen out any structural resonances present in the load floor.

2.3 Tie-down: The simulated load must be securely attached to the vehicle cargo bed using steel banding, web strapping, and/or dunnage. It must be secure enough to prevent movement between load and bed.

2.4 Accelerometers. Transducers must be mounted on the structural members of the cargo bed at locations that measure the input acceleration forces imparted to the load if an input control strategy is to be employed. If a response control strategy is planned then accelerometers should be mounted on structurally stiff locations at the base of the package or items being transported. The number of locations must be sufficient to describe the cargo bed environment. Care should be taken to avoid placing accelerometers in inappropriate places, i.e., the relatively thin steel plate that comprises most cargo bed surfaces.

3. VEHICLE PREPARATION FOR DATA ACQUISITION - INSTALLED EQUIPMENT.

Accelerometers must be mounted on the vehicle walls, deck, and roof, as well as on brackets and shelves that are integral parts of the vehicle, as close as possible to the point(s) of attachment of the existing/planned installed equipment. The purpose is to measure the vibration environment of the vehicle at the input location(s) of the installed equipment which has the same configuration as the equipment subsequently used as a test item during laboratory testing. For instance, if a piece of equipment is mounted on a bracket in the vehicle and that bracket will not appear as part of the equipment during subsequent laboratory testing, the environment should be measured on the bracket as the input to the equipment.

If a mounting platform exists and the equipment to be installed thereon is not available, use a model of the equipment with the same mass and center of gravity. This ensures that the reaction of the installed equipment will be included in the data recorded at the input to the mounting platform.

In the situation in which the test item is instrumented and may be integrated into the control scheme as such as response control or possibly as a limit location, it is critical that any surrogate hardware employed must have strong dynamic similarity to the tactical hardware. It is recommended that a comprehensive modal test of the surrogate hardware be conducted to ensure proper dynamic response is maintained. In some instances, similarity acceptance criteria may be called out, to which the modal parameters of the surrogate hardware must comply.

The difference between the mechanical impedances of mountings for field-installed and laboratory-installed equipment should be considered, particularly for relatively massive equipment. A comparison of the field and laboratory frequency response functions is one method of evaluating this difference, and the use of average, extreme, or response laboratory vibration control techniques is considered a valid approach to minimizing any impedance mismatch.

4. DATA ACQUISITION PROCEDURE.

4.1 Data Acquisition.

There are several commercially available data acquisition systems that are capable of measuring and recording vibration data that would be suitable for VSD. The user needs to insure that the signal conditioning including the filter, sample rate and analog-to-digital converter (ADC) fidelity are acceptable for the measurements being made. For example an 8-pole (48 dB/octave, 160 dB/decade) Butterworth filter would require a sample rate of approximately four times the filter frequency to minimize aliasing.

4.2 Cargo Schedules.

a. Attach tri-axial accelerometers to the structural members of the cargo bed in order to measure the vibration environment along three mutually perpendicular axes usually noted as vertical (V), transverse (T), and longitudinal (L). Normally, this orientation is relative to the axes of the vehicle, i.e., vertical is up/down, transverse is side/side, and longitudinal is front/rear. This is not mandatory but tends to be least confusing.

b. Check tie-down.

c. Insure that instrumentation is working properly and all transducers are calibrated.

d. Operate the vehicle at the prescribed speed(s) over the designated fixed profile courses, and record the data.

4.3 Installed Equipment Schedules.

a. Attach tri-axial accelerometers at the actual or proposed vehicle/installed equipment interface to measure input to the equipment as it will subsequently appear as a test item in the laboratory. Orient the accelerometers to measure data in the V, T, and L axes as described in paragraph 4.2 above.

b. Insure that instrumentation is working properly and all transducers are calibrated.

c. Operate the vehicle at the prescribed speed(s) over the designated fixed profile courses, and record the data.

5. DATA REQUIRED.

Care must be taken when recording data to ensure that it can be correlated with data taken during previous tests of the same type of vehicle. Parameters such as sampling rate and filtering will affect the ability to compare/combine environments during analysis. The analysis filter bandwidth is particularly important and must be recorded. Comparing/combining different data sets must be done using the same analysis filter bandwidth. Obtain the following:

a. An accurate log of accelerometer locations and axis orientations.

b. An accurate log of test courses and speeds.

c. Recorded data in terms of acceleration amplitudes versus time for time intervals sufficient to ensure accurate analysis.

d. Graphic representation of the cargo load/installed equipment mounting configuration.

e. Filter type and cut-off frequency and data sampling rates.

After the data have been acquired it is necessary to insure that the data accurately represent the physical phenomenon that was measured. This can be accomplished by inspecting the data visually and by performing amplitude distributions and other time and frequency domain statistical analysis. There are certain anomalies that need to be identified and corrected before the data can be considered valid. These include but are not limited to outliers (wild points) and shifts in the bias level of a transducer (DC shifts).

Thorough documentation is absolutely critical in all phases of the LVTS development process. During the data acquisition phase, a general list of resources such as vehicle specific serial numbers, identification of all instrumented assets, transducers, data recorders, filters, and software employed shall be included as part of the final report in all

VSD efforts. A detailed calibration list shall be included for all transducers and signal analysis equipment employed during the data acquisition phase. All user defined parameters such as sampling frequency and filter settings shall also be recorded.

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METHOD 514.8, ANNEX F, APPENDIX B
Combination of Spectra (Statistical)

1. COMBINING SPECTRA.

This Appendix provides basic definitions and purely statistical approaches for combining spectra. The techniques discussed in this Appendix, combined with addressing mission scenarios and fatigue equivalence, formulate the basis for the VSD techniques that are discussed in Annex F, Appendixes C and D.

After the scenario is selected and representative data are acquired, it is usually necessary to combine appropriate data into a single descriptor of the environment. For Single-Degree-of-Freedom (SDOF) vibration testing, this descriptor is generally the auto spectral density (ASD) function, a frequency based representation of the measured vibration amplitudes. Multiple-Degree-of-Freedom (MDOF) vibration testing will also require knowledge of the Cross Spectral Density (CSD) properties of motion. Although basic CSD definitions will be discussed, the MDOF VSD case will not be addressed in this Appendix. For further discussion of MDOF techniques refer to Method 527.2.

1.1 Auto and Cross Spectral Densities.

Consider the following basic scalar definitions as presented by Bendat and Piersol (reference e). The discussions assume two stationary (ergodic) Gaussian random processes, $\{x(t)\}$ and $\{y(t)\}$. The finite Fourier Transforms of $\{x(t)\}$ and $\{y(t)\}$ are defined as:

$$X(f) = X(f,T) = \int_0^T x(t)\, e^{-j2\pi f t} dt$$
$$Y(f) = Y(f,T) = \int_0^T y(t)\, e^{-j2\pi f t} dt$$

The auto, $G_{xx}(f)$, $G_{yy}(f)$, and cross, $G_{xy}(f)$, spectral densities of $x(t)$and $y(t)$ for an "unlimited time" length T are defined respectively as:

$$G_{xx}(f) = 2 \lim_{T\to\infty} \frac{1}{T} E[|X(f,T)|^2]$$

$$G_{yy}(f) = 2 \lim_{T\to\infty} \frac{1}{T} E[|Y(f,T)|^2]$$

$$G_{xy}(f) = 2 \lim_{T\to\infty} \frac{1}{T} E[X^*(f)Y(f)]$$

Estimates of $G_{xx}(f)$, $G_{yy}(f)$ and $G_{xy}(f)$ as computed over a "finite time" interval are defined as:

$$\tilde{G}_{xx}(f) = \frac{2}{T}[|X(f,T)|^2]$$

$$\tilde{G}_{yy}(f) = \frac{2}{T}[|Y(f,T)|^2]$$

$$\tilde{G}_{xy}(f) = \frac{2}{T}[X^*(f)Y(f)]$$

and will have a discrete spectral resolution of $B_e \approx \Delta f = \frac{1}{T}$. There will generally be unacceptably large random error associated with this "raw" estimate. In practice the random error is reduced, by computing n_d different averages of length T to obtain a "smooth" estimate defined as:

$$\hat{G}_{xx}(f) = \frac{2}{n_d T} \sum_{i=1}^{n_d} \left[\left| X_i\left(f, T\right) \right|^2 \right]$$
$$\hat{G}_{yy}(f) = \frac{2}{n_d T} \sum_{i=1}^{n_d} \left[\left| Y_i\left(f, T\right) \right|^2 \right] \qquad \text{B.1}$$
$$\hat{G}_{xy}(f) = \frac{2}{n_d T} \sum_{i=1}^{n_d} \left[X_i^*\left(f\right) Y_i\left(f\right) \right]$$

In practice, one will also have to consider the effects of overlapping and windowing options.

1.2 Confidence Interval of ASD Estimates.

During the data collection phase of a VSD effort, every effort will be made to acquire a sufficiently long record of field data to ensure an accurate estimate of the ASD and CSD. In reality, it is not always possible to acquire sufficiently long time histories as to minimize error in the spectral estimates of interest. Given that the number of averages n_d is not a constant for all measurements, one should track the error associated with spectral estimates as they are the basis for the VSD procedures that are the interest of this annex.

As shown in reference e, the sampling distribution for an ASD estimate may be written in terms of the Chi squared distribution as:

$$\frac{\hat{G}_{xx}\left(f\right)}{G_{xx}\left(f\right)} = \frac{\chi_n^2}{n} \qquad n = 2n_d$$

Observe that the number of degrees of freedom $n = 2n_d$ results from the fact that each instantaneous estimate of the complex number $X\left(f\right)$ consists of statistically independent real and imaginary components.

Statistical confidence bands can be placed around this estimate of $G_{xx}\left(f\right)$ as:

$$\frac{n\hat{G}_{xx}\left(f\right)}{\chi^2_{n;\frac{\alpha}{2}}} \le G_{xx}\left(f\right) \le \frac{n\hat{G}_{xx}\left(f\right)}{\chi^2_{n;1-\frac{\alpha}{2}}} \qquad \text{B.2}$$

where: α defines the confidence interval (i.e., for a 90 percent confidence interval α =.1)

Observe that the confidence intervals are strictly related to the accuracy of estimate of $G_{xx}\left(f\right)$ and in no manner addresses the scatter within individual spectral bins of the individual averages used to compute $\hat{G}_{xx}\left(f\right)$.

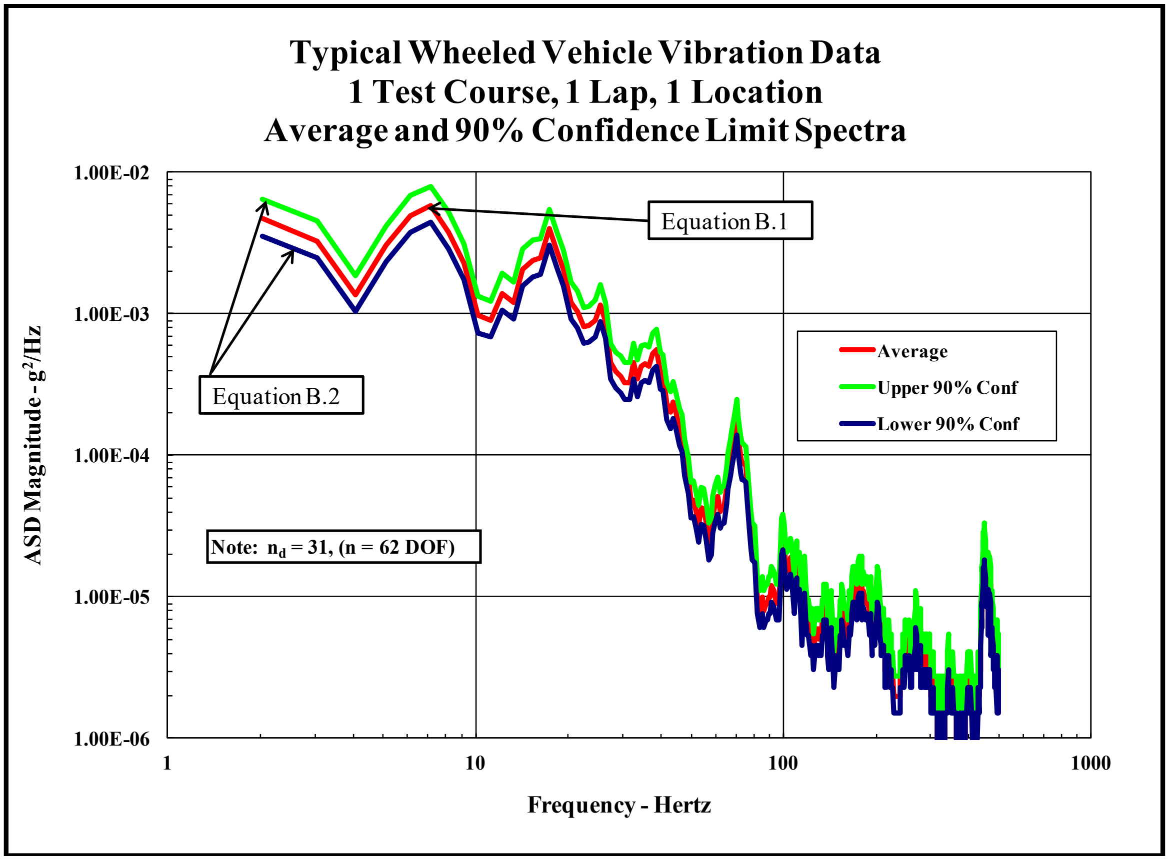


Figure 514.8F-B.1. 90-percent confidence limits for n_d = 31 linear spectral averages.

2. STATISTICAL CONSIDERATIONS FOR DEVELOPING LIMITS ON AN ENSEMBLE OF DATA.

This paragraph provides information relative to the statistical characterization of a set of data for the purpose of defining an upper limit of the data set related to statistical/probabilistic considerations. This section is based on the summary of work in reference g and is summarized in Method 516.8, Annex B.

Information in this paragraph is generally applicable to frequency domain estimates that are either predicted based on given information or time domain measurements processed in the frequency domain according to an appropriate technique i.e., for stationary random vibration, the processing would be an ASD; for a very short transient the processing could be a Shock Response Spectrum (SRS) , an Energy Spectral Density (ESD), or a Fourier Spectrum (FS). Given estimates in the frequency domain, information in this Appendix will allow the establishment of upper limits of the data in a statistically correct way.

2.1 Basic Estimate Assumptions.

Prediction estimates, measurement estimates, or a combination of prediction and measurement estimates may be considered in the same manner. It is assumed that uncertainty in individual measurements (processing error) does not affect the limit considerations. For measured field data digitally processed such that estimates of the SRS, ESD, FS, or ASD are obtained for single sample records, it is useful to examine and summarize the overall statistics of "similar" estimates selected in a way so as to not bias the summary statistics. To ensure the estimates are not biased, the measurement locations might be chosen randomly, consistent with the measurement objectives. Similar estimates may be defined as (1) estimates at a single location on materiel that has been obtained from repeated testing under essentially identical experimental conditions; (2) estimates on a system that have been obtained from one test, where the estimates are taken (a) at several neighboring locations displaying a degree of response homogeneity or (b) in "zones" i.e., points of similar response at varying locations; or (3) some combination of (1) and (2). In any case, it is assumed that there is a certain degree of homogeneity among the estimates across the frequency band of interest. This latter assumption generally requires that (1) the set of estimates for a given frequency have no significant "outliers" that can cause large sample variance estimates, and (2) larger input stimulus to the system from which the measurements are taken implies larger estimate values.

2.2 Basic Estimate Summary Preprocessing.

There are two ways in which summaries may be obtained. The first way is to use an "enveloping" scheme on the basic estimates to arrive at a conservative estimate of the environment, and some qualitative estimate of the spread of basic estimates relative to this envelope. This procedure is dependent upon the judgment of the analyst and, in general, does not provide consistent results among analysts. The second way is to combine the basic estimates in some statistically appropriate way and infer the statistical significance of the estimates based upon probability distribution theory. Reference g summarizes the current state of knowledge relative to this approach and its relationship to determining upper limits on sets of data. In general, the estimates referred to and their statistics are related to the same frequency band over which the processing takes place. Unfortunately, for a given frequency band, the statistics behind the overall set of estimates are not easily accessible because of the unknown distribution function of amplitudes for the frequency band of interest. In most cases the distribution function can be assumed to be normal, provided the individual estimates are transformed to a "normalizing" form by computing the logarithm to the base ten of the estimates. For ESD and FS estimates, the averaging of adjacent components (assumed to be statistically independent) increases the number of degrees of freedom in the estimates while decreasing the frequency resolution with the possible introduction of statistical bias in the estimates. For ASD estimates, averaging of adjacent components can be useful provided the bias error in the estimate is small; i.e., the resolution filter bandwidth is a very small fraction of the overall estimate bandwidth. For SRS estimates, because they are based on maximum response of a single-degree-of-freedom system as its natural frequency is varied, adjacent estimates tend to be statistically dependent and, therefore, not well smoothed by averaging unless the SRS is computed for very narrow frequency spacing. In such cases, smoothing of SRS estimates is better accomplished by reprocessing the original time history data at a broader natural frequency spacing, e.g., 1/6th octave as opposed to 1/12th octave. There is no apparent way to smooth dependent SRS estimates mathematically when reprocessing cannot be performed, and the acceptable alternative is some form of enveloping of the estimates. The larger the sample size, the closer the logarithm transform of the estimates is to the normal distribution unless there is a measurement selection bias error in the experiment. Finally, generally, before application, the upper limits obtained in the paragraphs to follow are smoothed by straight line segments intersecting at spectrum "breakpoints." No guidance is provided in this appendix relative to this "smoothing" or "enveloping" procedure, e.g., whether estimates should be clipped or enveloped and the relationship of the bandwidth of the estimates to the degree of clipping, etc., except that such smoothing should be performed only by an experienced analyst. Reference g discusses this further.

2.3 Parametric Upper Limit Statistical Estimate Assumptions.

In all the formulas for the estimate of the statistical upper limit of a set of N predictions or measurements,

$$\left\{x_1, x_2, \cdots, x_N\right\}$$

it is assumed that (1) the estimates will be logarithm transformed to bring the overall set of measurements closer to those sampled of a normal distribution and (2) the measurement selection bias error is negligible. Since the normal and "t" distribution are symmetric, the formulas below apply for the lower bound by changing the sign between the mean and the standard deviation quantity to minus. It is assumed here that all estimates are at a single frequency or for a single bandwidth, and that estimates among bandwidths are independent so that each bandwidth under consideration may be processed individually, and the results summarized on one plot over the entire bandwidth as a function of frequency. For

$$y_i = \log_{10}\left(x_i\right) \quad i = 1, 2, \cdots N$$

Mean estimate for true mean, μ_y is given by

$$\mu_y = \frac{1}{N}\sum_{i=1}^{N} y_i$$

and the unbiased estimate of the standard deviation for the true standard deviation σ_y is given by

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^{N}\left(y_i - \mu_y\right)^2}{N-1}}$$

2.3.1 NTL - Upper Normal One-Sided Tolerance Limit.

The upper normal one-sided tolerance limit on the proportion β of population values that will be exceeded with a confidence coefficient, γ , is given by $NTL\left(N,\beta,\gamma\right)$, where

$$NTL\left(N,\beta,\gamma\right) = 10^{\mu_y + \sigma_y k_{N,\beta,\gamma}}$$

where $k_{N,\beta,\gamma}$ is the one-sided normal tolerance factor given in Table 514.8F-B.I for selected values of $N, \beta,$ and γ . NTL is termed the upper one-sided normal tolerance interval (of the original set of estimates) for which 100β percent of the values will lie below the limit with 100γ percent confidence. For β = 0.95 and γ = 0.50, this is referred to as the 95/50 limit.

