METHOD 514.5

VIBRATION

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METHOD 514.5

VIBRATION

NOTES:

Tailoring is essential. Select methods, procedures, and parameter levels based on the tailoring process described in Part One, paragraph 4, and Appendix C. Apply the general guidelines for laboratory test methods described in Part One, paragraph 5 of this standard.

Organization. The main body of this method is arranged similarly to the other methods of MIL-STD-810F. A considerable body of supplementary information is included in the Annexes. With the exception of table 514.5-I, all tables and figures for the entire method are in Annex C. Reference citations to external documents are at the end of the main body (paragraph 6). The annexes are as follows:

ANNEX A - TAILORING GUIDANCE FOR VIBRATION EXPOSURE DEFINITION

ANNEX B - ENGINEERING INFORMATION

ANNEX C - TABLES AND FIGURES

1. SCOPE.

1.1 Purpose.

Vibration tests are performed to:

a. Develop materiel to function in and withstand the vibration exposures of a life cycle including synergistic effects of other environmental factors, materiel duty cycle, and maintenance. Combine the guidance of this method with the guidance of Part One and other methods herein to account for environmental synergism.

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

1.2 Application.

a. General. Use this method for all types of materiel except as noted in MIL-STD-810F, Part One, paragraph 1.3 and as stated in section 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 B for definitions and guidance.

c. Vibration life cycle. Table 514.5-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 guidance for estimating vibration levels and durations and for selection of test procedures. Annex B provides definitions and engineering guidance useful in interpreting and applying this method. International Test Operations Procedure (ITOP) 1-2-601 (ref d) includes an assortment of specific ground vehicle and helicopter vibration data.

d. Manufacturing. The manufacture and acceptance testing of materiel involves vibration exposures. These exposures are not directly addressed herein. It is assumed that the manufacturing and acceptance process completed on the units that undergo environmental testing are the same as the process used to produce deliverable units. Thus the environmental test unit(s) will have accumulated the same damage prior to test as a delivered unit accumulates prior to delivery. The environmental test then verifies the field life of delivered units. 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 units is not shortened. An example might be a pre-production unit completely assembled in one building, whereas production units are partially assembled at one site and then transported to another site for final assembly. Such exposures could be incorporated as pre-conditioning to the test program.

e. Environmental Stress Screen (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 units used for environmental test as pre-conditioning for the environmental tests. (See Annex A, paragraph 2.1.3 and Annex B, paragraph 2.1.8.)

1.3 Limitations.

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

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

c. Manufacture and maintenance. Vibration associated with processes at the manufacturer’s facility, or experienced during maintenance is not addressed herein. Guidance concerning transportation environments may be applicable to transportation elements of manufacture or maintenance processes.

d. Environmental Stress Screen (ESS). No guidance for selection of ESS exposures is contained herein. Some discussion is in Annex A, paragraph 2.1.3.

2. TAILORING GUIDANCE.

2.1 Selecting the Method.

Essentially all materiel will experience vibration, whether during manufacture, transportation, maintenance, or operational use. The procedures of this method address most of the life cycle situations during which vibration is likely to be experienced. Select the procedure or procedures most appropriate for the materiel to be tested and the environment to be simulated. See table 514.5-I for a general listing of vibration exposures and test procedures as related to environmental life cycle elements. See Annex A for guidance on determining vibration levels and durations.

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

b. Conservatism with measured data. The guidance in this document encourages the use of materiel-specific measured data as the basis for vibration criteria. Due to limitations in numbers of transducers, accessibility of measurement points, linearity of data at extreme conditions, and other causes, measurements do not include all extreme conditions. Further, there are test limitations such as single axis versus multi-axis, and practical fixtures versus platform support. Apply margin to measured data in deriving test criteria to account for these variables. When sufficient measured data are available, use statistical methods as shown in method 516.5.

c. Conservatism with predicted data. Annex A of this method and other sources such as the Mission Environmental Requirements Integration Technology (MERIT) computer program provide information which can be used to generate alternate criteria for those cases where measured data are unavailable. These data are based on envelopes of wide ranges of cases and are conservative for any one case. Additional margin is not recommended.

2.1.1 Effects of environment.

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

a. Chafed wiring.

b. Loose fasteners/components.

c. Intermittent electrical contacts.

d. Electrical shorts.

e. Deformed seals.

f. Failed components.

g. Optical or mechanical misalignment.

h. Cracked and/or broken structures.

i. Migration of particles and failed components.

j. Particles and failed components lodged in circuitry or mechanisms.

k. Excessive electrical noise.

l. Fretting corrosion in bearings.

2.1.2 Sequence.

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

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

b. Unique to this method. Generally, expose the test item to the sequence of individual vibration tests that follow the sequence of the life cycle. For most tests, this can be varied if necessary to accommodate test facility schedules or for other practical reasons. However, always perform some tests in the life cycle sequence. 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. Table 514.5-I provides a list of vibration environments by category versus test procedure. Descriptions of each category listed in this table are included in Annex A along with information for tailoring the test procedures of paragraph 4 below, and alternate test criteria for use when measured data are not available. In general, test materiel for each category to which it will be exposed during an environmental life cycle. Tailor test procedures to best accomplish the test purpose (see Annex B, paragraph 2.1), and to be as realistic as possible (Annex A, paragraph 1.2).

2.2.1 Procedure selection considerations.

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

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 A, paragraph 2.4.1) is sometimes substituted for transportation and maintenance vibration requirements.

c. Transportation configuration versus application configuration. 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.

2.2.2 Difference among procedures.

a. Procedure I - General Vibration. Use Procedure I for those cases where a test item is secured to a vibration exciter and vibration is applied to the test item 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. Annex A includes descriptions of various phases typical of an environmental life cycle along with discussions of important parameters and guidance for developing test parameters. Annex B has further guidance in interpretation of technical detail.

2.3.1 Climatic conditions.

Many laboratory vibration tests are conducted under Standard Ambient Test Conditions as discussed in Part One, paragraph 5. However, when the life cycle events being simulated occur in environmental conditions significantly different than standard conditions, consider applying those environmental factors during vibration testing. Individual climatic test methods of this standard include guidance for determining levels of other environmental loads. Methods 520.2, "Temperature, Humidity, Vibration, Altitude," and 523.2, "Vibro-Acoustic/Temperature," contain specific guidance for combined environments testing.

TABLE 514.5-I. Vibration environment categories.

Life Phase	Platform	Category	Materiel Description	Level & Duration Annex A	Test [1/]
Manufacture / Maintenance	Plant Facility / Maintenance Facility	1. Manufacture / Maintenance processes	Materiel / assembly / part	2.1.1	[2/]
		2. Shipping, handling	Materiel / assembly / part	2.1.2	[2/]
		3. ESS	Materiel / assembly / part	2.1.3	[3/]
Transportation	Truck / Trailer / Tracked	4. Restrained Cargo	Materiel as restrained cargo [4/]	2.2.1	I
		5. Loose Cargo	Materiel as loose cargo [4/]	2.2.2	II
		6. Large Assembly Cargo	Large assemblies, shelters, van and trailer units [4/]	2.2.3	III
	Aircraft	7. Jet	Materiel as cargo	2.2.4	I
		8. Propeller	Materiel as cargo	2.2.5	I
		9. Helicopter	Materiel as cargo	2.2.6	I
	Ship	10. Surface Ship	Materiel as cargo	2.2.7	I
	Railroad	11. Train	Materiel as cargo	2.2.8	I
Operational	Aircraft	12. Jet	Installed Materiel	2.3.1	I
		13. Propeller	Installed Materiel	2.3.2	I
		14. Helicopter	Installed Materiel	2.3.3	I
	Aircraft Stores	15. Jet	Assembled stores	2.3.4	IV
		16. Jet	Installed in stores	2.3.5	I
		17. Propeller	Assembled / Installed in stores	2.3.6	IV/I
		18. Helicopter	Assembled / installed in stores	2.3.7	IV/I
	Missiles	19. Tactical Missiles	Assembled / installed in missiles (free flight)	2.3.8	IV/I
	Ground	20. Ground Vehicles	Installed in wheeled / tracked / trailer	2.3.9	I/III
	Watercraft	21. Marine Vehicles	Installed Materiel	2.3.10	I
	Engines	22. Turbine Engines	Materiel Installed on	2.3.11	I
	Personnel	23. Personnel	Materiel carried by/on personnel	2.3.12	[2/]
Supplemental	All	24. Minimum Integrity	Installed on Isolators / Life cycle not defined	2.4.1	I
	All Vehicles	25. External Cantilevered	Antennae, airfoils, masts, etc.	2.4.2	[2/]

[1/] Test procedure – see paragraph 4
[2/] See Annex A reference.
[3/] Use applicable ESS procedure.
[4/] See paragraph 2.3.2.

2.3.2 Test item configuration.

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

a. Loose cargo. The method contained herein is a general representation based on experience as well as measurement, and is not tailorable (see Annex A, paragraph 2.2.2 for details). The most realistic alternative for truck, trailer, or other ground transportation is to utilize Procedure III. Note that Procedure III requires the transportation vehicle and a full cargo load.

b. Restrained cargo. Procedure I assumes no relative motion between the vehicle cargo deck or cargo compartment and the cargo. This applies directly to materiel that is tied down or otherwise restrained such that no relative motion is allowed considering vibration, shock, and acceleration loads. When restraints are not used or are such as to allow limited relative motions, provide allowance in the test set up 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 effect the vibration transmitted to individual items. Ensure the test item configuration includes appropriate numbers and groupings of materiel items.

2.4 Test Item Operation.

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

3. INFORMATION REQUIRED.

The following information is required to conduct and document vibration tests adequately. Tailor the lists to the specific circumstances, adding or deleting items as necessary. Although generally not required in the past, perform fixture and materiel modal surveys when practical. These data are useful in evaluating test results, and in evaluating the suitability of materiel against changing requirements or for new applications. These data can be particularly valuable in future programs where the major emphasis will be to utilize 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.

a. General. See Part One, paragraphs, 5.7 and 5.9, and Appendix A, Tasks 405 and 406 of this standard.

b. Specific to this method.

(1) Test fixture requirements.

(2) Test fixture modal survey procedure.

(3) Test item/fixture modal survey procedure.

(4) Vibration exciter control strategy.

(5) Test tolerances.

(6) Requirements for combined environments.

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

(8) Axes of exposure.

(9) Measurement instrumentation configuration.

(10) Test shutdown procedures for test equipment or test item problems, failures, etc.

(11) Test interruption recovery procedure.

(12) Test completion criteria.

c. Specific to Procedure.

(1) Procedure II - Loose cargo vibration. Define the orientation of test item(s) in relation to the axis of throw of the test table.

(2) Procedure III - Large assembly transportation. Define the test vehicle(s), loading(s), surface(s), distance(s), and speed(s).

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

3.2 During Test.

Collect the information listed in Part One, paragraph 5.10, and in Appendix A, Tasks 405 and 406 of this standard.

3.3 Post-Test.

a. General. See Part One, paragraph 5.13, and Appendix 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) Fixture modal analysis data.

(6) All vibration measurement data.

4. TEST PROCESS.

Tailor the following sections as appropriate for the individual contract or program. Note that if these sections are directly referenced in a contract, they will generally not comply with current and future Department of Defense requirements for contractual language.

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 utilizes standard laboratory vibration exciters (shakers), slip tables, and fixtures. Choose the specific exciters to be used based on size and mass of test items and fixtures, the frequency range required, and the low frequency stroke length (displacement) required.

4.1.2 Procedure II - Loose cargo transportation.

Simulation of this environment requires use of a package tester (figure 514.5C-5) that imparts a 25.4 mm (1.0 inch) peak-to-peak, circular 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).

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

b. Fencing. 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.

Note: Comparison of plywood bed and steel bed data show no statistical difference. Also, steel bed requires less maintenance and U. S. Army trucks use steel beds. See reference a.

4.1.3 Procedure III - Large assembly transportation.

The test facility for this method is a test surface(s) and vehicle(s) representative of transportation and/or service phases of the environmental life cycle. The test item is loaded on the vehicle and restrained or mounted to represent the life cycle event. The vehicle is then driven over the test surface in a manner that reproduces the transportation or service conditions. The test surfaces may include designed test tracks (e.g., test surfaces at the U. S. Army Aberdeen Test Center, 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 utilizes standard laboratory vibration exciters (shakers) driving the test item directly or through a local fixture. The test item is supported by a test frame independent of the vibration exciters (see paragraph 4.4.4). Select the specific exciters based on size and mass of test items and fixtures, frequency range, and low frequency stroke length (displacement) required.