The following table from reference g, contains the k value for selected $N, \beta,$ and γ . In general this method of estimation should not be used for small N with values of β and γ close to 1 since it is likely the assumption of the normality of the logarithm transform of the estimates will be violated.

Table 514.8F-B.I. Normal Tolerance Factors for Upper Tolerance Limit.

N	γ = 0.50			γ = 0.90			γ = 0.95		
	β = 0.90	β = 0.95	β = 0.99	β = 0.90	β = 0.95	β = 0.99	β = 0.90	β = 0.95	β = 0.99
3	1.50	1.94	2.76	4.26	5.31	7.34	6.16	7.66	10.55
4	1.42	1.83	2.60	3.19	3.96	5.44	4.16	5.14	7.04
5	1.38	1.78	2.53	2.74	3.40	4.67	3.41	4.20	5.74
6	1.36	1.75	2.48	2.49	3.09	4.24	3.01	3.71	5.06
7	1.35	1.73	2.46	2.33	2.89	3.97	2.76	3.40	4.64
8	1.34	1.72	2.44	2.22	2.76	3.78	2.58	3.19	4.35
9	1.33	1.71	2.42	2.13	2.65	3.64	2.45	3.03	4.14
10	1.32	1.70	2.41	2.06	2.57	3.53	2.36	2.91	3.98
12	1.32	1.69	2.40	1.97	2.45	3.37	2.21	2.74	3.75
14	1.31	1.68	2.39	1.90	2.36	3.26	2.11	2.61	3.58
16	1.31	1.68	2.38	1.84	2.30	3.17	2.03	2.52	3.46
18	1.30	1.67	2.37	1.80	2.25	3.11	1.97	2.45	3.37
20	1.30	1.67	2.37	1.76	2.21	3.05	1.93	2.40	3.30
25	1.30	1.67	2.36	1.70	2.13	2.95	1.84	2.29	3.16
30	1.29	1.66	2.35	1.66	2.08	2.88	1.78	2.22	3.06
35	1.29	1.66	2.35	1.62	2.04	2.83	1.73	2.17	2.99
40	1.29	1.66	2.35	1.60	2.01	2.79	1.70	2.13	2.94
50	1.29	1.65	2.34	1.56	1.96	2.74	1.65	2.06	2.86
∞	1.28	1.64	2.33	1.28	1.64	2.33	1.28	1.64	2.33

2.3.2 NPL - Upper Normal Prediction Limit.

The upper normal prediction limit is the value of x (for the original data set) that will exceed the next predicted or measured value with confidence coefficient, γ, and is given by

$$NPL(N,\gamma) = 10^{\mu_y + \sigma_y \sqrt{1+\frac{1}{N}}\, t_{N-1;\alpha}}$$

where $\alpha = 1-\gamma$ and $t_{N-1;\alpha}$ is the student t distribution variable with $N-1$ degrees of freedom at the $100\alpha = 100(1-\gamma)$ percentage point of the distribution. This estimate, because of the assumptions behind its derivation, requires careful interpretation relative to measurements made in a given location or over a given zone (reference g).

2.4 Nonparametric Upper Limit Statistical Estimate Assumptions.

If there is some reason to believe that the data, after it has been logarithm-transformed, will not be sufficiently normally distributed to apply the parametric limits defined above, consideration must be given to nonparametric limits, i.e., limits that are not dependent upon assumptions concerning the distribution of estimate values. In this case there is no need to transform the data estimates. All of the assumptions concerning the selection of estimates are applicable for nonparametric estimates. With additional manipulation, lower bound limits may be computed.

2.4.1 ENV – Upper Limit.

The maximum upper limit is determined by selecting the maximum estimate value in the data set.

$$ENV(N) = \max\{x_1, x_2, \cdots x_N\}$$

The main disadvantage of this estimate is that the distributional properties of the estimate set are neglected so that no probability of exceedance of this value is specified. In the case of outliers in the estimate set, $ENV(N)$ may be far too conservative. $ENV(N)$ is also sensitive to the bandwidth of the estimates.

2.5 DFL – Upper Distribution-Free Tolerance Limit.

The distribution-free tolerance limit that uses the original untransformed sample values is defined to be the upper limit for which at least the fraction β of all sample values will be less than the maximum predicted or measured value with a confidence coefficient of " γ ". This limit is based on order statistic considerations.

$$DFL(N,\beta,\gamma) = x_{\max}; \gamma = 1 - \beta^N$$

where $x_{\max}$ is the maximum value of the set of estimates, β, is the fractional proportion below $x_{\max}$, and γ is the confidence coefficient. $N, \beta,$ and γ are not independently selectable. That is

(1) Given N and assuming a value of β, $0 \le \beta \le 1$, the confidence coefficient can be determined.

(2) Given N and γ, the proportion β can be determined.

(3) Given β and γ, the number of samples can be determined such that the proportion and confidence can be satisfied (for statistical experiment design).

$DFL(N,\beta,\gamma)$ may not be meaningful for small samples of data, $N \le 13$, and comparatively large β, $\beta > .95$. $DFL(N,\beta,\gamma)$ is sensitive to the estimate bandwidth.

2.6 ETL – Upper Empirical Tolerance Limit.

The empirical tolerance limit uses the original sample values and assumes the predicted or measured estimate set is composed of N measurement points over M frequency resolution bandwidths for a total of NM estimate values. That is

$$\{x_{11}, x_{12}, \cdots x_{1M}; x_{21}, x_{22}, \cdots x_{2M}; x_{N1}, x_{N2}, \cdots x_{NM}\}$$

where m_j is the average estimate at the j^{th} frequency bandwidth over all N measurement points

$$m_j = \frac{1}{N}\sum_{i=1}^{N} x_{ij} \quad j = 1, 2, \cdots M$$

m_j is used to construct an estimate set normalized over individual frequency resolution bandwidths. That is

$$\{u\} = \{u_{11}, u_{12}, \cdots u_{1M}; u_{21}, u_{22}, \cdots u_{2M}; u_{N1}, u_{N2}, \cdots u_{NM}\}$$

$$\text{where : } \quad u_{ij} = \frac{x_{ij}}{m_j} \quad i = 1, 2, \cdots N; \quad j = 1, 2, \cdots, M$$

The normalized estimate set, $\{u\}$, is ordered from smallest to largest and

$u_\beta = u_{(k)}$ where $u_{(k)}$ is the k^{th} ordered element of set $\{u\}$ for $0 < \beta = \dfrac{k}{MN} \le 1$

is defined. For each resolution frequency bandwidth, then

$$ETL(\beta) = u_\beta m_j = x_{\beta j} \quad j = 1, 2, \cdots M$$

Using m_j implies that the value of $ETL(\beta)$ at j exceeds β percent of the values with 50 percent confidence. If a value other than m_j is selected, the confidence level may increase. It is important that the set of estimates is homogeneous to use this limit, i.e., they have about the same spread in all frequency bands. In general, apply this limit only if the number of measurement points, N, is greater than 10.

2.7 Example from Measured Data.

An example consisting of typical wheeled vehicle data (4 test courses, 3 data runs, 2 locations) is considered. The ensemble consists of a total of 24 average ASD measurements. The normal tolerance limit (NTL) of the 24 item ensemble (without being logarithm transformed) was computed as, $NTL(N,\beta,\gamma) = \mu + k\sigma$ as described in paragraph 2.4, and is illustrated in Figure 514.8F-B.2. For this example, $\beta = .95$ and $\gamma = .75$ were selected, yielding a value of $k = 1.91$ interpolated from Table 514.8F-B.I.

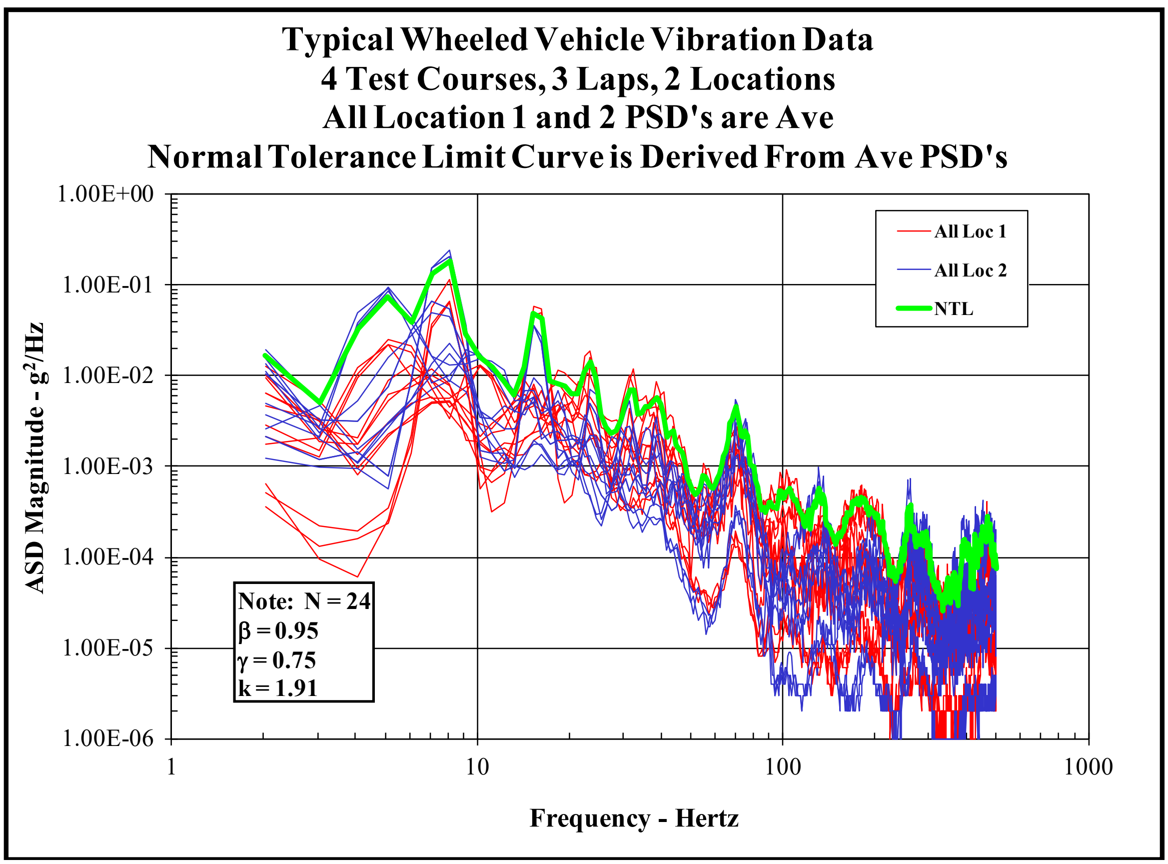


Figure 514.8F-B.2. Example normal tolerance limit applied to typical wheeled vehicle data.

3. COMMON ANALYSIS FUNCTIONS AND STATISTICAL DEFINITIONS OF VSD DATA ENSEMBLES.

In preparation for a VSD effort, vibration time histories are recorded for a series of test conditions (defined as “events” in Annex F, paragraph 3) also referred to as "runs". An event is defined (for ground vehicles) as operation over a specific uniform terrain, for a specific test item configuration (load, tire pressure, etc.) at a constant speed. For an aircraft, one may have a list of events defined in terms of various modes of flight (level flight, rolling maneuvers, etc.) conducted at various airspeeds. A common form of analysis involves converting the complete time history (of a particular channel) into the compressed frequency domain format of the ASD function by dividing the time history into equal length data blocks and computing the ASD for each of the data blocks independently. When combining spectra, it is assumed that the spectra being combined represent a homogeneous set. (i.e., overall spectral levels are comparable and the spectra have the same general shape). If this is not the case, combining spectra should be avoided and another "spectra category" should be added to represent the test condition. When computing estimates of these ASD functions, it is desirable to compute the linear average (assuming the number of samples is sufficiently large (n_d >30), the standard deviation and the peak, all as a function of frequency, over the length of a test run. The standard deviation represents the variation in the spectral data, as a function of frequency, at a given location on the vehicle due to randomness of the test process. Although the data are stationary, excursions about the mean occur in both the time and frequency domains.

In addition to computing the mean ASD of an individual event, the standard deviation, and peak versions of the ASD are often of interest. For ease of illustration, the following symbolic structure will be employed:

$$G_m\left(f\right) = \text{ASD(mean)} = \hat{G}_{xx}\left(f\right) \qquad \text{B.3}$$

$G_i\left(f\right)$ = ASD(instantaneous) ASD computed over a single time interval T

$$G_d\left(f\right) = \text{ASD(Standard Deviation)} = G_d\left(f\right) = \left[\frac{1}{n_d-1}\sum_{i=1}^{n_d}\left(G_i\left(f\right)-G_m\left(f\right)\right)^2\right]^{\frac{1}{2}}$$

$$G_s\left(f\right) = \text{ASD(Sum)} = G_m\left(f\right)+G_d\left(f\right) \qquad \text{B.4}$$

$$G_p\left(f\right) = \text{ASD(Peak)} = MAX_{i=1}^{i=n_d}\left[G_i\left(f\right)\right] \qquad \text{B.5}$$

Note that, statistically speaking, the normalized error for the (Peak) spectrum could be very high because of the limited number of degrees of freedom available from the peak values of $G_i\left(f\right)$. This spectrum is a maxi-max auto spectral density estimate and should be used with caution (if at all). An example generation of the spectra discussed above as computed from data acquired from a typical wheeled vehicle data is shown in Figure 514.8F-B.3.

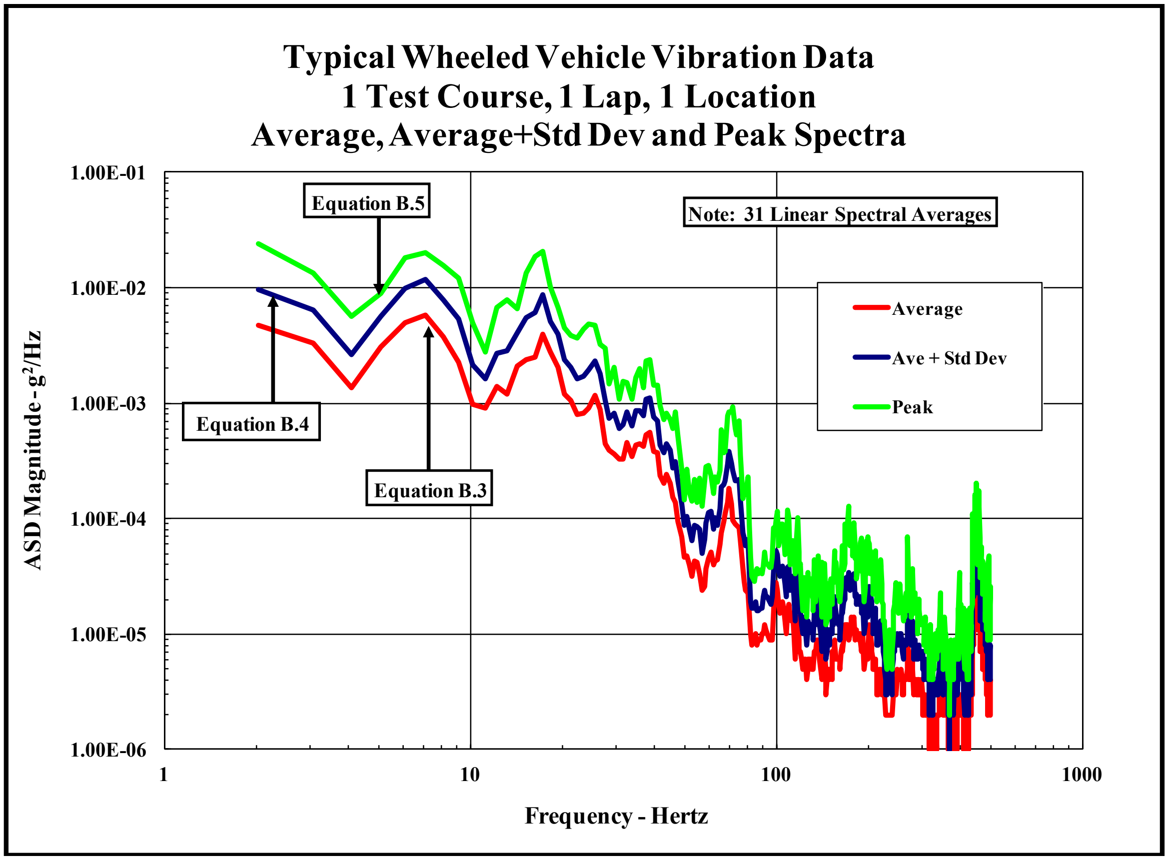


Figure 514.8F-B.3. Average, average plus standard deviation, and peak spectra.

During the VSD process, classical statistics are often employed in somewhat of an ad hoc manner to address unknowns and sample size limitations. The data from many locations and many test events can be combined (by axis) using different techniques to produce representative composite spectra. The first technique is a simple linear average of all average spectra from all channels and all events to produce an overall average spectrum. If the mean and the median of the distribution are the same (which is the case for Gaussian data), this represents approximately the 50th percentile of the spectral data. A second technique is a "standard" conservative approach often integrated into the VSD process in which the ASD(Sum) spectra from each channel and each event are combined by using the average of these spectra with the addition of one standard deviation. The standard deviation computed during this process represents considerations such as the spectral variance due to location, test course differences, and courses not considered and is not the same as $G_d(f)$. Mathematically this spectral average is shown as:

$$G_a(f) = \frac{1}{M} \sum_{i=1}^{M} G_{s_i}(f)$$

Where, ***M*** represents the number of events considered in the computation of the average spectra.

The standard deviation of ASD values due to variations in test courses and instrumentation locations as a function of frequency is defined as:

$$G_e(f) = \left[\frac{1}{M-1} \sum_{i=1}^{M} \left[G_{s_i}(f) - G_a(f) \right]^2 \right]^{\frac{1}{2}}$$

The final spectral measurement defined is:

$$G_f(f) = G_a(f) + G_e(f) \qquad \text{B.6}$$

Computation of $G_f(f)$ is a key component used in the VSD techniques defined in Annex F, Appendix D.

Consider the same ensemble of data as discussed in paragraph 2.7 (typical wheeled vehicle data (4 test courses, 3 data runs, 2 locations)). Figure 514.8F-B.4 includes an overlay of all 24 spectra with the average of the ensemble of $G_s(f)$ spectra shown in yellow and the final representative spectrum, $G_f(f)$, shown in green.

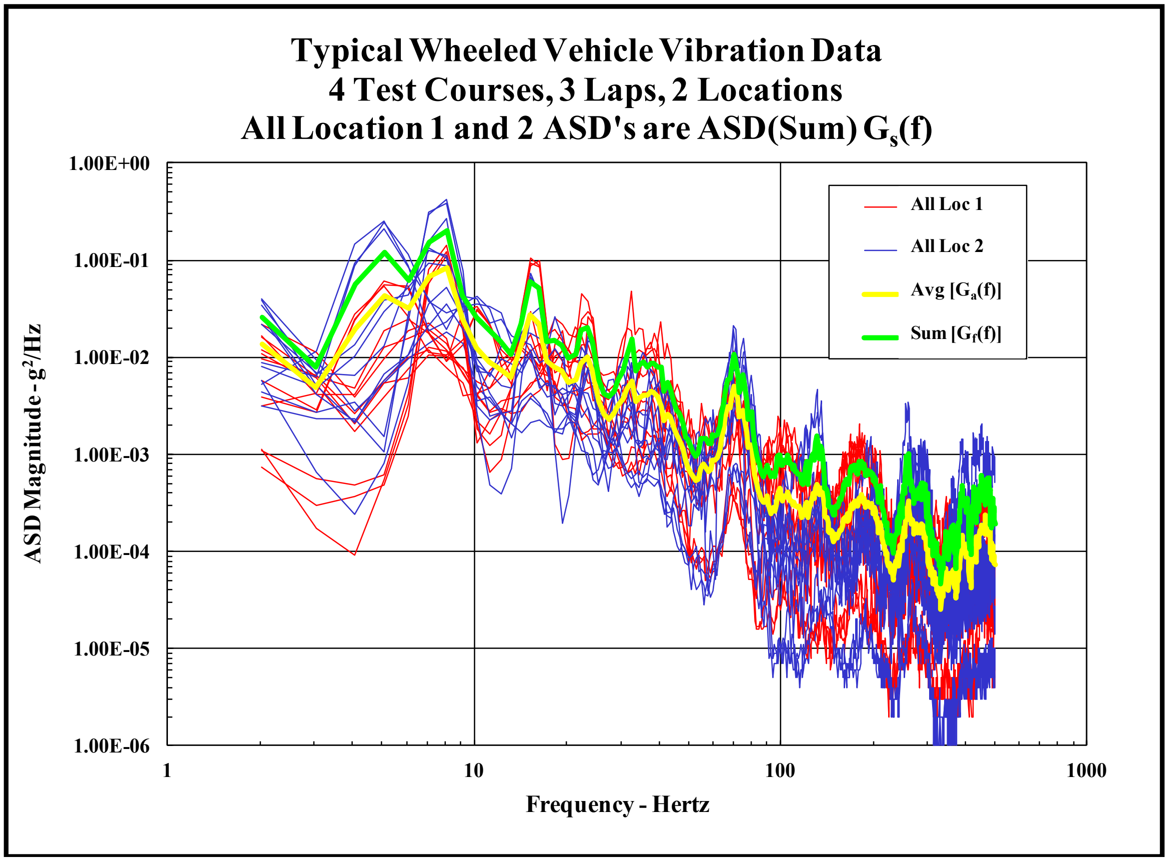


Figure 514.8F-B.4. Combination of 24 individual spectra.

It is desirable for a vibration schedule to be a conservative estimate of the true environment within some credible bounds. A conservative estimate is required for two reasons. First, the test sample size is limited (usually one vehicle) and some allowance must be made for differences within a class of vehicle. Second, vibration control systems take the test specification in ASD form and create a time history (to drive the shaker) by assuming a Gaussian distribution of amplitudes in the time domain. Wheeled vehicle vibration data is nearly Gaussian, but generally has larger "tails" (i.e., more data at high levels and higher peak levels) than a Gaussian distribution of the same mean and standard deviation. Since damage occurs at the tails of the distribution (and not around the mean), it is necessary to amplify the overall level so that the Gaussian process will produce the higher levels commensurate with the measured data. Merely enveloping the peak spectra provides conservatism but results in an over-test since the test rms level is generally much greater than the highest individual level measured. To ensure that the final spectral estimate is at least as large as the actual measured data, this spectrum can be adjusted (amplified or attenuated) so that its rms value is in reasonable agreement with the largest rms value measured at any location during any data run provided the corresponding spectra are similar in shape.

The resultant spectrum shown in Figure 514.8F-B.5 is compared to an envelope of all the average spectra from the data set (in this case, 24 spectra). Note that the resultant test spectrum is approximately an envelope of the individual spectra.

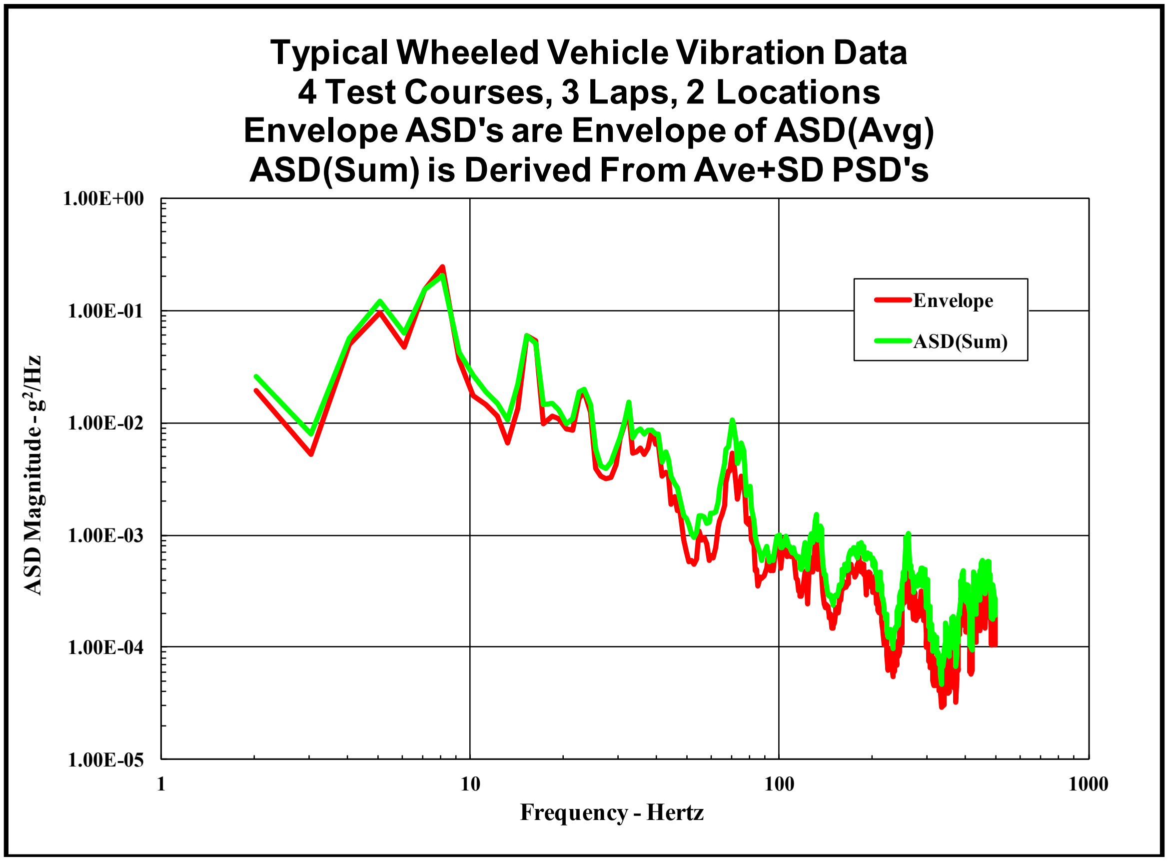


Figure 514.8F-B.5. Comparison of resultant test spectrum (green line) to envelope of individual spectra (red line).

It is important to note that the spectrum described above may be composed of different operating conditions which are not present for the duration assigned to the total environment. For example, if certain frequency components were contributed by operation over a particular test course, they would be applied to the test as if those components occurred for the entire duration, not just the segment represented by operation over that particular test course. In this case, test duration would also apply conservatism to the process, which may or may not be desirable. Problems of this nature are addressed further in the Annex F, Appendix D.

METHOD 514.8, ANNEX F, APPENDIX C
Combination of Spectra (Fatigue Damage Spectra)

1. FATIGUE DAMAGE SPECTRUM METHOD OF COMBINING SPECTRA.

In 1995, Henderson and Piersol introduced the concept of the fatigue damage spectrum to compare the potential damage to a test item exposed to different tests that had approximately a normal amplitude distribution (reference f). The fatigue damage spectrum is a spectral representation of a fatigue damage index as a function of any system's natural frequency. This spectrum is computed directly from the auto spectral density (ASD) function representing a test situation or a field environment, and provides a relative fatigue damage estimate based on acceleration level and exposure time. As opposed to the pure statistical techniques discussed in Appendix B, consideration of the exposure time as well as spectral and fatigue characteristics makes the FDS an attractive technique in development of a LVTS.

The fatigue damage spectrum is computed from:

$$DP(f_n) = f_n T \left(\frac{G(f_n)}{f_n \zeta} \right)^{\frac{b}{2}} \qquad \text{C.1}$$

where:

$DP(f_n)$ = Damage index as a function of system natural frequency

f_n = System natural frequency (variable), Hz

T = Exposure time in environment, seconds

$G(f_n)$ = ASD for a given environment, g^2/Hz

ζ = Damping ratio of system at dominant natural frequency expressed as a decimal

b = Fatigue curve slope value when computed as a linear fit in a log-log domain.

As discussed in Annex F, paragraph 9.2.1.2, the parameter *m* employed in Equation (9.1) 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 effect of mean stress correction, the contributions of elastic and plastic strain, the waveshape of the strain time history, etc. Historically, a value of $m = 7.5$ has been used for random environments, but values between 5 and 8 are commonly used (note the exponent is $\left(\frac{m}{2}\right)$ in Equation 9.5 when addressing ASD values). One may consider a similar substitution of *m* for *b* when using Equation C.1.

Since fatigue damage is based on a cumulative effect of various environments or conditions, a cumulative fatigue damage index can be calculated as the sum of the fatigue damage spectra for individual environments. Thus,

$$DP_t(f_n) = \sum_{i=1}^{N} DP_i(f_n) \qquad \text{C.2}$$

where:

$DP_t(f_n)$ = Total damage index spectrum.

$DP_i(f_n)$ = Individual environment damage spectra as defined in equation C.1.

2. EXAMPLE APPLICATION OF FATIGUE DAMAGE SPECTRUM.

Historically, four specific test courses at Aberdeen Test Center (ATC) have been used to generate data for vibration specifications for wheeled vehicles. It is improbable to relate the actual amount of each of these road surfaces to any real world scenario (e.g., determine how much Belgian Block a vehicle will encounter for a particular scenario), however it is possible to compute exposure times for operations at ATC and use this information to compute a fatigue damage spectrum by test course. Substantial precedence for using these course and speeds in full vehicle tests exists (first introduced as Large Assembly Transport Test of MIL-STD-810B, June 1967), so it is logical to use them as a basis for simulation. Each course has a measured length and is traversed at a nominal speed, leading to an exposure time. This information is presented in Table 514.8F-C.I.

Table 514.8F-C.I. Test Course Lengths, Speeds and Exposure Times

Test Course	Length, m (ft)	Nominal Speed, km/hr (mph)	Exposure Time, sec
Belgian Block	1200 (3940)	32.2 (20)	134
Two-Inch Washboard	250 (822)	16.2 (10)	56
Radial Washboard	74 (243)	24.1 (15)	11
Three Inch Spaced Bump	233 (764)	32.2 (20)	26
Total	1757 (5769)		227

The exposure times can be used with equation C.1 and the appropriate test course ASDs to produce a fatigue damage spectrum for each test course. Using the same set of typical wheeled vehicle data as before, the fatigue spectra are shown in Figure 514.8F-C.1. For this example, ζ was chosen to be 0.05 (5-percent critical damping) and the exponent m was substituted for b, and was assigned a value of 7.5.

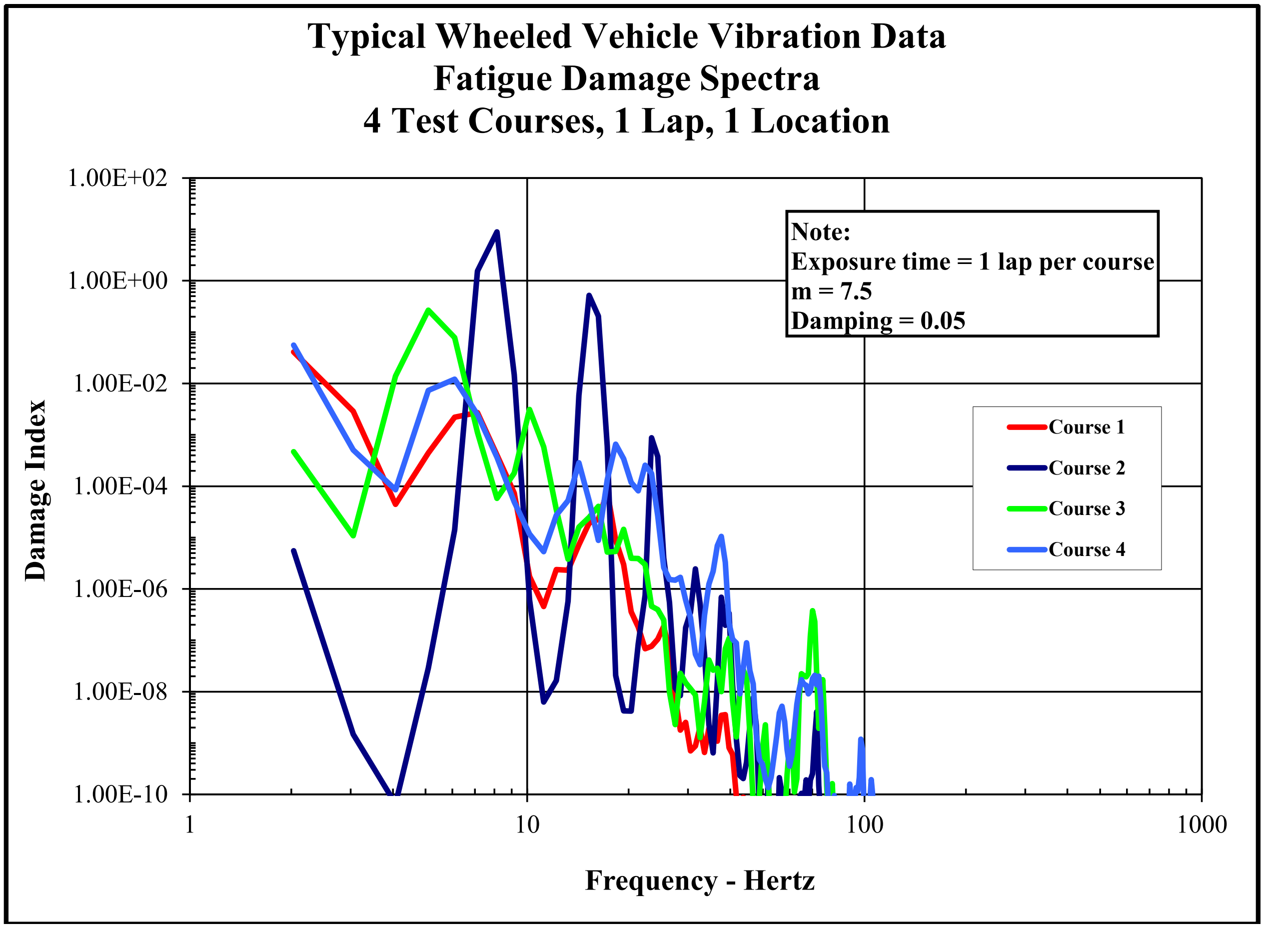


Figure 514.8F-C.1. Fatigue damage spectra for specific test courses.

The cumulative fatigue damage spectrum (equation C.2) is shown by the lavender line in Figure 514.8F-C.2 and represents a fatigue damage index derived from a complete lap of the four specified test courses.

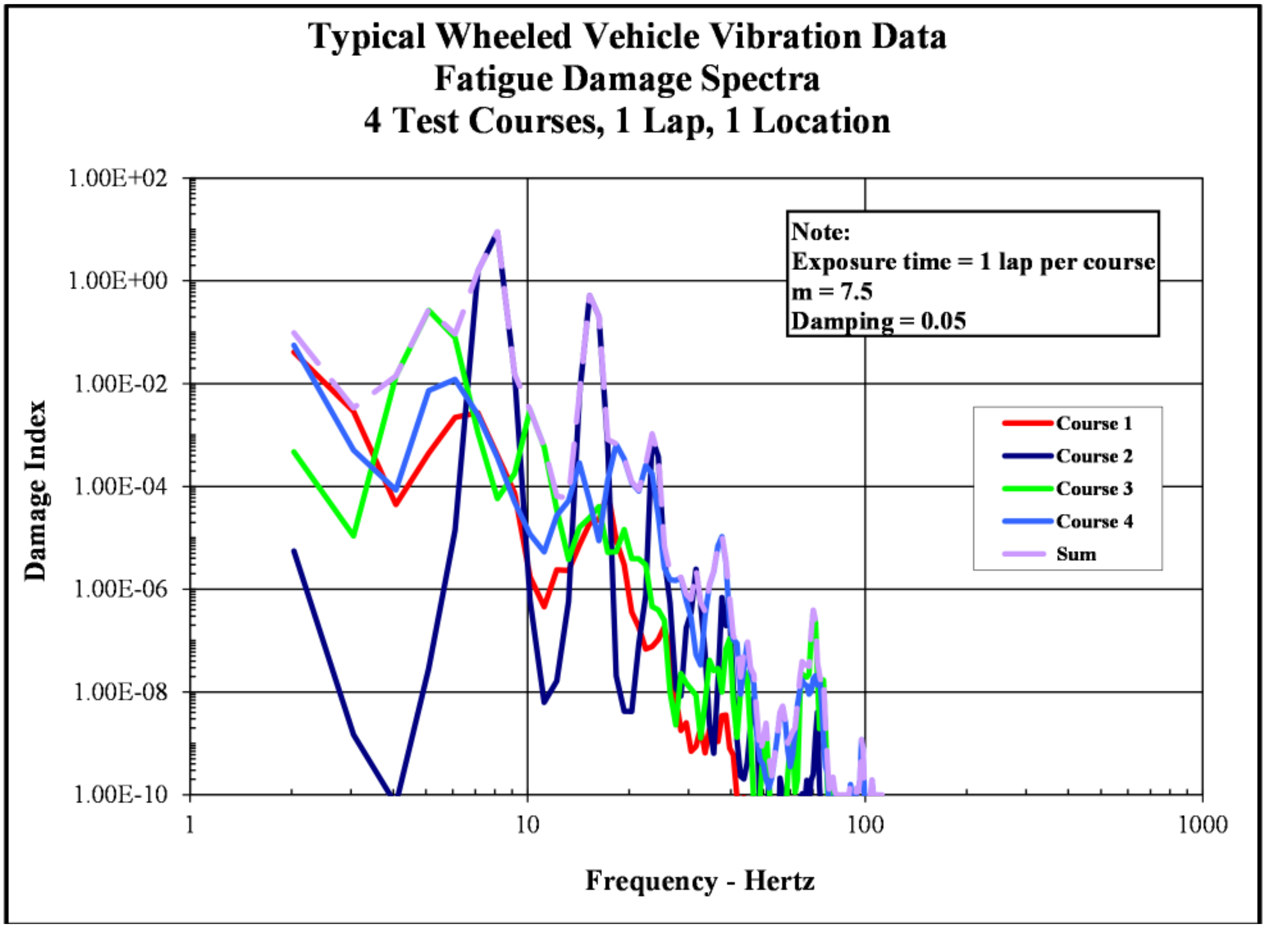


Figure 514.8F-C.2. Cumulative fatigue damage spectrum (lavender line).