4.2 Controls.

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

4.2.1 Control strategy.

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

4.2.1.1 Acceleration input control strategy.

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

4.2.1.2 Force control strategy.

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

4.2.1.3 Acceleration limit strategy.

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

4.2.1.4 Acceleration response control strategy.

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

4.2.1.5 Open loop waveform control strategy.

Monitoring accelerometers are mounted at locations on/in the test item for which measured data are available. The exciter is driven by an appropriately compensated time/voltage waveform obtained directly from (1) field measured data, or (2) a specified digitized waveform, and monitor acceleration responses are measured. In general, the compensated voltage waveform will be determined in the same way that a voltage waveform is determined for a shock test, i.e., from a convolution of the desired response waveform with the system impulse response function. This strategy is not generally applicable to the procedures of method 514.5. It is more generally used for control of transient or short duration, time-varying random vibration of method 516.5.

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.

Care must be taken to examine field measured response probability density information for non-Gaussian behavior. In particular, determine the relationship between the measured field response data and the laboratory replicated data relative to three sigma peak height limiting that may be introduced in the laboratory test.

a. Vibration environment. Maintain the acceleration spectral density at a control transducer within +2.0 dB or −1.0 dB over the specified frequency range. This tolerance is 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/octive) occur in the spectrum, these tolerances may have to be increased. When increases are required, exercise care to ensure the selected tolerances are the minimum attainable, and that attainable tolerances are compatible with test objectives. In any case, tolerances should not exceed ±3 dB over the entire test frequency range and +3, −6 above 500 Hz. These tolerances should be limited to a maximum of 5% of the test frequency range. Otherwise, change the tests, fixtures, or facilities so test objectives can be met. For Procedure IV, Assembled Aircraft Stores, the allowable deviation is ±3 dB.

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. For control and analysis systems of fast Fourier transform (FFT) type, use a resolution of at least 400 frequency lines. For wider frequency ranges the use of 800 frequency lines is recommended. Ensure the number of statistical degrees of freedom is not be less than 120.

c. Root mean square (RMS) "g." Do not use RMS g for 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. Define the tolerances on RMS g monitoring values based on the test variables and the test equipment. Do not use random vibration RMS g as a comparison with sinusoidal peak g. These values are unrelated.

4.2.2.2 Peak sinusoidal acceleration.

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

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

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

4.2.2.3 Frequency measurement.

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

4.2.2.4 Cross axis accelerations.

Ensure vibration acceleration in two axes mutually orthogonal and orthogonal to the drive axis is less than or equal to 0.45 times the acceleration (0.2 times the spectral density) in the drive axis at any frequency. In a random vibration test the cross axis acceleration spectral density often has high but narrow peaks. Consider these in tailoring cross-axis tolerances.

4.3 Test interruption.

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

b. Specific to this method.

(1) When interruptions are due to failure of the test item, analyze the failure to determine root cause. With this information, make a decision to restart, to replace, to repair failed components and resume, or to declare the test complete. Tailor this decision to the test and the test objectives. See Annex B, paragraph 2.1 for descriptions of common test types and a general discussion of test objectives.

(2) If a qualification test is interrupted because of a failed component and the component is replaced, continuation of the test from the point of interruption will not verify the adequacy of the replaced component. Each replaced component must experience the full vibration requirement prior to its acceptance. Additional guidance is provided in paragraph 5.2.

4.4 Test Setup.

See Part One, paragraph 5.8.

4.4.1 Procedure I - General vibration.

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

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

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

4.4.2 Procedure II - Loose cargo transportation.

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.” (Note that "multiple test items" refers to identical test items and not to a mixture of unrelated items.)

a. Rectangular cross section items. Position the test item on the package tester bed in its most likely shipping orientation. If the most likely shipping orientation cannot be determined, place the test item on the bed with the longest axis of the test item parallel to the long axis of the table (throw axis). Position the wooden impact walls and sideboards so as to allow impacting on only one end wall (no rebounding) and to prevent rotation of the test item through 90 degrees. Do not separate multiple test items by sideboards. The first half of the test is to be conducted with this orientation. The second half is to be conducted with the orientation of the test item rotated 90 degrees.

b. Circular cross section items with 4 or more test items. Place the impact walls so as to form a square test area with the walls parallel and perpendicular to the throw axis. Use the following formulae to determine the dimensions. Determine the slenderness ratio for individual test items by $R_T = L/D$, where R_T = the item slenderness ratio; L = the item length; D = the item diameter. Calculate an R_R value for defining the test area as follows:

$$R_R = N L / [0.767 L N^{1/2} - 2 S_W - (N-1) S_B]$$

where:

S_W = spacing between the test item and the side wall

S_B = spacing between test items

(S_W and S_B are chosen based on test item geometry to provide realistic impacting with impact walls and between test items. 25 mm is a typical value for both.)

N = number of test items where N > 3

If the $R_T > R_R$, the length of each side of the test area is given by "X" where:

$$X = 0.767 L N^{1/2}$$

If $R_T \leq R_R$, the length of each side of the test area is given by "W" where:

$$W = N D + 2 S_W + (N-1)S_B$$

c. Circular cross section items with 3 or fewer test items. Determine the slenderness ratio for individual test items by $R_T = L/D$. Calculate an R_R value for defining the test area as follows:

$$R_R = N L / [1.5 L - 2 S_W - (N-1) S_B]$$

If $R_T > R_R$, the length of each side of the test area is given by "X" where:

$$X = 1.5 L$$

If $R_T \leq R_R$, the length of each side of the test area is given by "W" where:

$$W = N D + 2 S_W + (N-1) S_B$$

Place the test item on the package tester, inside the impact walls, in a random manner. Because part of the damage incurred during these tests is due to items impacting each other, use more than 3 test items if possible.

4.4.3 Procedure III - Large assembly transportation.

Install the test item in/on the vehicle in its intended transportation or service configuration. If the 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 reference b). Also, ensure the selection of test surfaces, test distances, and test speeds are appropriate for the specified vehicles and their anticipated use.

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

c. Tie-down/mounting arrangements. During the test, it is important to reproduce the more adverse arrangements that could arise in normal use. For example, during transportation, relaxation of tie-down strap tension could allow the cargo to lift off the cargo bed and result in repeated shock conditions. Excessive tightening of webbing straps could prevent movement of test items and thereby reduce or eliminate such shocks.

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

a. Captive carriage test fixture. Suspend the test item from a structural support frame by means of the operational service store suspension equipment (bomb rack, launcher, pylon, etc.). Ensure that 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 that 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. In the past, stores have been hard mounted to large shakers. Do not attempt this because this has proven to be inadequate. Recent test experience with F-15, F-16, and F/A-18 stores indicates that including a structural support/reaction mass greatly improves the match between flight measured data and laboratory vibrations, particularly at lower frequencies.

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

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

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

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

(1) Transmit vibration to the store by means of rods (stingers) or other suitable devices running from vibration exciters to the store. Separate drive points at each end of the store in each axis are recommended. Ideally, the store will be driven simultaneously at each end. However, it can be driven at each end separately. A single driving point in each axis aligned with the store aerodynamic center has also been successful. Use drive points on the store surface 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) This test is intended to represent a highly random, highly uncorrelated vibration condition. Thus, when two vibration exciters are used simultaneously, the two drive signals are uncorrelated. Note that two drive signals that start out uncorrelated and that are from two separate controllers may

become correlated unless uncorrelation is forced. In general, the use of two vibration exciters will require some knowledge of current dual drive testing capabilities that include specification of the vibration exciter cross spectral density matrices.

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 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, if any, between field measurement data and laboratory measurement data.

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

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

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

4.5 Test Execution.

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

4.5.1 Preparation for test.

4.5.1.1 Preliminary steps.

Before starting 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 functional 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 that 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.

4.5.2 Procedure I - General vibration.

Step 1. Perform a visual inspection of the test item and an operational check. If a failure is noted, proceed as in paragraph 4.3.

Step 2. Conduct fixture modal survey and verify that fixture meets requirements, if required.

Step 3. Mount the test item to the test fixture in a manner dynamically representative of the life cycle event simulated.

Step 4. 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 5. Conduct test item modal survey, if required.

Step 6. Perform a visual inspection of the test item and, if applicable, an operational check. If failure is noted, proceed as in paragraph 4.3.

Step 7. Apply low level vibration to the test item/fixture interface. If required, include other environmental stresses.

Step 8. Verify that the vibration exciter, fixture, and instrumentation system functions as required.

Step 9. Apply the required vibration levels to the test item/fixture interface, as well as any other required environmental stresses.

Step 10. Verify that vibration levels at test item/fixture interface 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 11. 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 shut down procedure (paragraph 3.1b(10)). Determine the reason for the shift and proceed in accordance with the test interruption recovery procedure (paragraph 3.1b(11)).

Step 12. When the required duration has been achieved, stop the vibration. Depending on the test objectives, the test plan may call for additional exposures at varied levels prior to shut down. If so, repeat steps 6 through 12 as required by the test plan before proceeding.

Step 13. 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 3.1b(11)).

Step 14. Verify that the instrumentation functions as required and perform an operational check of the test item. If a failure is noted, proceed as in paragraph 4.3.

Step 15. Repeat steps 1 through 14 for each required excitation axis.

Step 16. Repeat steps 1 through 15 for each required vibration exposure.

Step 17. Remove the test item from the fixture and Inspect the test item, mounting hardware, packaging, etc. Refer to paragraph 4.3 if there are failures.

4.5.3 Procedure II - Loose cargo transportation.

Step 1. Perform a visual inspection of the test item and an operational check.

Step 2. Conduct test item modal survey, if required.

Step 3. Place the test item(s) on the package tester within the restraining fences in accordance with paragraphs 4.1.2 and 4.4.2.

Step 4. Install instrumentation sufficient to measure any required parameters. Ensure that the total accuracy of the instrumentation system is sufficient to meet specified accuracy requirements.

Step 5. Operate the package tester for one-half of the prescribed duration.

Step 6. Perform a visual inspection of the test item and an operational check. If a failure is noted, proceed as in paragraph 4.3.

Step 7. Reorient the test item(s) and/or the fencing/impact walls in accordance with paragraph 4.4.2.

Step 8. Operate the package tester for one-half of the prescribed duration.

Step 9. Perform a visual inspection of the test item and an operational check. If a failure is noted, proceed as in paragraph 4.3.

4.5.4 Procedure III - Large assembly transportation.

Step 1. Perform a visual inspection of the test item and an operational check. If a failure is noted, proceed as in paragraph 4.3.

Step 2. Mount the test item(s) on/in the test vehicle as required in the test plan.

Step 3. 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 4. Subject the vehicle containing the test item to the specified test conditions.

Step 5. Perform a visual inspection of the test item and an operational check. If a failure is noted, proceed as in paragraph 4.3.

Step 6. Repeat steps 1 through 5 for additional test runs, test loads, or test vehicles as required by the test plan.

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. Place the test item in an operational mode and verify that it functions properly.

Step 4. Apply low level vibration to the vibration exciter/store interface(s) to ensure that the vibration exciter and instrumentation system function properly. For acceleration feedback control, use an initial input level 9 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 9 dB below the required test monitor value at all frequencies. For bending moment feedback control, use an initial input level that is 9 dB down from the required test monitor transducer spectrum.

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

Step 6. When the input vibration is adjusted such that the required input response (A1) is achieved, measure the off-axis response(s) (A2, A3). 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 balance the equation. 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.

$$2 = (R_1/A_1 + R_2/A_2) \text{ or, } 3 = (R_1/A_1 + R_2/A_2 + R_3/A_3)$$

where;
R_i = Test requirement level in g^2/Hz or $(N\text{-}m)^2$/Hz or $(in\text{-}lb)^2$/Hz for i = 1 - 3, and
A_i = Response 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 when vibration is being applied in the vertical axis, use the equation below as follows.

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

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

For vibration being applied in the horizontal axis, use the equation below as follows.

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

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

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

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

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

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

Step 8. Monitor the vibration levels and test item performance continuously through the exposure. If levels shift, performance deviates beyond allowable limits, or failure occurs, shut down the test in accordance with the test shut down procedure (paragraph 3.1b(10)). Determine the reason for the anomaly and proceed in accordance with the test interruption recovery procedure (paragraph 3.1b(11)).

Step 9. When the required duration has been achieved, stop the vibration. Depending on the test objectives, the test plan may call for additional exposures at varied levels prior to shut down. If so, repeat steps 6 through 9 as required by the test plan before proceeding.