The same process was performed for 2 measurement locations independently using cumulative data for 3 laps. The cumulative spectra for each location were then averaged and enveloped for comparison and are shown in Figure 514.8F-C.3.

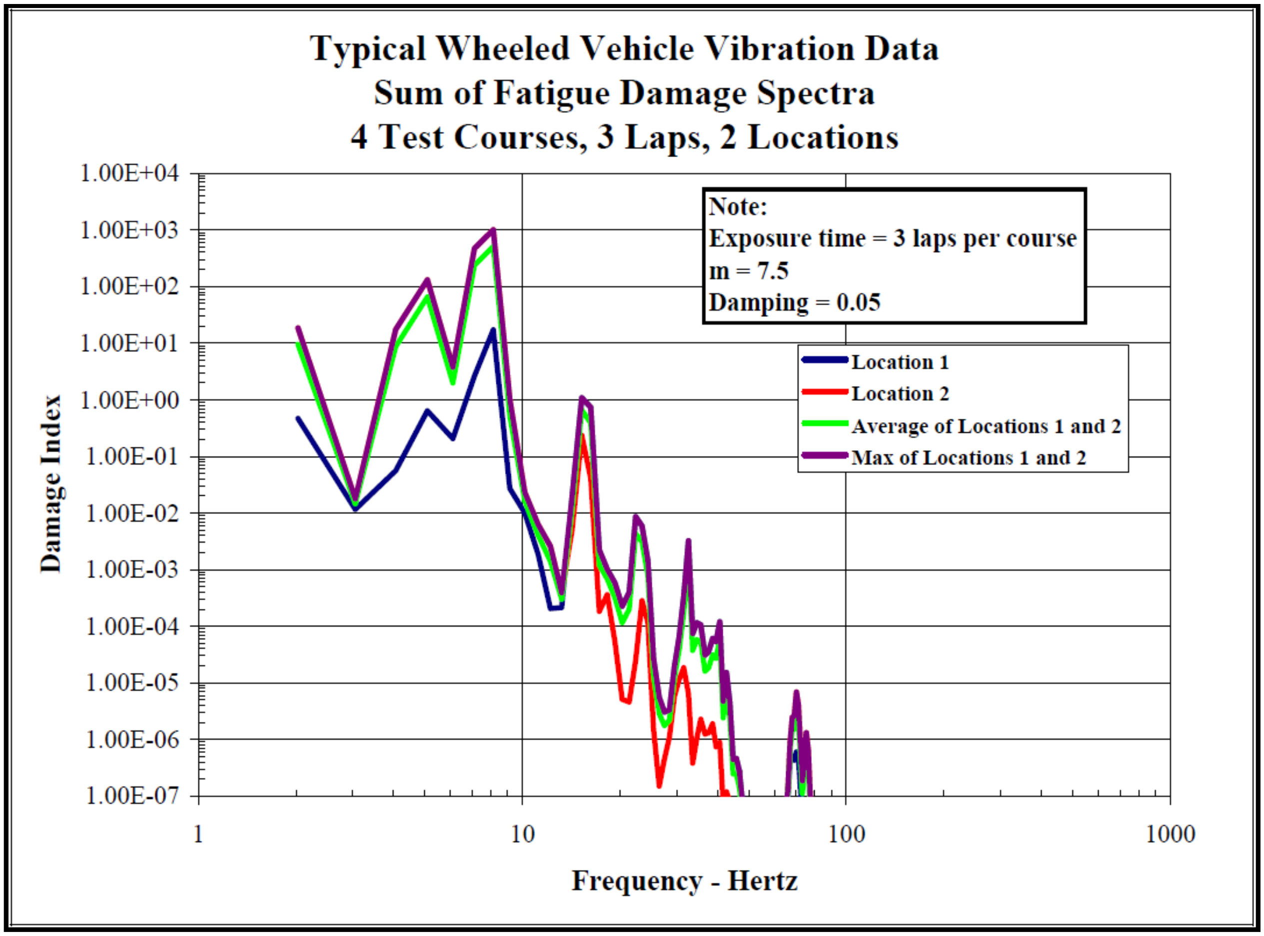


Figure 514.8F-C.3. Cumulative fatigue spectra from locations 1 and 2.

If an overall exposure time is selected, equation C.1 can be reworked to provide an ASD level based on the fatigue spectrum computed from Equation C.2.

$$G(f_n) = f_n \zeta \left(\frac{DP(f_n)}{f_n T} \right)^{\frac{2}{b}} \qquad \text{C.3}$$

where:

$DP(f_n)$ = Cumulative damage index as a function of system natural frequency

f_n = System natural frequency (variable), Hz

T = Total exposure time in environment, seconds

$G(f_n)$ = Equivalent ASD for a given DP(f_n), T, g^2/Hz

ζ = Damping ratio of system at dominant natural frequency expressed as a decimal

b = Fatigue curve slope value when computed as a linear fit in log-log domain.

Using an exposure time equal to 3 times the total value listed in Table 514.8F-C.I (to account for 3 laps) and the fatigue damage spectra (average and max) shown in Figure 514.8F-C.3, an equivalent representative ASD was calculated from equation C.3. The spectra derived from the average and maximum fatigue damage spectra are shown in Figure 514.8F-C.4. For this data set, the fatigue damage spectra for locations 1 and 2 were nearly the same producing an average spectrum that is about the same as the enveloped spectrum. The enveloped or maximum spectrum is compared to the resultant spectrum computed from the statistical process and from a spectrum derived from the envelope of all original spectra and is shown in Figure 514.8F-C.5.

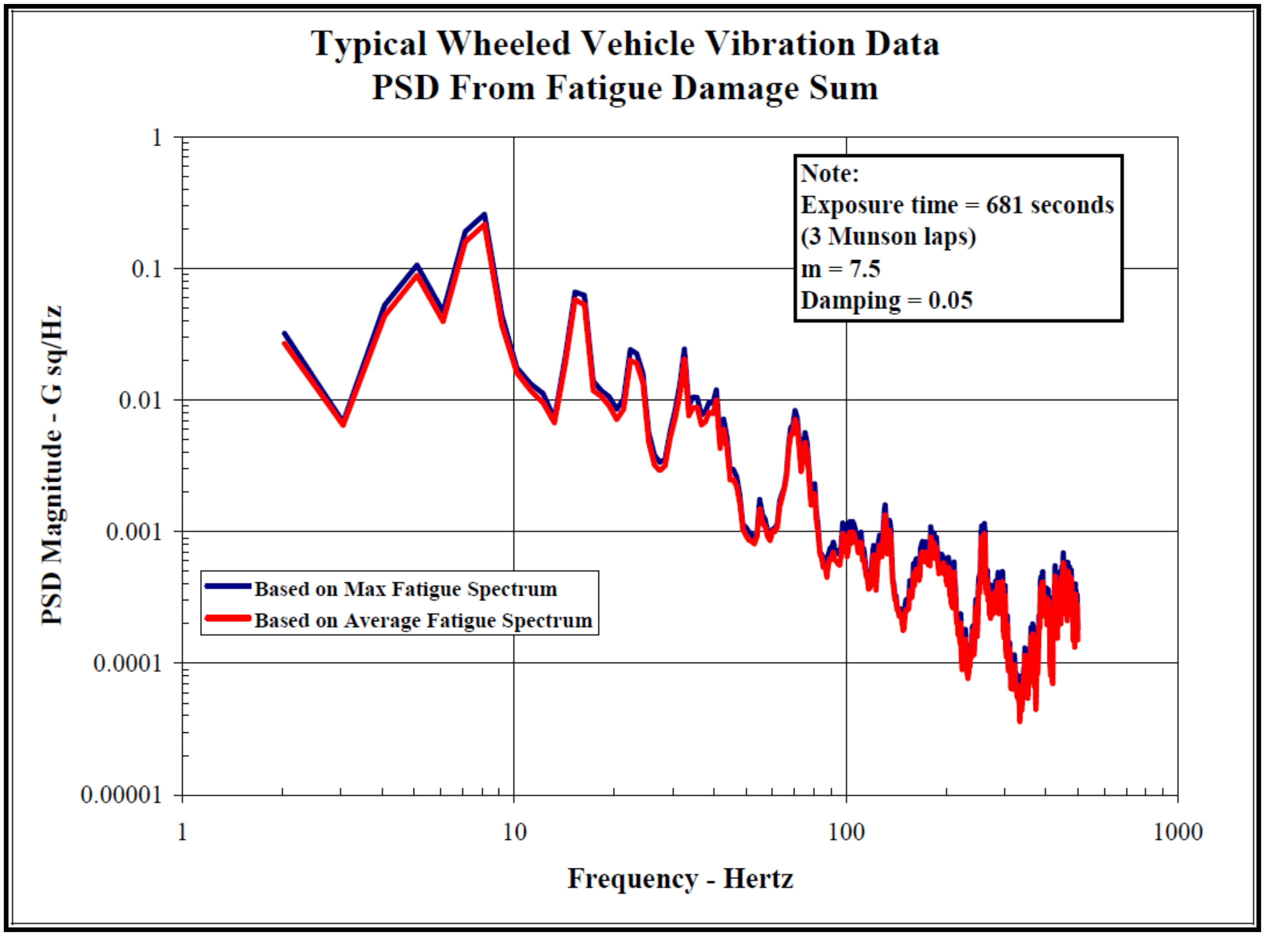


Figure 514.8F-C.4. Combined vibration power spectra developed from average and maximum fatigue damage Spectra.

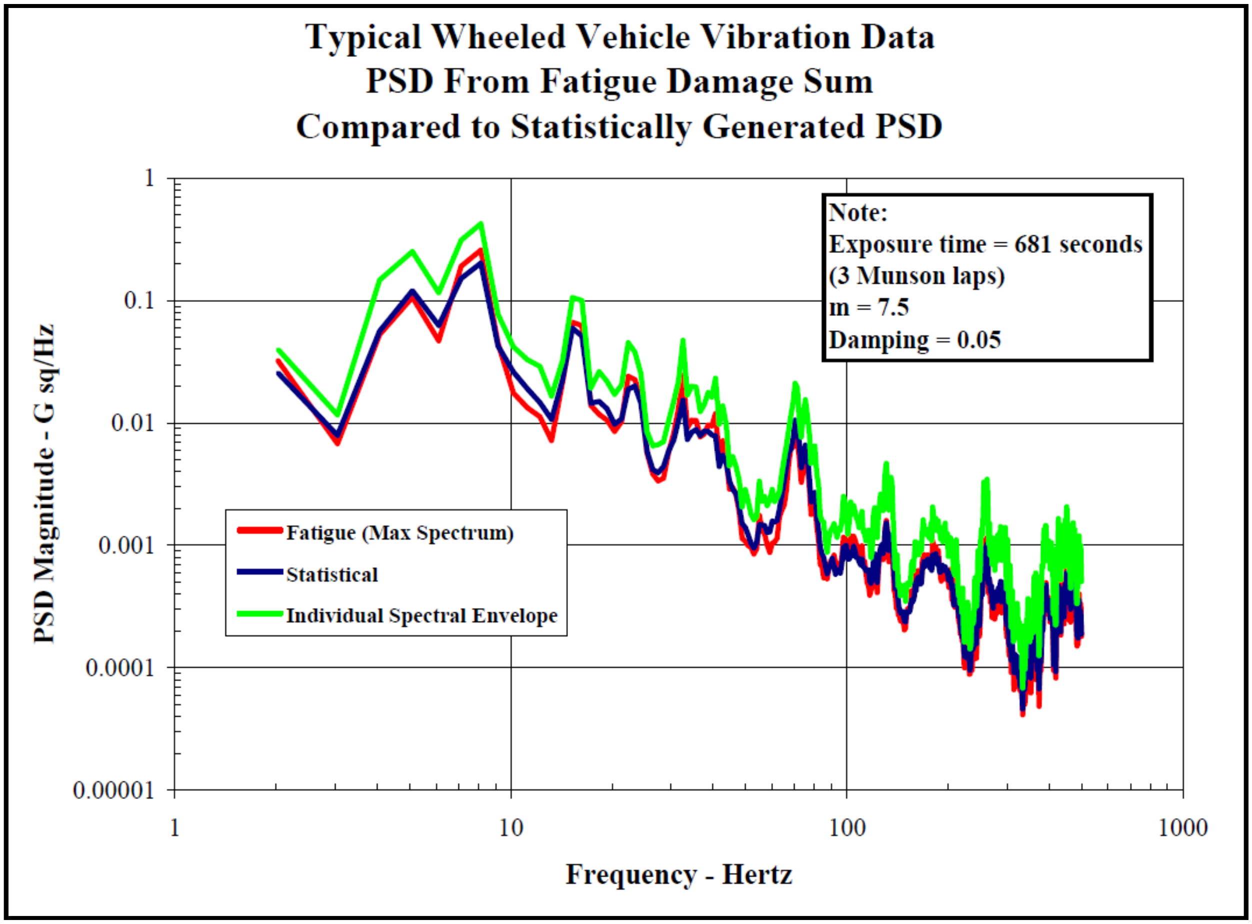


Figure 514.8F-C.5. Comparison of combined vibration power spectrum developed from the fatigue damage spectrum, from the statistical process and from an envelope process.

The three processes (fatigue spectrum, statistical and envelope) produce specifications that are roughly the same shape. The specification derived from the fatigue damage spectrum technique has lower levels than those produced by the envelope process and nearly the same (but generally lower) levels than those produced by the technique developed in Appendix B. The statistical technique contains an implied assumption that each environment has the same exposure time and weights the spectral values toward the most severe spectrum due to the inclusion of spectral variance (the addition of a standard deviation) in the process. Therefore, it is likely that the statistical process will produce higher levels than the fatigue damage process unless the most severe spectra also have the longest exposure times.

The process was repeated for an exponent value of $m = 5$ as a comparison. A comparison of the fatigue damage spectra (maximum) for the two exponents is shown in Figure 514.8F-C.6, and a comparison of the vibration power spectra developed from each exponent is presented in Figure 514.8F-C.7.

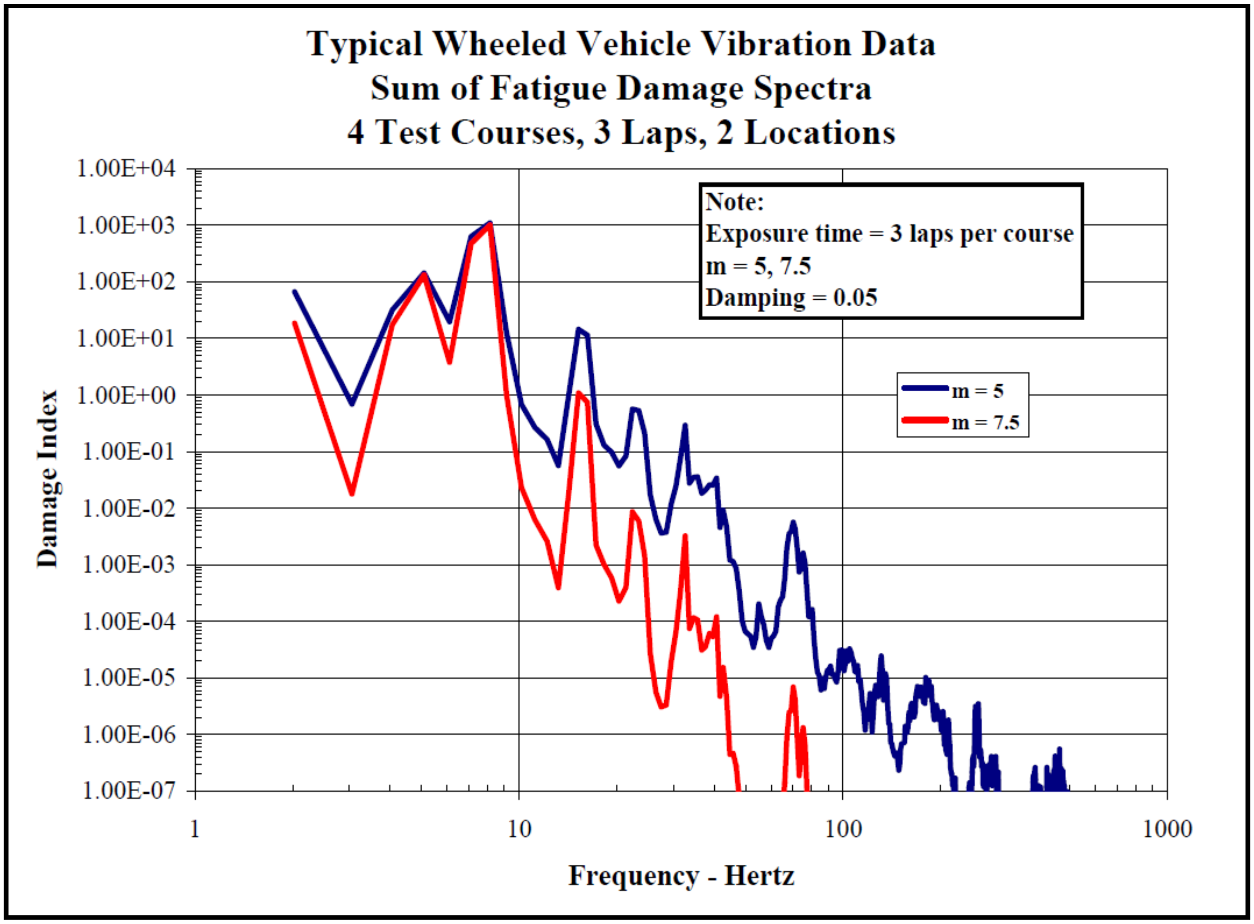


Figure 514.8F-C.6. Fatigue damage spectra for two exponents.