Step 10. 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 3.1b(11)).

Step 11. 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 a failure is noted, proceed as in paragraph 4.3.

Step 12. Repeat steps 1 through 11 for each required excitation axis.

Step 13. Repeat steps 1 through 12 for each required vibration exposure.

Step 14. Remove the test item from the fixture and inspect the test item and mounting hardware. Refer to paragraph 4.3 if there are failures.

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 not enough to determine that something broke due to high cycle fatigue or wear. It is necessary to relate the failure to the dynamic response of the materiel to the dynamic environment. Thus, include in failure analyses a determination of resonant mode shapes, frequencies, damping values and dynamic strain distributions in addition to the usual material properties, crack initiation locations, etc. (See Annex B, paragraph 2.5).

5.2 Qualification Tests.

When a test is intended to show formal compliance with contract requirements the following definitions are recommended.

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

b. Test completion. "A vibration qualification test is complete when all elements of the test item have successfully passed a complete test. When a failure occurs, stop the test, analyze the failure, and repair the test item. Continue the test until all fixes have been exposed to a complete test. Each individual element is considered qualified when it has successfully passed a complete test. 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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ANNEX A

TAILORING GUIDANCE FOR VIBRATION EXPOSURE DEFINITION

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.

It is highly 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 514.5-I contains an outline of the following section with references to the paragraph numbers.

2. VIBRATION ENVIRONMENTS.

2.1 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.

2.1.1 Category 1 - Manufacturing/Maintenance processes.

All materiel will experience some vibration during manufacture and maintenance.

a. <u>Manufacture</u>. If manufacturing processes are identical for all items (including test items), this exposure is common and additional testing is not required. However, evaluate this environment and include it in design calculations when significant. When different serial number items (lots) experience significant differences in vibration exposure during manufacture, select vibration test specimens from those items that experience the maximum vibration exposure.

b. <u>Maintenance</u>. Evaluate this environment and include it in design and test exposures when significant.

c. <u>Exposure levels</u>. Measure exposure levels. Where levels vary between serial number items, use the maximum values.

d. <u>Exposure durations</u>. Determine exposure durations from the manufacturing and/or maintenance processes. Where durations vary between serial number items, use the maximum values.

2.1.2 Category 2 - Shipping and handling.

Parts, subassemblies, and materiel are subject to vibration of handling and transportation within and between manufacturing and maintenance facilities. If handling and transportation are identical for all items (including test articles), this exposure is common and testing is not required. However, evaluate this environment and include it in design calculations when significant. When there are significant differences between exposures to different serial number items (lots), select vibration test articles from those items that experience the maximum vibration exposure.

a. Exposure levels. Where transportation is by normal commercial means, use the applicable guidance of Annex A, paragraph 2.2. For other conditions, measure exposure levels.

b. Exposure durations. Where transportation is by normal commercial means, use the applicable guidance of Annex A, paragraph 2.2. Determine exposure durations from manufacturing and maintenance planning.

2.1.3 Category 3 - Environmental Stress Screen (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 times 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.

a. Exposure levels. Use specified exposure levels for part, subassembly, and materiel ESS.

b. Exposure durations. Use the maximum allowable production and maintenance exposure durations for part, subassembly, and materiel ESS.

2.2 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 1.3.b in the front part of this method, and Annex B, 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 516.5 for guidance on shock environments.

c. Shock or vibration isolation. Materiel as packaged for shipment should not have very low resonant frequencies (see Annex B, 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 Annex A, paragraphs 2.2.4 and 2.2.5).

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

Note: Annex A, paragraph 2.2.3, below, for truck/trailer large assembly cargo can be tailored to any cargo size or tiedown configuration when high accuracy of ground vehicle transport environmental measurement or test is required.

2.2.1 Category 4 - Truck/trailer/tracked - restrained 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 4-2. This environment may be divided into two phases, truck transportation over U.S. highways and mission/field transportation. Mission/field transportation is further broken down into two-wheeled trailer/wheeled vehicles and tracked vehicle categories.

a. Truck transportation over U. S. highways. This involves movement from the manufacturer's plant to any continental United States storage or user installation. (Data are available for U.S. 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.

b. 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, semi-trailers, and/or tracked vehicles. Typical distances for this phase are 500 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.

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

(1) Truck transportation over U. S. highways. Derive exposure levels from Annex C, figure 514.5C-1. These figures are based upon 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.

(2) Two-wheeled trailer and wheeled vehicles. Exposures are shown in Annex C, figures 514.5C-2 and 514.5C-3. Both trucks and two-wheeled trailers are utilized between the Forward Supply Point (FSP) and at the Using Unit (USU). Trailer vibration levels are significantly higher; use these to represent the wheeled vehicle environment. However, when materiel is too large for the two-wheeled trailer, use the composite wheeled levels.

(3) Tracked vehicles. A representative tracked vehicle spectrum shape is given in Annex C, figure 514.5C-4. Note that this figure is based on sweeping across the narrow band spikes as discussed in reference f that also contains detailed criteria for some tracked vehicles. Testing to this requirement will require a narrow band random-on-random vibration exciter control strategy.

d. Exposure durations. Base durations on the materiel Life Cycle Environment Profile. Annex C, table 514.5C-I shows the typical field/mission transportation scenario with the most typical vehicles.

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

(2) 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 vehicle is 40 minutes per 804.6 kilometers (500 miles) traveled (per axis).

(3) Tracked vehicles. Use environmental life cycle durations. See reference f for further guidance.

2.2.2 Category 5 - Truck/trailer/tracked - 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. 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 (references g and h) determined that a standard package tester (300 rpm, circular synchronous mode) (Annex C, figure 514.5C-5) provides a reasonable simulation of the loose cargo transportation environment. The movement of the package tester bed is a 2.54 cm (1.0 inch) diameter orbital path at 5 Hz (each point on the bed moves in a circular path in a plane perpendicular to the horizontal plane). The test item is allowed to collide with established test setup restraints.

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

b. 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 storage area to a Using Unit (see Annex C, table 514.5C-I). Scenario times in the materiel Life Cycle Environment Profile should be ratioed to define exposure times.

2.2.3 Category 6 - Truck/trailer/tracked - large assembly cargo.

For large materiel, it is necessary to recognize that the materiel and the transport vehicle vibrate as a flexible system (see Annex B, 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, trailer, tracked vehicle, or materiel mounted in a shelter that is then mounted on a truck, trailer, or dolly set. Ensure the materiel is mounted and secured on the transport vehicle(s) that is used during actual transport. Provide instrumentation to measure vertical vibration of the materiel mounts, cargo floor, or shelter floor. Provide additional instrumentation as needed to determine the vibration of the materiel and critical subassemblies.

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

a. Exposure levels. The assemblage should be in its deployment configuration and mounted on the vehicle for which it was designed. If the assemblage is to be contained in a shelter, it should be installed within the shelter in the deployment configuration. The exposure consists of traversing the transport vehicle over a prepared test course. The test course and vehicle speeds should represent the transportation terrain/road conditions of the Life Cycle Environment Profile. Note that 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 U.S. Army Aberdeen Test Center (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.

(1) Coarse washboard (150 mm waves 2 m apart) 8 km/hr

(2) Belgian block 24 km/hr

(3) Radial washboard (50 mm to 100 mm waves) 24 km/hr

(4) Two inch washboard (50 mm) 16 km/hr

(5) Three inch spaces bump (75 mm) 32 km/hr

b. Exposure durations. Ensure the durations (distances over) of each test course segment/speed combination are in accordance with the scenario(s) of the Life Cycle Environment Profile.

2.2.4 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 A, paragraph 2.3.1.

a. Low frequency vibration. Vibration criteria typically begins at 15 Hz. At frequencies below 15 Hz, it is assumed that the cargo does not respond dynamically (see Annex B, 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 513.5.

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 B, 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 System Program Office responsible for the aircraft type for this evaluation.

c. Exposure levels.

(1) Vibration qualification criteria for most jet cargo airplanes are available through the System Program Office responsible for the aircraft type. These criteria are intended to qualify equipment for permanent installation on the airplanes and are conservative for cargo. However, function criteria for equipment located in the cargo deck zones can be used for cargo if necessary. The guidance of Annex A, paragraph 2.3.1 can also be used to generate conservative criteria for specific airplanes and cargo.

(2) Annex C, figure 514.5C-6 shows the cargo compartment zone functional qualification levels of the C-5, C/KC-135, C-141, E-3, KC-10, and T-43 aircraft. Also, shown on the figure is a curve labeled "General Exposure." These are the recommended criteria for jet aircraft cargo. 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 Annex C, figure 514.5C-6 is used, select a duration of one minute per takeoff. Determine the number of takeoffs from the Life Cycle Environment Profile. Otherwise, take durations from the Life Cycle Environment Profile.

2.2.5 Category 8 - Aircraft - propeller.

Cargo vibration environments on propeller aircraft are dominated by relatively high amplitude, approximately sinusoidal spikes at propeller passage frequency and harmonics. Because of engine speed variations, the frequencies of the spikes vary over a bandwidth. There is wide band vibration at lower levels across the spectra. This wide band vibration is primarily due to boundary layer flow over the aircraft. These sources are discussed in Annex A, paragraph 2.3.2.

a. Low frequency vibration. Vibration criteria typically begin at 15 Hz. At frequencies below 15 Hz it is assumed that the cargo does not respond dynamically (see Annex B, 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.

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 B, 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 System Program Office responsible for the aircraft type for this evaluation.

c. Exposure levels. Contact the System Program Office responsible for the aircraft for vibration criteria. If no criteria are available, measurements of cargo deck vibration in the aircraft are recommended. As a last resort the guidance of Annex A, paragraph 2.3.2 can be used.

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

2.2.6 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 A, paragraph 2.3.3.

b. Sling loads. Cargo carried as sling loads below a helicopter is normally subjected to low level random vibration due to turbulent flow around the cargo with narrow band peaks due to helicopter main rotor blade passage. In addition, there will be low frequency (primarily vertical) motions due to the sling suspension modes (similar to vibration isolator modes, see Annex B, 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 Annex C, table 514.5C-IV. 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 A, paragraph 2.3.3. A revised version of reference f, scheduled for 1998 release, contains tailored criteria for specific helicopters.

(2) There is no current source of data to define slung cargo vibration levels. However, these levels should be low and should not be a significant factor in design of materiel that has a reasonable degree of ruggedness. Materiel that has been designed for vibration levels and durations equal to or exceeding the suggested minimum integrity test of Annex A, paragraph 2.4.1 should not be affected by this environment.

(3) Exposure durations. Take durations from the Life Cycle Environment Profile or from reference f.

2.2.7 Category 10 - Ship - surface ship.

The vibration environment of cargo carried in ships is fundamentally the same as for materiel installed on ships. See Annex A, paragraph 2.3.10.

a. Exposure levels. See Annex A, paragraph 2.3.10.

b. Exposure durations. See Annex A, paragraph 2.3.10.

2.2.8 Category 11 - Railroad - train.

Cargo vibration levels for rail transport are generally low in level and moderately wideband. Vertical axis vibration is typically more severe than lateral and longitudinal. See ITOP 1-1-050 (reference e).

a. Exposure levels. Annex C, figure 514.5C-7 provides a general definition of railcar vibration. The levels are such that this environment will not significantly affect materiel or packaging design in most cases. In those cases where the levels of Annex C, figure 514.5C-7 are significant to materiel, take measurements to determine the actual environments.

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

2.3 Operational Service.

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

2.3.1 Category 12 - Fixed wing aircraft - jet aircraft.

The vibration environment for materiel installed in jet aircraft (except engine-mounted, see Annex A, paragraph 2.3.11 and gunfire-induced, see method 519.5) 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 516.5 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 A, paragraph 2.4.1).

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 (reference i). Aerodynamically induced vibration usually predominates in vehicles that operate at transonic speeds at lower altitudes or supersonic speeds at any altitude (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 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 515.5 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. As 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 B, 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 Annex C, table 514.5C-III and figure 514.5C-8 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 Annex C, table 514.5C-III for heavier materiel. However, evaluate the installation of materiel weighing more than roughly 72 kg (160 lb.) for dynamic interaction. (See Annex B, 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 B, paragraph 2.4.2), 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.