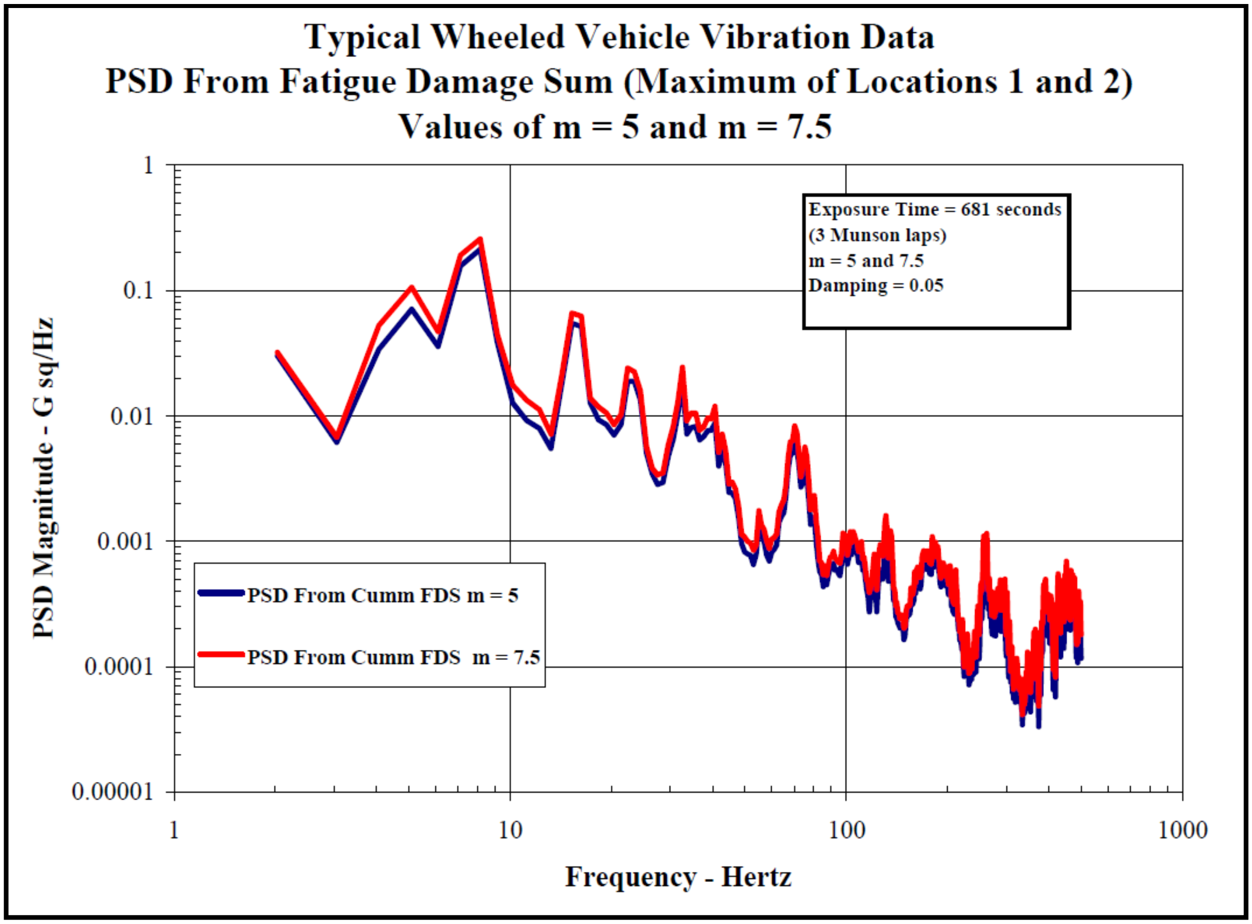


Figure 514.8F-C.7. Comparison of combined vibration power spectra developed from two exponents.

For this set of measured environments (acceleration spectra) and associated exposure times, the final combined spectrum is somewhat independent of the value of the exponent chosen. Forty percent of the spectral amplitudes for the two exponents were within 1 dB (based on m=7.5 as the reference), 80 percent were within 2 dB and all were within 2.4 dB.

Documentation of the spectral combination process, including assumptions (e.g., value of b), is essential. The final combined spectrum should be compared to the original input spectra to ensure that the resultant spectrum is a reasonable representation of the measured environment.

3. FDS APPROACH TO DEVELOPMENT OF A LVTS.

In summarizing the example provided in the previous section, a single ASD was computed, representative of the ensemble of data acquired from making three passes over four specific road courses. The ASD derived from the inverse of the cumulative FDS is compared to the envelope of the data ensemble as shown in Figure 514.8F-C.5. From Figure 514.8F-C.7 it is clear that the spectral shapes and amplitudes are very similar for the ASD's derived in the examples in previous section for both selections of m (m=5 and m=7.5). From Figure 514.8F-C.5 it is also clear that the ASD computed from the inverse cumulative FDS falls significantly below the envelope of the data ensemble. Employing equation 9.5, one could easily compress the test time by increasing the magnitude of the ASD. This can be accomplished by changing the T parameter of equation C.3. As in Annex F, paragraph 9, one should always use caution in employing time compression techniques. When dealing with data of a similar spectral characteristic, a conservative approach would be to limit the final compressed spectral shape to the spectral shape of the envelope of the original data ensemble. Reviewing the spectral shapes of the ASD's computed from the inverse cumulative FDS and the envelope of the original data ensemble, it is clear that the ratio between the two curves is not the same at each spectral line. Therefore, one will need to set some criteria, which is often test specific, for addressing the amount of time compression employed. In the example discussed in this Appendix, the average ratio between 2 and 100 Hz was set at the compression ratio. This spectral band was considered to be of primary importance for this example since the data set was from a wheeled vehicle and the spectrum is dominated by energy below 100 Hz. Figure 514.8F-C.8 illustrates the effect of time compression based on the ratio described above. Using the time compressed spectral shape, the test time reduces from 681 seconds (the actual time spent on the courses) to either 72 seconds (when *m*=5) or 54 seconds (when *m*=7.5). As a final step, the analyst will usually reduce the number of breakpoints (smooth the spectral shape) while maintaining the overall G-rms level.

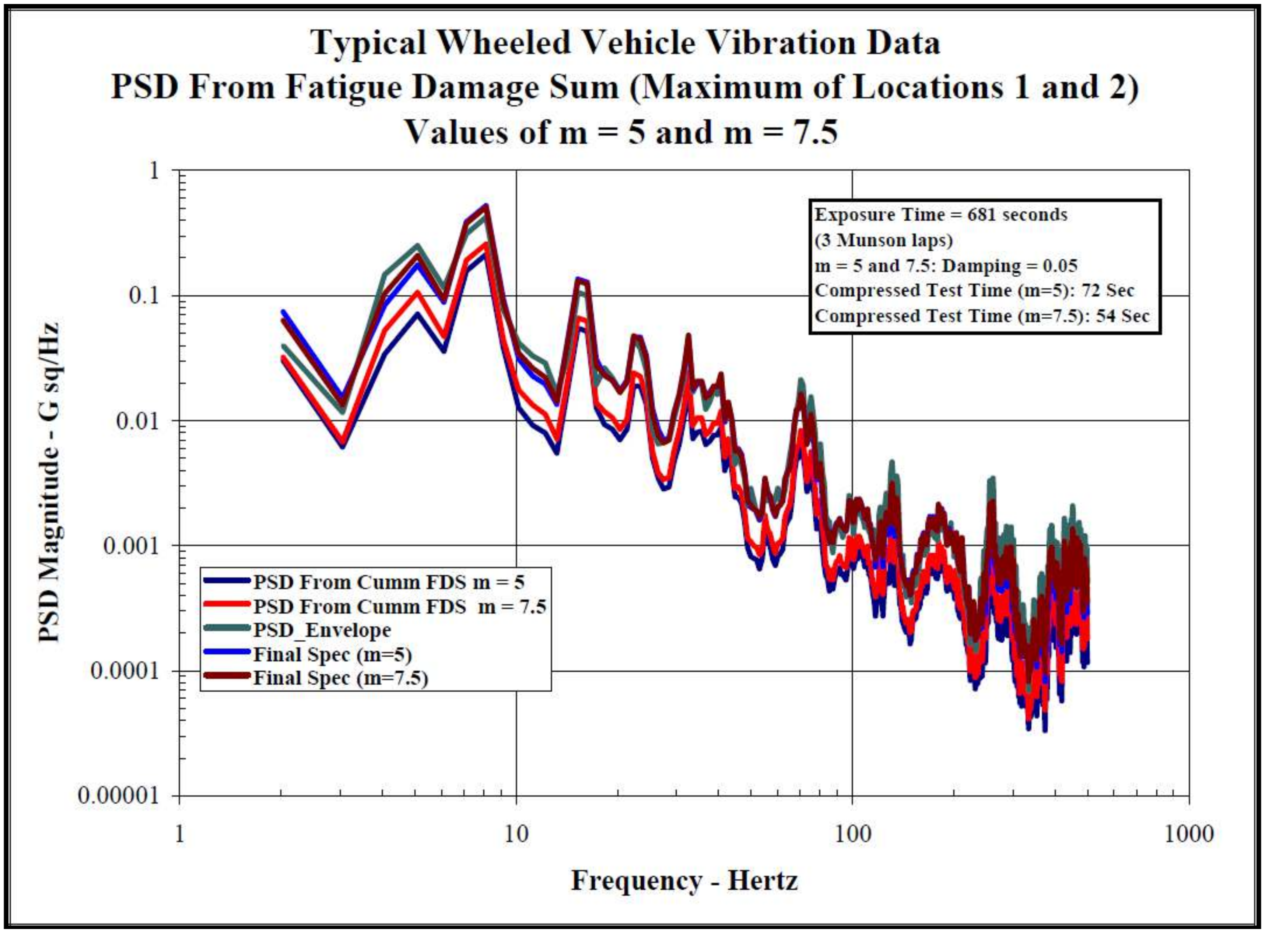


Figure 514.8F-C.8. Time compression of ASD's computed from the inverse cumulative fatigue damage spectrum.

This example is relatively simple; however, the techniques could easily be expanded to address more complex ensembles of data to include spectra with either narrowband or tonal components.

METHOD 514.8, ANNEX F, APPENDIX D
Vibration Specification Development Procedure

1. INTRODUCTION.

This Appendix outlines a Vibration Schedule Development (VSD) procedure designed to combine an ensemble of vibration events and associated exposure times into a smaller set of vibration profiles and associated run times. The vibration events are in the form of a set of digital data files that collectively represent the full fatigue exposure of the test item. The goal is to produce a small set of Laboratory Vibration Test Schedules (LVTS) that can induce equivalent fatigue exposure with a vibration exciter. The procedure can be used to develop broadband random, Sine-on-Random (SOR) or Narrowband Random on Random (NBROR) LVTS. Figure 514.8F-D.1 illustrates the VSD procedure in an abbreviated block diagram format.

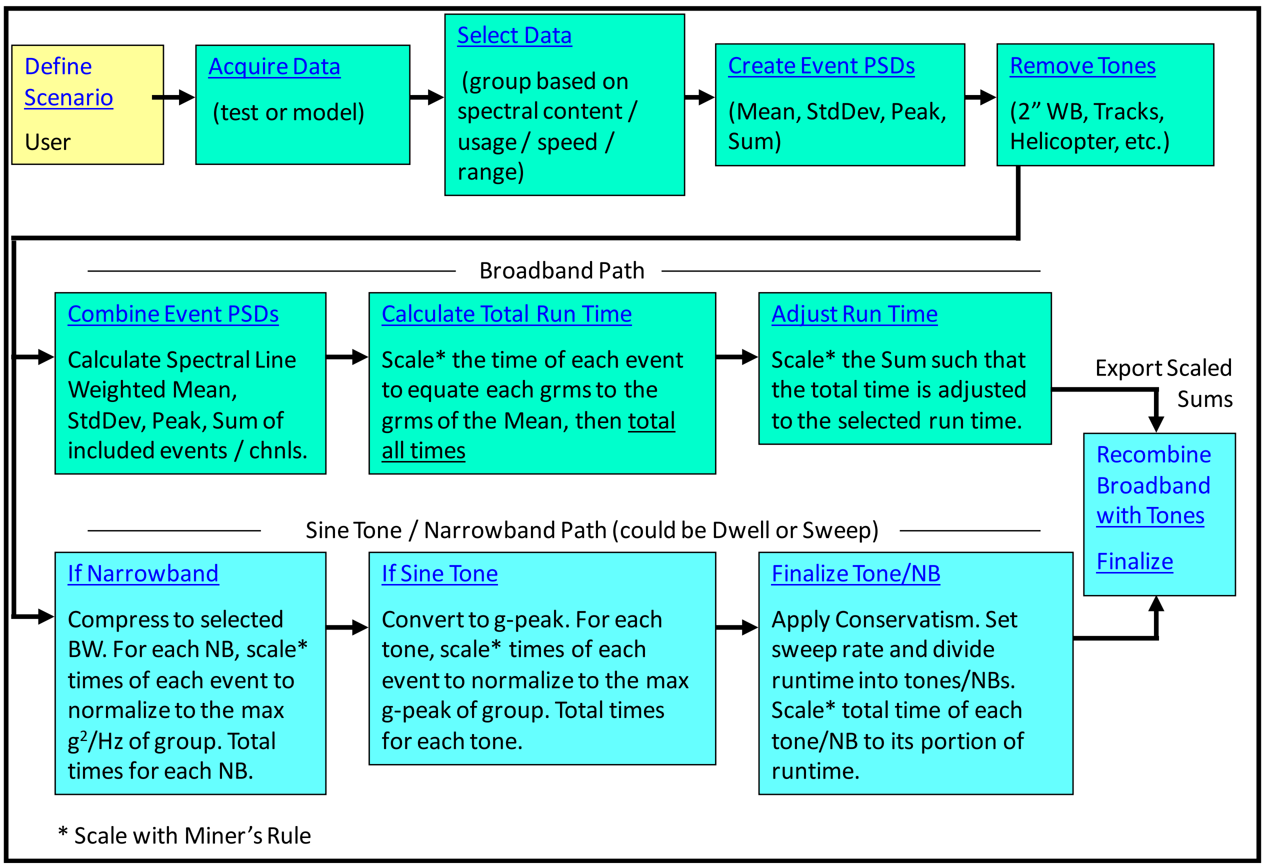


Figure 514.8F-D.1. VSD flowchart.

Data are typically processed in multiple channel sets, as it is often desirable that specific channels are processed with common frequency resolution or be reduced to common test times to allow development of schedules based on multiple locations. The procedure is best implemented in specially designed software. Software tools should be developed to implement the following:

a. A general-purpose signal analysis package used as a pre-processing tool prior to the actual schedule development. Routine pre-processing analyses includes: Time Histories, RMS vs. Time, Min/Max, Kurtosis, Histograms, Skewness and Stationarity.

b. Specialized routines to manage the test database and manipulate the test data as necessitated by the VSD procedure. The routines can be grouped into a single software package for ease of implementation. The package should manipulate the event files and output an intermediate LVTS in ASCII or spreadsheet format.

c. Spreadsheets developed to produce final LVTS's using files generated by the specialized software. Spreadsheets provide a convenient method for addressing activities such as combining multiple channel profiles into a single LVTS, processing narrowband and/or sine tones, combining narrowband and broadband components, inclusion of fleet severity factors and scaling test times to user selected values.

d. A subroutine to pick a series of breakpoints to represent the broadband profile generated by the process. The points should be picked such that the shape and rms level of the vibration profile are preserved with the minimal number of breakpoints.

The following definition is provided to aid in method discussion. A review of the definitions found in Annex F, paragraph 3 would also be beneficial.

Sum-Set – A matrix of ASDs used as an organizational tool for process implementation. There are two types of sum-set, the single-event ASD sum-set and the group sum-set. The two sum-sets will be defined as required in this Appendix.

Before the VSD process begins a number of parameters must be defined. Table 514.8F-D.I lists some parameters relevant for the process. Other parameters will be discussed in subsequent sections of this document as necessary.

The process can be implemented as discussed in the following sections.

Table 514.8F-D.I. VSD Required Parameters

Block Size	The number of data samples to include in ASD calculation. The block size is typically set equal to the sample rate to give a 1 second block and 1 Hz ASD resolution.
Window Type	The window type to use for ASD calculation, typically Hann.
Minimum g-rms threshold	Used to assure low level events will not overly affect LVTS ASD shape. The threshold is set as a g-rms ratio (default 50%) of the maximum ASD in the group.
Crest Factor Threshold	These thresholds can be used to alert the analyst if a section of data is grossly non-Gaussian. The analyst can then decide if the data should be excluded from the development process.
Skewness Threshold	
Kurtosis Threshold	
Start Frequency	This is the start frequency for the broadband portion of the LVTS. This is typically set to 5 Hz or the frequency of the lowest tonal component.
End Frequency	This is the upper limit of the LVTS bandwidth. This should be set by a review of the data. Typically used values include 200 Hz, 500 Hz, or 2000 Hz.
N_e, N_g	Analyst defined factors defining the number of standard deviations to use in the process (default = 1). N_e is for an individual event and N_g is for combining multiple events.
M_e, M_g	Analyst defined factors to limit conservatism in the process. M_e is for an individual event and M_g is for combining multiple events.
DC Component	Remove the DC components from the time domain data before calculation of ASDs. The DC component is often a result of signal conditioner offset and can be removed without affecting LVTS development.

2 BROADBAND PROFILE DEVELOPMENT.

2.1 File Setup (Step 1).

Step 1 is to define the test data of interest by selecting from the data files available on disk. The events selected should collectively represent the expected vibration exposure of the test item. It may be necessary to divide the events into groups of similar ASD shape and level, and produce LVTS separately for each group.

2.2 Select Event Start and End Time (Step 2).

During the collection of the raw field data, it is common practice to begin acquisition prior to reaching a desired speed or start of a particular road surface or maneuver. For this reason, the analyst may need to select only a portion of the digitized data set provided for a particular event. It is helpful to define the start and end time of the data set to be carried forward in the VSD process.

2.3 Time Block Drop (Step 3).

Given fixed start and end times, data block size, and overlap percentage, the number and order of data blocks is also fixed. There is the possibility of corrupt data, or bad blocks, within the identified data segment (i.e., momentary telemetry dropouts, off speed sections, shock event, etc.). The analyst must be able to identify specific data blocks for exclusion in the subsequent spectral computations. To prevent discontinuities in the data, the blocks should not be deleted from the time data, but simply excluded during ASD calculation. In the event that the amount of measured data is limited, the analyst may be required to salvage available data through careful removal of limited dropouts in the data set that can be proven to be non-mechanical in nature (i.e., telemetry dropouts). Such manipulation is always a last resort and should be conducted by an experienced analyst.

Modern vibration control systems produce drive signals with Gaussian amplitude distributions. Therefore, the block drop utility should be implemented to warn the analyst if a particular block is grossly non-Gaussian in nature. One possible approach if to calculate the Crest Factor, Skewness, and Kurtosis of each block, and warn the analyst if user defined threshold values were exceeded. The analyst should then have the option to accept or reject that block. If a data set is highly non-stationary or non-Gaussian in nature a TWR test may be recommended in lieu of a classical spectral based vibration test.

The number of averages comprising a given ASD may vary as a function of the event time. For statistical relevance, a minimum of thirty-two (32) valid data blocks is recommended for ASD calculation. For any event consisting of less than 32 averages after block drop, 50 percent overlap can be used to effectively double the number of blocks available.

2.4 Calculate ASD Average (Step 4).

Once the data blocks for processing are selected, a single-event ASD sum-set is generated for each channel and each event. A single-event ASD sum-set includes five ASDs, an average, peak hold, standard deviation, sum, and spectral spike removed, as defined in Table 514.8F-D.II. The first four ASDs of the sum-sets are calculated during Step 4. The average, denoted as ASD(Avg), is a standard n average ASD, where n is the number of data blocks selected for processing during block drop. Individual ASDs are calculated for each data block and then averaged on a spectral line basis to produce the ASD(Avg). The ASD(Sum) is calculated by adding N_e standard deviations to the ASD(Avg), where N_e is a user selected value typically set to 1. The ASD(Sum) becomes the working ASD and is passed forward to the next step. Use of the ASD(Sum) is intended to address severity variance across the vehicle fleet of interest. To minimize overly high ASD(Sum) levels, due for example to high standard deviations resulting from ground vehicle speed fluctuations, the ASD(Sum) is constrained to be no higher than M_e *ASD(Avg) where M_e is a user defined parameter typically set to 2. The ASD(Sum) is also limited to the ASD(Peak) level at each spectral line. In the rare scenario in which there exists specific information as to how the vehicle being used to acquire the test data compares to the fleet, the Parameter N_e should be customized accordingly.