2.3.2 Category 13 - Fixed wing aircraft - propeller aircraft.

The vibration environment for materiel installed in propeller aircraft (except engine-mounted, see Annex A paragraph 2.3.11, and gunfire induced, see method 519) is primarily propeller induced. The vibration frequency spectra consists of a broadband background with superimposed narrow band spikes (see references n through t). The background spectrum results from various random sources (see Annex A, paragraph 2.3.1) combined with many lower level periodic components due to the rotating elements (engines, gearboxes, shafts, etc.) associated with turboprops. The spikes are produced by the passage of pressure fields rotating with the propeller blades. These occur in relatively narrow bands centered on the propeller passage frequency (number of blades multiplied by the propeller rpm) and harmonics.

a. Constant propeller speed. Most current propeller aircraft are constant-speed machines. This means that rpm is held constant and power changes are made through fuel flow changes and variable-pitch blades, vanes, and propellers. These machines produce the fixed frequency spikes of Annex C, figure 514.5C-9. These spikes have a bandwidth because there is minor rpm drift, the vibration is not pure sinusoidal (Annex B, paragraph 2.3.3), and to account for materiel resonant frequency differences as modeled or tested and as manufactured and installed on the aircraft.

b. Varying propeller speed. When propeller speed varies during operation, a spectrum or set of spectra similar to Annex C, figure 514.5C-9 is required to define vibration levels. The spikes on these spectra would have bandwidths encompassing the propeller speed variations of operation. Separate spectra may be required to describe individual mission segments.

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

d. Exposure levels. Whenever possible, use flight vibration measurements to develop vibration criteria. In the absence of flight measurements, the levels of Annex C, table 514.5C-II can be used with the spectra of Annex C, figure 514.5C-9. These levels are based on C-130 and P-3 aircraft measurements (references p through t) and are fairly representative of the environments of these aircraft. The decline of spike acceleration spectral density with frequency is based on data analyzed in a spectral density format.

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

2.3.3 Category 14 - Rotary wing aircraft - helicopter.

Helicopter vibration (for engine-mounted materiel, see Annex A, paragraph 2.3.11, and for gunfire induced vibration, see method 519.5) is characterized by dominant peaks superimposed on a broadband background, as depicted in Annex C, figure 514.5C-10. 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 Annex A, paragraph 2.3.1). Vibration levels and spectrum shapes vary widely between helicopter types and throughout each helicopter, depending on strength and location of sources and the geometry and stiffness of the structure. Thus, the need for measured data is acute.

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

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

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

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

e. Exposure levels.

(1) For reasons stated above, the exposure levels for materiel installed in helicopters should be derived from field measurement (a revised version of reference f due for release in 1998 contains criteria for specific helicopters). When measured data are not available, levels can be derived from Annex C, figures 514.5C-10 and 514.5C-11, and table 514.5C-IV. These levels are intended to envelope potential worst-case environments. They do not represent environments under which vibration sensitive materiel should be expected to perform to specification. However, the materiel is expected to survive undamaged and to function to specification at the completion of the test. Materiel costs are often strongly influenced by the performance required in a vibration environment. Consequently, field measurement based vibration criteria can be very important.

(2) To determine levels, divide the aircraft into zones as shown in Annex C, figure 514.5C-11. Use the source frequencies of the main rotor in determining the values of A_1, A_2, A_3, and A_4 (Annex C, table 514.5C-IV) for all materiel locations except those defined below. For materiel located in the horizontal projection of the tail rotor disc, use the source frequencies of the tail rotor. In addition, ensure criteria for materiel located in an overlap of main and tail rotor zones includes both sets of frequencies. Fundamental main and tail rotor source frequencies of several helicopters are given in Annex C, table 514.5C-IV. For materiel located on or in close proximity to drive train components such as gearboxes and drive shafts, use the source frequencies of that drive train component (i.e., gear mesh frequencies, shaft rotational speeds). Determine these from the drive train data for the particular helicopter.

f. Exposure durations. When measured data are used to establish exposure levels, take durations from the Life Cycle Environment Profile. When levels are derived from Annex C, figures 514.5C-10 and 514.5C-11, and table 514.5C-IV, use a duration of four (4) hours in each of three (3) orthogonal axes for a total test time of twelve (12) hours. This represents a 2600-hour operational life. The fatigue relationship shown below may be used to trade test time for exposure level. Make the calculation separately for each sinusoid and each segment of the broadband background.

$$t_f = 4.0\,(A_D / A_T)^M$$

where:

t_f = actual test time per axis

A_D = default test amplitude

A_T = actual test amplitude

M = 6 (materiel exponent for sinusoidal vibration, see Annex B, paragraph 2.2)

2.3.4 Category 15 – Aircraft stores – assembled, jet aircraft.

Assembled jet aircraft stores may encounter three distinct vibration environments; external captive carriage, internal captive carriage, and free flight.

Note: High frequency vibration (beginning at or below 1000 Hz) cannot be practically transmitted to a store mechanically. Combine store vibration and acoustic testing (method 523.2). These test excitations in combination produce a much more realistic test.

a. Captive flight – external carriage. Vibration (for gunfire induced vibration see method 519.5) experienced by a store carried externally on a jet aircraft arises primarily from four sources:

(1) 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 (references u, v, and w).

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

(a) In single carriage, excitation is relatively independent of the carrying aircraft and mounting location on the aircraft. Local flow disturbances such as pylon wakes will vary considerably between aircraft and between store stations on a given aircraft. In general, these do not greatly effect overall store vibration. But, they may severely effect local structures such as tail fins that, in turn, may increase levels of store vibration. See Annex A, paragraph 2.4.2 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.

(b) An extensive program of measurement and analysis was accomplished to characterize this environment (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 523.2. 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. Note that this method also includes low frequency vibration transmitted from the carrying aircraft (see below).

(3) 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 B, paragraph 2.3.4).

(a) 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" above.

(b) Flight test measurements on the F-15 with various external stores, (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.

(c) 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.

(d) 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. Note that 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 section 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.

(4) 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.

(a) 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.

(b) Acoustic resonance of simple cavities is typically handled as an acoustic environment (see method 515.5). Any hole, opening, inlet, etc. that allows airflow to enter the store or a cavity in the store can produce high intensity acoustic resonance responses.

b. 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.

(1) 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.