Table 514.8F-D.II. Single-Event ASD Sum-Set

Nomenclature	Definition
ASD(Avg)	A standard n_d average ASD. *(See* $G_m(f)$ *as defined in Appendix B)*
ASD(Peak)	Calculated by holding the maximum amplitude of each spectral line over n_d averages. *(See* $G_p(f)$ *as defined in Appendix B)*
ASD(Stdv)	Calculated by determining the standard deviation of each spectral line over n averages. *(See* $G_d(f)$ *as defined in Appendix B)*
ASD(Sum)	Calculated by adding N_e standard deviations to the average for each spectral line. ASD(Sum) = N_e *ASD(Stdv) + ASD(Avg) N_e is a user defined variable typically set to 1. ASD(Sum) is limited by ASD(Peak) and M_e *ASD(Avg) where M_e is a user defined variable typically set to 2. *(See* $G_s(f)$ *as defined in Appendix B)*
ASD(SpkRmvd)	ASD(Sum) after Frequency Spectral spike Removal.

2.5 Spectral spike Removal (Step 5).

For combined SOR or NBROR environments, the sine tones or narrowbands must be processed separately from the broadband random. Step 5 provides a method of removing the sine tones or narrowbands from the ASD(Sum) spectra when required.

To insure accuracy and to isolate unexpected inconsistencies in the data, the spectral spikes are selected and removed by the analyst acting interactively in a program loop using a graphical interface such as that shown in Figure 514.8F-D.2. The analyst selects the beginning and ending frequency of all spectral spikes for which removal is desired. Intermediate points are then replaced with a logarithmic interpolation of the two endpoints to produce the broadband ASD(SpkRmvd), shown as magenta in Figure 514.8F-D.2. This is the fifth ASD of the single-event ASD sum-set and becomes the working ASD for the broadband profile development.

Note that the width of the spectral spikes removed will depend on a number of factors, including, but not limited to, the nature of the data and the frequency resolution of the ASD calculations. Typically, the data should be pre-processed to determine if the data is more narrowband random or more sinusoidal in nature. This information determines how the narrow-band energy will be processed.

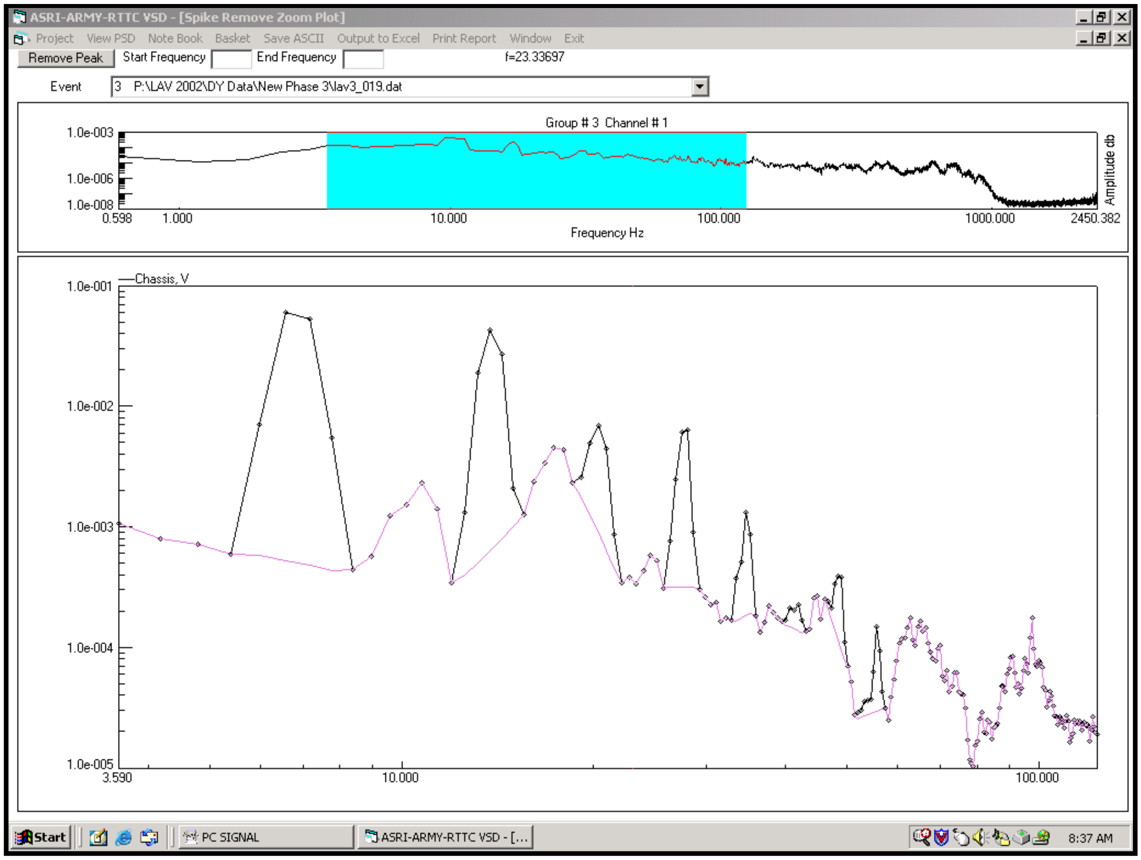


Figure 514.8F-D.2. Spectral spike removal window.

The nature of the vibration is dependent upon the vehicle and field environment. For example, an item mounted on a wheeled vehicle and driven on primary (paved) roads will be exposed to a broadband random forcing function. A wheeled vehicle driven over a periodic washboard course will typically produce a combined SOR vibration environment, as will a rotary wing aircraft. A tracked vehicle usually produces a combined NBROR vibration. The nature of the data (sine or narrorband) needs to be determined at this point. Refer to Annex F, paragraph 4 for more discussion on the nature of the vibration. Although the frequency resolution selected for ASD calculations will affect the width and amplitude of spectral spikes, it will not affect the total g-rms of the spectral spikes removed. For that reason the g-rms of the spectral spikes, rather than the ASD amplitude, should be used when processing the narrowband information.

The energy corresponding to the removed spectral spikes can be exported in a form that facilitates spreadsheet analysis. This allows external processing of the narrowband energy. Two spreadsheets should be produced. One containing the center frequency, width, and the total g-rms of all spectral spikes removed from all ASD(Sum); and another containing the same information from all ASD(Avg). The average numbers are used for SOR developments while the sum numbers are used for NBROR developments. The procedures used to process the narrowband information are presented in paragraph 3.

An example spectral spike removed spreadsheet is provided in Table 514.8F-D.III. The example contains the energies removed from the ASD(Avg). The ASD(Sum) table is identical except the g-rms levels are derived from the ASD(Sum) instead of the ASD(Avg). This particular example is of a wheeled vehicle on a two-inch washboard course. Note that the fundamental and two additional harmonics were removed from each of three events (5, 7.5, and 10 mph 2” washboard).

Table 514.8F-D.III. Spectral Spike Removed Table, Average

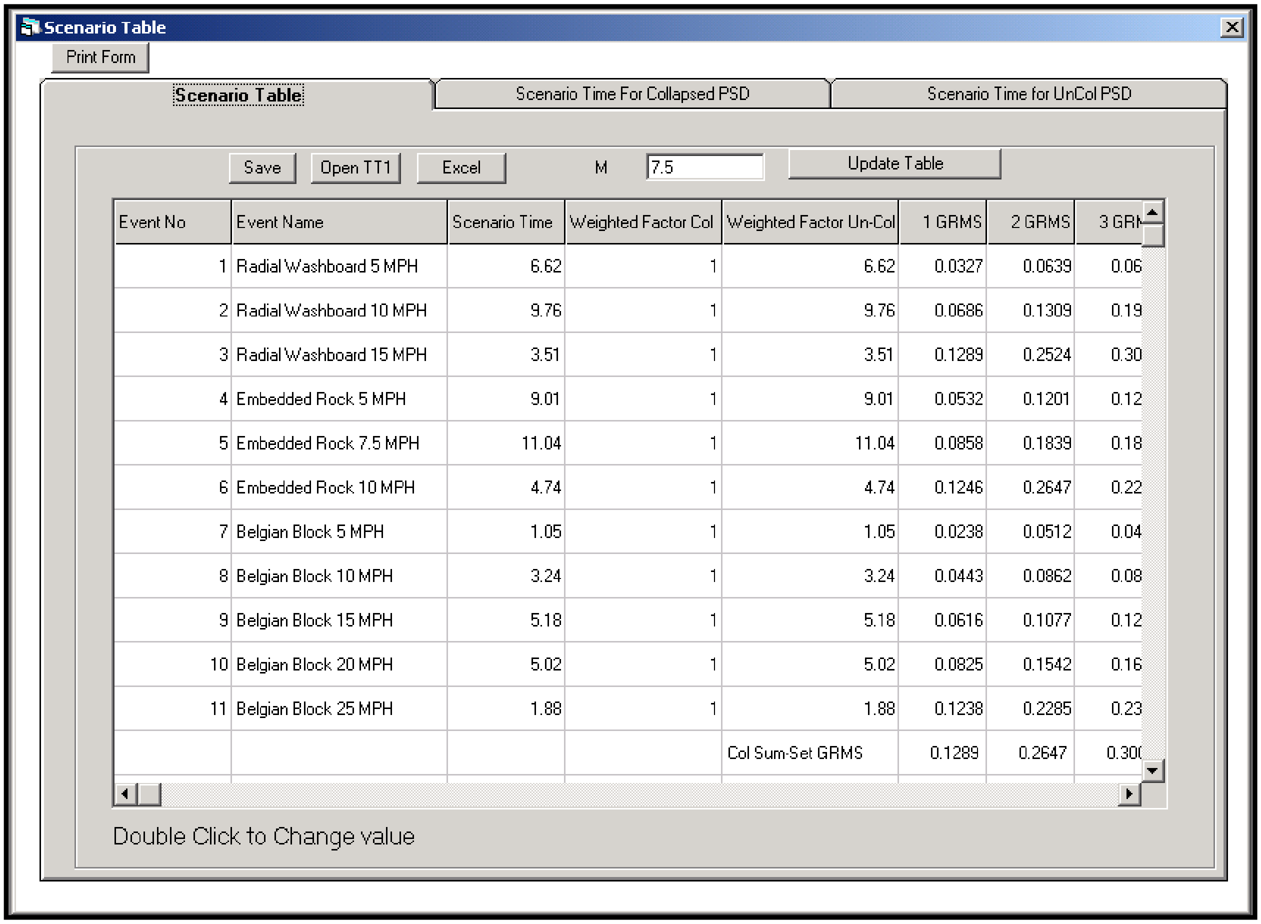
Project File :	Example Wheeled Vehicle						
Total Miles:	1000	Block size :	4096	Start Freq : 3		Raw ASD	W-UCol ASD
Date Proc :9/16/2002		Window Type :	Hann	End Frq : 500	N :	1	1
Time Proc :6:37:44 AM		Min g-rms :	0.5	Rmv DC : Y	M :	2	2
					Total G-RMS of removed Spectral spike		
Channel					1	2	3
Description					Channel 1	Channel 2	Channel 3
Type					ASD(Avg)	ASD(Avg)	ASD(Avg)
Test Time					30	30	30
	Event	Beta Dist Time	Center Freq	Bandwidth Selected	g-rms	g-rms	g-rms
1 Harmonic	5 mph 2” WB	8.31	3.67	6	0.1534	2.79E-02	5.31E-02
	7.5 mph 2” WB	21.28	5.50	5	0.2691	3.41E-02	0.134565
	10 mph 2” WB	7.47	7.33	7	0.5755	8.74E-02	0.5730498
2 Harmonic	5 mph 2” WB	8.31	7.33	6	0.1118	3.49E-02	7.37E-02
	7.5 mph 2” WB	21.28	11.00	7	8.72E-02	3.22E-02	5.18E-02
	10 mph 2” WB	7.47	14.67	6	8.98E-02	2.67E-02	0.211421
3 Harmonic	5 mph 2” WB	8.31	11.00	6	0.06546	4.01E-02	9.12E-02
	7.5 mph 2” WB	21.28	16.50	9	2.63E-02	2.94E-02	0.05846
	10 mph 2” WB	7.47	22.00	8	3.08E-02	3.75E-02	0.07558

2.6 Scenario Table (Step 6).

VSD requires knowledge of the exposure time for the individual events. For a ground vehicle, those times can be derived from the distribution of the system’s mission scenario into the individual events through the use of a Beta distribution. For a helicopter, the scenario times are typically derived from the aircrafts usage spectrum. Further discussion of scenario development and the Beta distribution can be found in Annex F, paragraph 7.4.

The event times can be provided in the form of scenario tables populated in Step 6 of the process. An example scenario table is provided in Table 514.8F-D.IV. The weighting factors will be discussed further in paragraph 2.7. The example scenario table also includes a user input field for the slope to be used for time compression calculations. The remaining fields should be calculated by the software and contain the total g-rms levels of the ASD(SpkRmvd), over the user defined bandwidth of interest, for each channel of each event. For example, Column “1 GRMS” contains the g-rms levels for channel 1 for all events.

Table 514.8F-D.IV. Scenario Table Input



Event No	Event Name	Scenario Time	Weighted Factor Col	Weighted Factor Un-Col	1 GRMS	2 GRMS	3 GRM
1	Radial Washboard 5 MPH	6.62	1	6.62	0.0327	0.0639	0.06
2	Radial Washboard 10 MPH	9.76	1	9.76	0.0686	0.1309	0.19
3	Radial Washboard 15 MPH	3.51	1	3.51	0.1289	0.2524	0.30
4	Embedded Rock 5 MPH	9.01	1	9.01	0.0532	0.1201	0.12
5	Embedded Rock 7.5 MPH	11.04	1	11.04	0.0858	0.1839	0.18
6	Embedded Rock 10 MPH	4.74	1	4.74	0.1246	0.2647	0.22
7	Belgian Block 5 MPH	1.05	1	1.05	0.0238	0.0512	0.04
8	Belgian Block 10 MPH	3.24	1	3.24	0.0443	0.0862	0.08
9	Belgian Block 15 MPH	5.18	1	5.18	0.0616	0.1077	0.12
10	Belgian Block 20 MPH	5.02	1	5.02	0.0825	0.1542	0.16
11	Belgian Block 25 MPH	1.88	1	1.88	0.1238	0.2285	0.23
				Col Sum-Set GRMS	0.1289	0.2647	0.30(

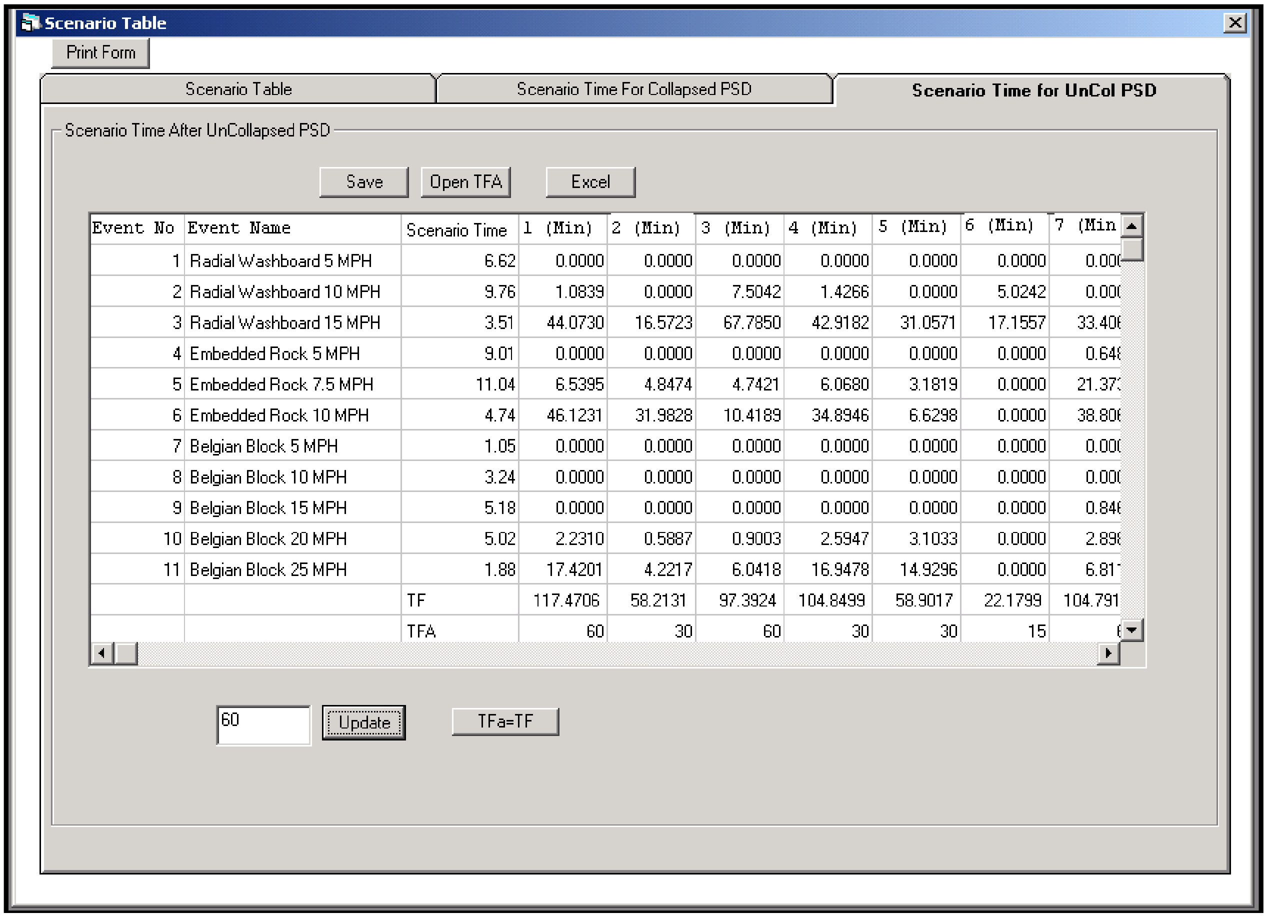
From this point forward, only the events with a g-rms above a threshold selected by the analyst will be processed. The threshold was presented in Table 514.8F-D.I (Minimum g-rms) and is set as a ratio of the maximum g-rms, typically 0.50. As higher level vibration dominates fatigue exposure, the exclusion of lower level events will have little effect on the final test time. When selecting the threshold for event inclusion, the analyst must consider both the preservation of the spectral information of the lower level events and the effects their shape will have on the more dominate, high level events. The events with a g-rms above the threshold will be referred to as "included events".

For each channel, the software should calculate the peak and average g-rms of the included events. The average becomes the base g-rms level utilized for processing. The base g-rms level will be the g-rms of the vibration profiles before final adjustment of test times is made.

The primary function of Step 6 (Scenario Table) is to calculate a vibration runtime associated with each event. The calculations are made using Equation 9-5, a standard method based on the Miner-Palmgren hypothesis for adjusting vibration spectra test times and levels. The slope (*m*) is typically set to a value of 7.5 for broadband random calculations. Further discussions of Miner's Rule can be found in Annex F, paragraph 9.0.

An example runtime table is provided in Table 514.8F-D.V. Individual events (1-11) are given in rows and individual channels (1-7) are given in columns. Table 514.8F-D.V has been populated by the software using equation 9-5 and the input provided in the Table 514.8F-D.IV. Note that the events for which the g-rms (given in Table 514.8F-D.IV) was less than 50 percent of the maximum g-rms (for the same channel) are set to a value of zero. For example, the maximum g-rms for channel 1 in Table 514.8F-D.IV is 0.1289 g-rms. Six of the eleven events have a g-rms greater than 0.0644 (0.5*0.1289) as reflected by the entries in Table 514.8F-D.V. The weighed-average g-rms of the six included events for channel 1 is 0.09198 g-rms. Application of Equation 9-5 for event 2 of channel 1, with G_1 = 0.0686 (from Table 514.8F-D.IV), G_2 = 0.09198 (the weighted-average g-rms), T_1 = 9.76 minutes (scenario time for event 2) yields a runtime for channel 1 and event 2 of T_2 = 1.0839, which is reflected in the entry of Table514.8F-D.V. The weighted rms is calculated by multiplying the scenario time by the associated g-rms. The weighted-average rms is the sum of the weighted g-rms values (for included events) divided by the sum of the scenario times (for included events). As all included events for a given channel are effectively normalized to the same g-rms level, the associated runtimes can simply be totaled to provide the overall runtime for that channel at that g-rms. The individual event run times are totaled in the row labeled TF in Table 514.8F-D.V. This total time is the run time required to provide equivalent broadband fatigue exposure to the system, assuming the broadband profile is also based on an average of the ASDs of the same group. The derivation of that average ASD will be discussed in paragraph 2.7.

Table 514.8F-D.V. Runtime Calculation



Event No	Event Name	Scenario Time	1 (Min)	2 (Min)	3 (Min)	4 (Min)	5 (Min)	6 (Min)	7 (Min
1	Radial Washboard 5 MPH	6.62	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00
2	Radial Washboard 10 MPH	9.76	1.0839	0.0000	7.5042	1.4266	0.0000	5.0242	0.00
3	Radial Washboard 15 MPH	3.51	44.0730	16.5723	67.7850	42.9182	31.0571	17.1557	33.40
4	Embedded Rock 5 MPH	9.01	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.64
5	Embedded Rock 7.5 MPH	11.04	6.5395	4.8474	4.7421	6.0680	3.1819	0.0000	21.37
6	Embedded Rock 10 MPH	4.74	46.1231	31.9828	10.4189	34.8946	6.6298	0.0000	38.80
7	Belgian Block 5 MPH	1.05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00
8	Belgian Block 10 MPH	3.24	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00
9	Belgian Block 15 MPH	5.18	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.84
10	Belgian Block 20 MPH	5.02	2.2310	0.5887	0.9003	2.5947	3.1033	0.0000	2.89
11	Belgian Block 25 MPH	1.88	17.4201	4.2217	6.0418	16.9478	14.9296	0.0000	6.81
		TF	117.4706	58.2131	97.3924	104.8499	58.9017	22.1799	104.791
		TFA	60	30	60	30	30	15	[illegible]

2.7 Calculate Weighted ASD (Step 7).

Steps 7 and 8 are used to complete the LVTS development process. At this point in the development process, an ensemble of single-event ASD sum-sets has been generated and consists of a sum-set for each channel of each event. The fifth ASD of the sum-set, the spectral spike removed ASD, is the working ASD for the VSD process. The multiple ASD(SpkRmvd) of a given channel (one for each event) must be combined to produce the broadband profile for that channel. The ASDs are combined using the methods discussed in the following paragraphs to produce a "group sum-set". The group sum-set, similar to the single-event ASD sum-set, includes a number of ASDs as defined in Table 514.8F-D.VI.

Table 514.8F-D.VI. Group Sum-Set Definition

ASD(Avg_g)	The weighted average of the ASD group. See Equation D.2-1. *(See* $G_a(f)$ *as defined in Appendix B)*
ASD(Peak_g)	Calculated by holding the maximum amplitude of each spectral line over all events.
ASD(Stdv_g)	The weighted standard deviation of the ASD group. See Equation D2.2-3. *(See* $G_e(f)$ *as defined in Appendix B)*
ASD(Sum_g)	Calculated by adding N_g standard deviations to the average for each spectral line. ASD(Sum_g) = N_g *ASD(Stdv_g) + ASD(Avg_g) Calculated by adding N_g standard deviations to the average for each spectral line. ASD(Sum) = N_e *ASD(Stdv) + ASD(Avg) N_g is a user defined variable typically set to 1. ASD(Sum) is limited by ASD(Peak) and M_g *ASD(Avg) where M_g is a user defined variable typically set to 2. *(See* $G_f(f)$ *as defined in Appendix B "for N=1")*
ASD(Final)	The ASD(Sum_g) scaled to a user selected final time.

The ASDs of the group sum-set, as with the single-event ASD sum-set, are calculated on a spectral line basis. The ASD(Avg_g) is an average of the ASD(SpkRmvd) for all events in the group (excluding those for which the g-rms is below the user defined threshold). Unlike the ASD(Avg) of the single-event ASD sum-set, the ASD(Avg_g) is not a standard n average ASD. Instead, the individual ASDs are weighted to the factors defined in the scenario table (see Table 514.8F-D.IV). Typically, the weighting factors are set equal to the individual event scenario times. The idea of a weighted approach is to produce a time-based calculation instead of an event-based calculation. In effect, weighting to the scenario time produces a separate ASD for each minute of the lifecycle, instead of an ASD for each event. Each minute of the system's lifecycle would then be weighted equally in determining the average. A similar method is used to calculate the standard deviation of the group ASD(Stdv_g).

Assuming there are n events that exceed the minimum g-rms, that W_i is weighting factor of each event, and that G_i is the g^2/Hz level of each event, then for each spectral line:

$$ASD(Avg\_g) = \frac{\sum_{i=1}^{n} W_i G_i}{\sum_{i=1}^{n} W_i} \qquad \text{D.2-1}$$

$$ASD(Stdv\_g) = \sqrt{\frac{\sum_{i=1}^{n} W_i * [G_i - ASD(Avg\_g)]^2}{\sum_{i=1}^{n} W_i}} \quad \text{D.2-2}$$

The ASD(Sum_g) is calculated by adding N_g standard deviations to the average, where N_g is a user defined variable typically set to 1. Use of the ASD(Sum_g) is intended to account for factors such as differences in road surfaces, driver variances, and consideration of road surfaces not included in the data acquisition phase and other relevant variables. The ASD(Sum_g) is constrained to be no higher than M_g*ASD(Avg_g) where M_g is a user defined parameter with a default value of 2.0. The ASD(Sum_g) is also limited to the ASD(Peak_g) level at each spectral line. Although some additional processing may be required, the ASD(Sum_g) coupled with the runtime calculated in the previous step now represent the equivalent lifetime fatigue of an item mounted at that location. Recall that each channel represents a vibration axis for a given location. The ASD(Sum_g) becomes the working ASD and is passed forward to the next step.

In some cases multiple channels (or locations) must be combined into a single LVTS. This can be accomplished by simply enveloping the channels later in the VSD process. However, it is possible to combine multiple channels concurrently with the event combination. Assuming j is a list of m channels to combine, then for each spectral line:

$$ASD(Avg\_g) = \frac{\sum_{j=1}^{m} \sum_{i=1}^{n} W_{ij} G_{ij}}{\sum_{j=1}^{m} \sum_{i=1}^{n} W_{ij}} \quad \text{D.2-3}$$

$$ASD(Stdv\_g) = \sqrt{\frac{\sum_{j=1}^{m} \sum_{i=1}^{n} W_{ij} * [G_{ij} - ASD(Avg\_g)]^2}{\sum_{j=1}^{m} \sum_{i=1}^{n} W_{ij}}} \quad \text{D.2-4}$$

2.8 Calculate Weighted Intermediate LVTS (Step 8).

The next step in the development of the broadband vibration profile is to adjust the run time. The software should allow the analyst to select the runtime for each channel. In the example of Table 514.8F-D.V, the runtime for each channel is shown in the TFA field. Runtimes are typically adjusted to round the times calculated by the software to even time increments or to exaggerate the test schedule when desired. Care must be taken to assure the final LVTS levels do not overly exceed the maximum levels measured in the field and that exaggeration, if used, is not excessive. See Annex F, paragraph 9.2.1.2 for a discussion of limiting exaggeration. Step 8 simply applies Equation 9.5 to scale the ASD(Sum_g) to the user selected runtime, producing the final broadband ASD, ASD(Final).

Depending on the control methods used, further processing may be required. For SOR control the broadband profile must be combined with the sine tone information. It may also be necessary to combine the profiles of several channels into a single LVTS. At this point it is helpful to export the ASD(Final) in a form that facilitates spreadsheet analysis. This allows ease of processing for multi-channel combination, recombining with narrowband or sine tone, changes in runtime, or other specialized processing.

Note that an alternate method of combining the broadband profiles of multiple events into a representative LVTS is discussed in paragraph 7. This alternate method would begin with the ASD(SpkRmvd) and would produce an alternate ASD(Final).

3. NARROWBAND RANDOM SPECIFICATION DEVELOPMENT PROCEDURE.

To allow greater flexibility in adapting to project specific requirements, the narrowband or sine tones removed from the broadband (see paragraph 2.5) can be processed in a spreadsheet. A sample narrowband random spreadsheet is provided in Table 514.8F-D.VII. The sample is of a wheeled vehicle on the 2-inch Washboard Course. Three tones were removed from each of three events (5, 7.5 and 10 mph). Note that sinusoidal processing, rather than narrowband random, would generally be used for a wheeled vehicle on the 2-Inch Washboard Course. The example is used for ease of discussion only, and will not affect the description of the process.

The following definitions provide a column-by-column description of the narrowband random processing procedures.

3.1 Event (Col. A) – This column lists the events and tones (or harmonics) removed from the broadband.

3.2 Speed on 2" WB (Col. B) – This column contains the ground speed of the given event.

3.3 Center Frequency Selected (Col C.) – The center frequencies of the narrowbands of interest may be set to the center frequencies of the narrowbands removed during spectral spike removal. However, it might be desirable to calculate the center frequency. For example, the center frequencies of a wheeled vehicle on a periodic course may be affected by slight changes in vehicle speed or the frequency resolution of ASD calculations. For proper control on an exciter table the tones must be harmonically related and are best set to the frequencies that would have resulted given ideal conditions. For a wheeled vehicle the frequencies can be calculated using the vehicle speed and the displacement of the periodic input (i.e., washboards spaced 0.6 meters apart). For a helicopter the frequencies can be set to the known blade passing frequency. Care should be taken to assure that the center frequency calculated does not vary significantly from the actual center frequency measured.

3.4 Test Time from Adjusted Beta Distribution (Col. D) – Generally, this column contains the times as calculated during scenario development (see Annex F, paragraph 7.1). However, the field is labeled "Adjusted" because it is sometimes necessary to combine the narrowbands of multiple events. For example, with a rotary wing aircraft the tones for all events are generally at the same frequencies (driven by the main rotor). A similar case results for narrowbands associated with tracked vehicles driven over multiple terrain types at the same speed. During processing, all narrowbands of like frequency must be combined into a single narrowband containing the combined energy of the group. Equation 9.1 or Equation 9.5 can be used to adjust the scenario times such that the g-rms of the individual narrowbands are normalized to some common g-rms, typically the maximum g-rms of the group. The adjusted test times of the individual tones (now all at the same g-rms level) are then totaled. This time is then entered into Column D of the narrowband table.

3.5 Actual Test Time (Col. E.) – This is the portion of the runtime for which the given narrowband will be within the given frequency region. Depending on the nature of the source vibration, the narrowbands will either dwell at a single frequency (i.e., helicopter) or sweep over a range of frequencies (i.e., tracked vehicle). In the case of sweeping narrowbands, the total run time selected by the analyst must be distributed across the sweep bandwidth, or the multiple narrowband breakpoints. The time is generally distributed equally between the multiple test points, with the two end points set to one half the time of the other points. See Annex F, paragraph 7.1 for an explanation of why the endpoints are treated differently.

3.6 Narrowband Bandwidth Selected (Col. F) – This field provides the width of each narrowband for vibration control. Note that the bandwidths of harmonically related tones must also be harmonically related. The bandwidth can established through a study of the individual events using pre-processing software.

3.7 Total g-rms of Tone ASD(Sum) (Col. G) – This field contains the g-rms of the narrowband energy removed from the ASD(Sum). In the case where multiple narrowbands must be combined, as discussed in paragraph 3.4, this number is the normalized g-rms used to combine the group.

3.8 Bandwidth Normalized g-rms (ASD) (Col. H.) – Modern control systems generally control to a ASD spectrum. Therefore, the g-rms values of the tones must be converted into ASD format. This is done by squaring the g-rms of Column G and dividing by the bandwidth of Column F, resulting in the g^2/Hz level of Column H. This g^2/Hz level represents the test level, before conservatism, associated with the test times of Column D.

Table 514.8F-D.VII. Narrowband Random Calculations

A	B	C	D	E	F	G	H	I	J	K	L
Tone Information					Narrowband Calculations						
Event	Speed on 2” WB	Center Freq Selected	Test Time from Adj Beta Dist	Actual Test Time	Narrowband Bandwidth Selected	Total g-rms of Tone ASD(Sum)	BandWidth Normalized g-rms (ASD)	ASD Adjusted to Test Time	Random Test Level	Ratio Adjusted to Normalized	Ratio Check
TONE 1 INFO											
5 mph 2” WB	5	3.67	55.41	30	2.5	2.67E-01	2.84E-02	3.35E-02	4.69E-02	1.18	
7.5 mph 2” WB	7.5	5.50	141.88	60	2.5	2.92E-01	3.42E-02	4.30E-02	6.02E-02	1.26	
10 mph 2” WB	10	7.33	49.80	30	2.5	4.77E-01	9.12E-02	1.04E-01	1.46E-01	1.14	
TONE 2 INFO											
5 mph 2” WB	5	7.33	55.41	30	5	1.13E-01	2.57E-03	3.03E-03	4.24E-03	1.18	
7.5 mph 2” WB	7.5	11.00	141.88	60	5	3.45E-01	2.38E-02	3.00E-02	4.20E-02	1.26	
10 mph 2” WB	10	14.67	49.80	30	5	3.72E-01	2.77E-02	3.18E-02	4.45E-02	1.14	
TONE 3 INFO											
5 mph 2” WB	5	11.00	55.41	30	7.5	2.67E-01	9.50E-03	1.12E-02	1.57E-02	1.18	
7.5 mph 2” WB	7.5	16.50	141.88	60	7.5	1.69E-01	3.80E-03	4.78E-03	6.69E-03	1.26	
10 mph 2” WB	10	22.00	49.80	30	7.5	2.41E-01	7.77E-03	8.89E-03	1.25E-02	1.14	

3.9 ASD Adjusted to Test Time (Col. I) – The g^2/Hz level of Column H is adjusted using Equation 9-5 to account for the difference in the scenario time (Column D) and the actual test time (Column E). A value of *m*= 7.50 is generally used when the engineering units are g^2/Hz.

3.10 Random Test Level (Col. J) - The g^2/Hz levels of Column I are scaled by a conservatism factor, generally 1.4, resulting in the narrowband random test levels of Column J. The conservatism factor is intended to account for variations in level due to differences in road conditions, road conditions not considered, drivers, pilots, weather conditions, and other relevant variables. These are the final narrowband test levels that will be included in the LVTS.

3.11 Ratio Adjusted to Normalized (Col. K) – This column contains the ratio of the "ASD adjusted to test time" to the "bandwidth normalized ASD levels" (Column I / Column H). This is to assure that excessive exaggeration has not been applied. Observe that commercially available vibration control systems currently restrict sweep rates to be either linear or logarithmic which, unfortunately, is generally not typical of most mission scenarios (i.e., refer to the shape of the speed distribution produced by a beta distribution). Forcing the narrowbands to sweep in either a linear or logarithmic manner will require magnitudes to be modified via Equation 9-5 as discussed in Annex F, paragraph 9. The analyst will need to be cautious in addressing the amount of time compression during this process. Column K in the example spreadsheet provides a quick visual check of compression employed in development of the narrowband portion of the spectrum.

3.12 Ratio Check (Col. L) – If the ratio if Column K exceeds a user selected factor, a flag is set in column L warns the analyst. Annex F, paragraph 9 recommends a limit factor of 2.0 when considering ASD (g^2/Hz) levels. In the event the ratio check indicates excessive scaling it may be helpful to divide the LVTS into multiple LVTS that each sweep over some portion of the full range. This will allow adjustment of the distribution of time into the separated ranges, but will increase the number of LVTS's required to represent the LCEP of interest. There will generally be some level of engineering judgment required during this phase of a LVTS development. For example, following the guidance of not increasing the ASD levels via time compression techniques by more than 2:1 is still viable for the higher level narrowbands or at any frequency known to be critical to the payload or carrier vehicle. However, if a low amplitude harmonic not associated with a critical frequency exceeds the 2:1 criteria for a limited portion of a sweep one could consider making an exception. For cases in which time compression techniques of the narrowbands result in excessive deviation from the 2:1 criteria, the analyst may be required to break the LVTS into multiple LVTS developments in which a finer breakdown of the mission scenario is addressed (i.e., develop a low, medium, and high speed LVTS per axis). One should also use caution to ensure that the ratio is no less than 1:1 for the higher level narrowbands or at any frequency known to be critical to the payload or carrier vehicle.

3.13 Tracked Vehicle Considerations.

The division into multiple LVTS discussed in the previous paragraph may be particularly helpful in the case of tracked vehicles. For tracked vehicles, the narrowband center frequency is a function of the vehicle speed. It may be possible to have a single broadband that represents all speeds, and to sweep the narrowband in a single sweep that encompasses all relevant speeds. However, if the broadband level changes significantly as a function of speed it may be desirable to split the multiple speeds into two or more LVTS, each of which include a given speed range.

4. SINE TONE SPECIFICATION DEVELOPMENT PROCEDURE.

The procedures for sine tone development are similar to those for narrowband random development. A sample sine tone spreadsheet is provided in Table 514.8F-D.VIII. The sample is of the same wheeled vehicle on the 2-Inch Washboard Course as the narrowband random example. Three tones were removed from each of three events (5, 7.5 and 10 mph). The following paragraphs provide a column-by-column description of the sine tone processing procedures.

Table 514.8F-D.VIII. Sine Tone Calculations

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Tone Information						Sine Tone Calculations								
Event	Speed on 2" WB	Sine Tone Freq Selected	Test Time from Adj Beta	Actual Test Time	Total g-rms of Tone ASD(Avg)	Sine G-Peak	Sine Peak Adjusted to Test Time	Sine Test Level	MAX Disp (inch Pk-Pk)	Disp Warn	Max Vel in/sec	Raw Data Vel	Ratio Adj Peak	Ratio Check
TONE 1 INFO														
5 mph 2" WB	5	3.67	55.41	30	0.218	3.09E-01	3.40E-01	4.08E-01	0.59		6.8	5.17	1.10	
7.5 mph 2" WB	7.5	5.50	141.88	60	0.245	3.47E-01	3.98E-01	4.78E-01	0.31		5.3	3.88	1.15	
10 mph 2" WB	10	7.33	49.80	30	0.406	5.74E-01	6.22E-01	7.47E-01	0.27		6.3	4.81	1.08	
TONE 2 INFO														
5 mph 2" WB	5	7.33	55.41	30	0.089	1.25E-01	1.38E-01	1.66E-01	0.06		1.4	1.05	1.10	
7.5 mph 2" WB	7.5	11.00	141.88	60	0.244	3.45E-01	3.96E-01	4.75E-01	0.08		2.7	1.93	1.15	
10 mph 2" WB	10	14.67	49.80	30	0.294	4.16E-01	4.51E-01	5.42E-01	0.05		2.3	1.74	1.08	
TONE 3 INFO														
5 mph 2" WB	5	11.00	55.41	30	0.192	2.72E-01	3.00E-01	3.60E-01	0.06		2.0	1.52	1.10	
7.5 mph 2" WB	7.5	16.50	141.88	60	0.121	1.71E-01	1.96E-01	2.35E-01	0.02		0.9	0.64	1.15	
10 mph 2" WB	10	22.00	49.80	30	0.173	2.44E-01	2.65E-01	3.17E-01	0.01		0.9	0.68	1.08	

4.1 Event (Col. A) – Same as paragraph 3.1.

4.2 Speed on 2" WB (Col. B) – Same as paragraph 3.2.

4.3 Sine Tone Frequency Selected (Col. C) – Same as paragraph 3.3, except instead of the center frequency of a narrowband tone it is a single frequency of a sine tone.

4.4 Test Time from Adjusted Beta Distribution (Col. D) – Same as paragraph 3.4.

4.5 Actual Test Time (Col. E) - Same as paragraph 3.5.

4.6 Total g-rms of Tone ASD(Avg) (Col. F) – Same as paragraph 3.7, except the g-rms comes from the ASD(Avg). The average ASD is used for sinusoidal data to prevent artificially high standard deviations from affecting the final test levels. If a spectral spike is truly sinusoidal, the standard deviation at the frequency of the spectral spike should be nearly zero. However, for ground vehicles, fluctuations in vehicle speed can result in errors in standard deviation calculations as the spectral spikes move with vehicle speed.

4.7 Sine G-Peak (Col. G) – For sinusoidal data, the g-rms values of Column F are simply converted to g-peak levels by multiplying by $\sqrt{2}$.

4.8 Sine Peak Adjusted to Test Time (Col. H) - The g-peak level of Column G is adjusted using Equation 9.1 to account for the differences in the scenario time (Column D) and the actual test time (Column E). A slope of m=6.29 is generally used when the units are in g-peak.

4.9 Sine Test Level (Col. I) - The g-peak levels of Column H are scaled by a conservatism factor, generally 1.2, resulting in the sine test levels of Column I. The conservatism factor is intended to account for variations in level due to differences in road conditions, road conditions not considered, drivers, pilots, weather conditions, and other relevant variables. These are the final sine test levels that will be included in the LVTS.

4.10 Max Displacement (inch Pk-Pk) (Col. J) – This is the displacement in inches, peak to peak, for a sine tone with a frequency of Column C and a level of Column I.

4.11 Displacement Warning (Col. K) – If the displacement calculated in Column J exceeds a user defined level, typically 1.5 inches, the analyst is flagged by this column.

4.12 Max Velocity in/sec (Col. L) – This is the maximum velocity resulting for the given test level. Care should be taken to assure the velocity levels do not exceed hardware capabilities.

4.13 Raw Data Velocity (Col. M) – This is the velocity based on the raw data measured in the field. This is provided to the analyst as a comparison point to the final velocity.

4.14 Ratio Adjusted Peak to Peak (Col. N) – This column is the ratio of the "sine peak adjusted to test time" to the "Sine G Peak" (Column H / Column G). This is to assure that excessive exaggeration has not been applied. Observe that commercially available vibration control systems currently restrict sweep rates to be either linear or logarithmic which, unfortunately, is generally not typical of most mission scenarios (i.e., refer to the shape of the speed distribution produced by a beta distribution). Forcing the sine tones to sweep in either a linear or logarithmic manner will require magnitudes to be modified via Equation 9-1 as discussed in Annex F, paragraph 9. The analyst will need to be cautious in addressing the amount of time compression during this process. Column O in the example spreadsheet provides a quick visual check of compression employed in development of the narrowband portion of the spectrum.

4.15 Ratio Check (Col. O) - If the ratio if Column N exceeds a user selected factor, a flag is set in column O warns the analyst. Exaggeration limits are discussed in Annex F, paragraph 9. In the event the ratio check indicates excessive scaling it may be helpful to divide the LVTS into multiple LVTS that each sweep over some portion of the full range. This will allow adjustment of the distribution of time into the separated ranges, but will increase the number of LVTS's required to represent the LCEP of interest. Additional information on this topic can be found in paragraph 3.12.

5. ALTERNATE BROADBAND DEVELOPMENT BASED ON FATIGUE DAMAGE SPECTRUM.

One method to develop a LVTS ASD(Final) and associated runtime was presented in paragraphs 2.6 to 2.8. An alternative approach could be derived from the Fatigue Damage Spectrum methods discussed in Appendix C.

6. FINAL DEVELOPMENT PROCEDURES.

The final stages of the VSD process can be completed in a spreadsheet file. Most procedures required to complete the VSD process, including the narrowband calculations presented in previous sections, can be incorporated into a spreadsheet package. The advantages of using a pre-developed spreadsheet, which has been heavily scrutinized, include: the elimination of errors that can occur during spreadsheet development, drastic reduction in development time, standardization of the VSD process, and the flexibility to incorporate project specific modifications.

A primary function of the spreadsheet should be to combine co-located channels into a single LVTS. Typically, this is accomplished by enveloping the multiple broadband profiles to create a single maxi-profile. Likewise, the sine or broadband levels of the multiple channels are enveloped. Since the maximum levels of the multiple development accelerometer channels become the final LVTS, maxi-control of multiple control accelerometers (located as similarly as possible to the corresponding development channels) is generally recommended.

The spreadsheet, or supporting software, should allow the analyst to select breakpoints. The original vibration profile includes a point for every spectral line over the full bandwidth. Breakpoints allow the shape and energy of the vibration profile to be represented with a minimal number of points. The breakpoints should match the shape and level of the original profile as closely as possible, particularly at frequencies near a system resonance. It might be desirable to scale the breakpoints such that the g-rms of the breakpoints equals that of the original profile. Care should be taken to assure scaling does not overly affect the ASD levels at frequencies of concern.

Other functions that could be included in the spreadsheet are: the ability to adjust the LVTS run time; checks to assure data accuracy and reduce development errors; calculations of broadband, narrowband, and sine tone parameters such as g-rms, displacement, velocity and sweep rates; combination of the broadband profile with the narrowband or sine tone profiles; and the presentation of data for review or for final publication.

As published, the final LVTS should include all information necessary to run the test in a laboratory. This information should include the control method, broadband breakpoints, the narrowband or sine tone breakpoints (if needed), control locations, control tolerances, runtime, sweep rates, sweep mode (logarithmic or linear), and any other required information.

Final LVTS's should be reviewed extensively to ensure the accuracy of the development process. One helpful tool for review is an overlay the final LVTS profile with the single-event ASDs of the measured field data. Gross errors in the development process are easily identified by the overlay. Other methods utilized during review include a comparison of like channels, a comparison to LVTS of similar vehicles, a comparison of input and response LVTS, a search for outliers, and a step-by-step review of the process.

7. COMBINING LVTS.

It is sometimes necessary to combine multiple LVTS into one. This can be due to the need to combine the exposure of more than one vehicle, or the desire to combine multiple LVTS developed for a single vehicle. For ASD's with similar spectral shapes, the following method can be used to combine the broadband portions of two or more LVTS. Refer to Table 514.8F-D.IX for an example of the calculations for combining two LVTS, LVTS01 and LVTS02. Note that each LVTS will consist of an ASD and an associated runtime. For the example assume LVTS01 Runtime = 30 min; LVTS02 Runtime = 15 min; Final Runtime = 20 min. First, Miner's Rule is utilized to perform a spectral line-by spectral line scaling of each LVTS to some normalized level. In the example each spectral line is normalized to the value of LVS02. This process assigns new test times to each spectral line of each LVTS. Once the power levels of the LVTS are equated, the individual times can simply be totaled on a spectral line basis. At this point a new combined LVTS has been created, LVTS_C. However, each spectral line has a varying associated test time. For the final step, the levels for each spectral line are scaled using Equation 9-5 such that all spectral lines are normalized to a final runtime selected by the analyst. A similar approach can be utilized to combine narrowbands or sine tones.

Table 514.8F-D.IX. LVTS Combination Example

Freq (Hz)	LVTS01 (G^2/Hz)	LVTS02 (G^2/Hz)	Norm Level (G^2/Hz)	LVTS01 New Time (min)	LVTS02 New Time (min)	Total New Time (min)	Final Run Time (min)	LVTS_C (G^2/Hz)
5	0.100	0.200	0.200	2.23	15.00	17.23	20.00	0.208
6	0.200	0.400	0.400	2.23	15.00	17.23	20.00	0.415
7	0.300	0.400	0.400	10.20	15.00	25.20	20.00	0.459
8	0.400	0.400	0.400	30.00	15.00	45.00	20.00	0.536
9	0.400	0.300	0.300	88.24	15.00	103.23	20.00	0.501

This method can also be used this to combine multiple events into a broadband LVTS, replacing the steps outline in paragraphs 2.6 through 2.8 above. An alternate method to add conservatism must be found, and care should be taken to assure the method does not corrupt the overall shape of the ASD set. Refer to paragraph 2.2.1 (main body of Method 514) for cautions associated with combining LVTS.

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METHOD 514.8, ANNEX F, APPENDIX E
Theoretical Aspects of Maximum Response

1. INTRODUCTION.

When a vibration excitation is applied to a mechanical system with one degree of freedom, the maximum value of the response of this system for a deterministic signal, or the probability of a maximum value for a random signal, can be calculated. This value is called the 'maximum' or the 'extreme' value. The maximum response spectrum is the curve that represents variations of the 'maximum' response value as a function of the natural frequency of the system with one degree of freedom, for a given damping factor ξ.

2. SINUSOIDAL EXCITATION.

Given a sinusoidal excitation with the form:

$$\ddot{x}(t) = \ddot{x}_m(t)\sin(2\pi f t)$$

The relative response displacement z(t) of a linear system with one degree of freedom is expressed:

$$z(t) = \frac{-\ddot{x}(t)}{\omega_0^2\left\{\left[1-\left(\frac{f}{f_0}\right)^2\right]^2 + 4\xi^2\left(\frac{f}{f_0}\right)^2\right\}^{\frac{1}{2}}}$$

For given values for f and f_0, z(t) is a maximum when $\ddot{x}(t) = \ddot{x}(m)$:

$$MRS = \omega_0^2 z(t) = \frac{-\ddot{x}(m)}{\left\{\left[1-\left(\frac{f}{f_0}\right)^2\right]^2 + 4\xi^2\left(\frac{f}{f_0}\right)^2\right\}^{\frac{1}{2}}}$$

The MRS is the curve representing the variations of $\omega_0^2 z_m$ versus f_0, for given value of ξ. The positive and negative spectra are symmetric. The positive spectrum goes through a maximum when the denominator goes through a minimum, i.e.:

$$MRS = \frac{\ddot{x}_m}{2\xi\sqrt{1-\xi^2}}$$

As an initial approximation, it can be considered that:

$$MRS = Q\ddot{x}_m$$

Example: MRS for a fixed sine excitation at 500 Hz with Q=5 (Figure 514.8F-E.1).

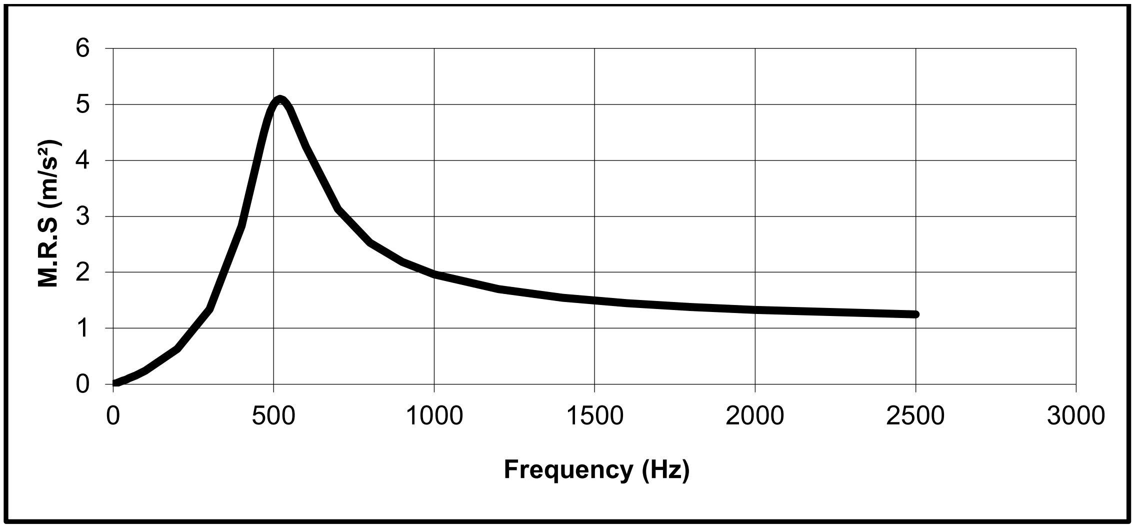

Figure 514.8F-E.1. MRS for a fixed sine excitation at 500 Hz with Q=5.

3. SWEPT SINE EXCITATION.

The MRS is extrapolated from the MRS of fixed sinusoidal signals at frequencies corresponding to the limits of the domain of sweeping.

Example: MRS for a swept sine from 300 Hz to 1200 Hz (Figure 514.8F-E.2).

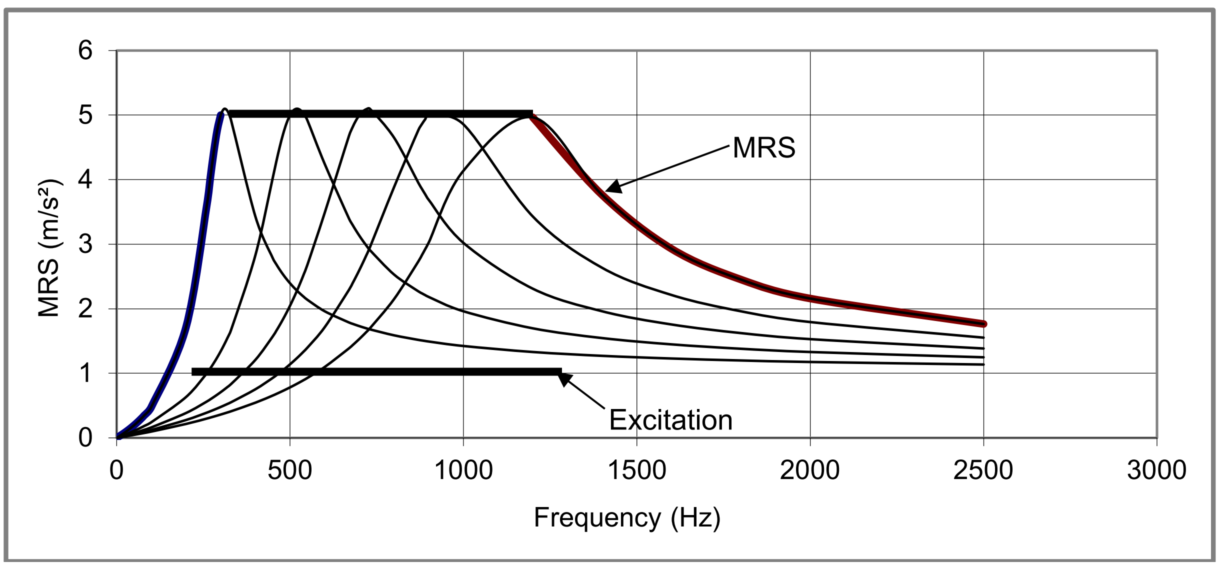

Figure 514.8F-E.2. MRS for a swept sine from 300 Hz to 1200 Hz.

4. RANDOM VIBRATION EXCITATION.

The MRS is calculated by considering the average number of times a threshold of the response z = a is exceeded with a positive slope for a time T. This number is given by the following equation for a Gaussian vibration:

$$N_a^+ = n_a^+ T = T e^{\frac{a^2}{2\pi_{eff}^2}}$$

Considering a threshold which is exceeded only once on the average, and setting $N_a^+ = 1$

$$a = z_{eff} \sqrt{2 \ln (n_0^+ T)}$$

which provides:

$$R = 4 \pi_2 f_0^2 z_s = 4 \pi_2 f_0^2 z_{eff} \sqrt{2 \ln (n_0^+ T)}$$

Example: MRS for a random vibration (Figure 514.8F-E.3) defined by:

100 – 300 Hz	0.5 g^2/Hz
300 – 600 Hz	1 g^2/Hz
600 – 1200 Hz	0.2 g^2/Hz

Q = 10

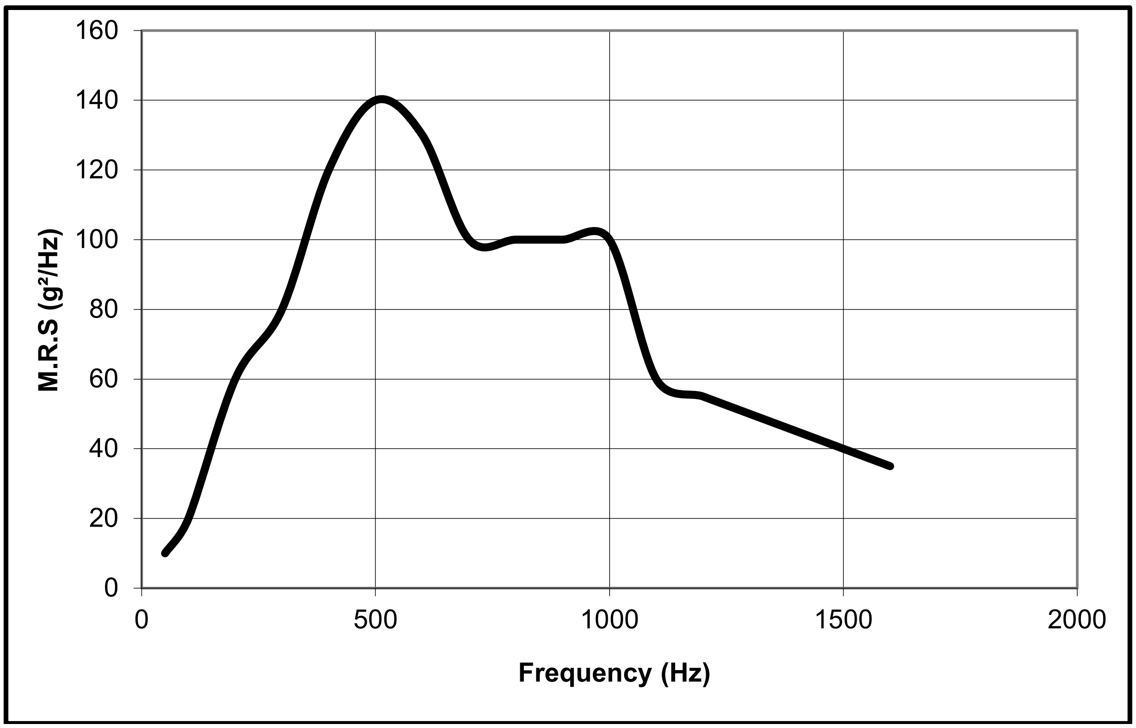

Figure 514.8F-E.3. MRS for a random vibration.

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METHOD 514.8, ANNEX F, APPENDIX F

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