(2) When the bay is opened in flight, a dramatic event occurs. This event is referred to as cavity resonance (references l and m) and results in high levels of turbulence inside the bay. This is wide band turbulence, and unless suppression devices are installed in the bay, with very high spikes across the spectrum. The low frequency portions of the disturbance are not likely to drive the store because disturbance wavelengths greatly differ from store dimensions. The high frequency part of the spectrum will significantly affect the store. Store vibration resulting from this turbulence cannot be adequately predicted. Acoustic characterizations of the turbulence exist for most active aircraft and the resulting vibration is best represented by the acoustic noise exposures of method 515.5.

(a) 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.

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

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 B, paragraph 2.3.4 and method 516.5) rather than steady state vibration.

c. 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.

(1) 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.

(2) 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.

(3) 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.

d. Exposure levels. Select test levels and spectra for three of the vibration environments, captive flight, free flight, and buffet from Annex C, table 514.5C-V and figures 514.5C-12 and 514.5C-13. 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 on 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 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.

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

2.3.5 Category 16 - Aircraft stores - materiel, jet aircraft.

Materiel installed within a jet aircraft store will experience the store vibration discussed in Annex A, paragraph 2.3.4. 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 Annex C, table 514.4C-V and figures 514.5C-13 and 514.5C-14. Note: use input control for vibration testing of this materiel rather than response control (see paragraph 4.2.1).

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

2.3.6 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 519.5). However, since the excitation sources are the same, it seems likely that store vibration will be similar to that of the carrying aircraft. See Annex A, paragraph 2.3.2 and Annex B, 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 Annex A, paragraph 2.3.4.

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 Annex C, table 514.5C-II and figure 515.5C-9 may be used to develop preliminary estimates of general vibration. The criteria of Annex C, figure 514.5C-13 may be applied for maneuver buffet vibration.

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

2.3.7 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 519.5.

a. Exposure levels. Derive exposure levels for helicopter-carried store materiel from field measurements (reference f contains criteria for specific helicopters). When measured data are not available, initial estimates can be derived from Annex C, figures 514.5C-10 and 514.5C-11, and table 514.5C-IV 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 Annex C, figure 514.5C-11. Most stores will be inside a vertical projection of the main rotor disc and should use the source frequencies of the main rotor in determining the values of A_1, A_2, A_3, and A_4 (see Annex C, table 514.5C-IV). Fundamental main rotor source frequencies of several helicopters are given in table 514.5C-IV.

b. Exposure durations. When measured data are used to establish exposure levels, take durations from the Life Cycle Environment Profile. When levels are derived from Annex C, figures 514.5C-10 and 514.5C-11, and table 514.5C-IV, 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.

2.3.8 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 are discussed in Annex A, paragraphs 2.3.4 through 2.3.7. Tactical carriage ground environments are discussed in Annex A, paragraph 2.3.9. Free flight environments are covered in Annex A, paragraphs 2.3.4.c and 2.3.5 in regard to aircraft carried missiles. These environments should be generally applicable to tactical missiles during free flight mission segments.

a. Exposure levels. There is no known source of data. For accurate definition of tactical missile store vibration, measurement of the actual environment is essential. The criteria of Annex C, table 514.5C-V and figure 515.5C-12 and figure 515.5C-14 may be used to develop preliminary estimates of free flight vibration.

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

2.3.9 Category 20 - Ground vehicles - ground mobile.

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 ITOP 1-2-601.) Terrain, road, and surface discontinuities, vehicle speed, loading, structural characteristics, and suspension system all affect this vibration. Note that gunfire criteria (method 519.5) 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. The spectra of Annex C, figures 514.5C-1 through 514.5C-3 are typical of cargo bed responses in wheeled vehicles and trailers. This may be unrealistic for installed materiel since it does not consider vehicle structural response beyond the heavily supported cargo bed. The large assembly cargo test of Annex A, paragraph 2.2.3 can be adapted to provide highly accurate tests for this materiel.

b. Track-laying vehicles. Track-laying vehicle environment (Annex C, figure 514.5C-4) is characterized by the strong influence of track-laying pattern. This environment is best represented by superimposing narrowband random (track-laying components) vibration at selected frequencies over a broadband random base.

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 presented in Annex A, paragraphs 2.2.1 and 2.2.2 may be adapted. Numerous measurements have been made and used to develop test criteria for tracked vehicles. Reference f contains criteria that may be used directly or adapted as necessary.

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

2.3.10 Category 21 - Watercraft - marine vehicles.

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. Note that gunfire vibration criteria per method 519.5 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 Annex C, figure 515.5C-15 for a duration of two hours along each of three orthogonal axes, and the sinusoidal requirements of MIL-STD-167, Type I (reference hh), with levels enveloping the highest values for each frequency. Note that this criteria 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.

2.3.11 Category 22 - Engines - turbine engines.

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

a. Constant speed. Many turbine engines are constant speed. This means that the rpm is held constant and power changes are made through fuel flow changes and variable pitch blades, vanes, and propellers. These machines produce the fixed frequency spikes of Annex C, figure 514.5C-16. These spikes have an associated bandwidth because there is minor rpm drift, the vibration is quasi-sinusoidal (see Annex B, 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 Annex C, figure 514.5C-16 to include the engine rpm range. Typically, the engine will have an rpm range associated with a power setting (i.e., idle, cruise, max continuous, take off, etc.). Thus, several spectra with different spike frequencies may be needed to represent all of the power conditions encountered during an engine life cycle.

c. Multiple rotors. Turbofan engines usually have two and sometimes three mechanically independent rotors operating at different speeds. Modify the spectra of Annex C, figure 514.5C-16 to include spikes for each rotor.

d. Design criteria. These vibration environments can be approximated in the laboratory by the narrowband random over broadband random test described in Annex B, 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 B, 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. Note that 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. Annex C, figure 514.5-16 levels can be used when measured data are not obtainable. These levels are rough envelopes of data measured on several Air Force aircraft engines.

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

2.3.12 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.

2.4 Supplemental Considerations.

2.4.1 Category 24 - All materiel - minimum integrity test.

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.

a. Basis for levels. Vibration levels and durations of Annex C, figures 514.5C-17 and 514.5C-18 are not based on application environments. Rather, experience has shown that materiel that withstands these exposures functions satisfactorily in the field, and that materiel tested to lower levels does not. These exposures are sometimes called "junk level" tests.

b. 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 that the materiel is adequately protected from vibration and shock during all phases of the environmental life cycle.

c. 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 B, paragraph 2.2.

d. Exposure levels. Test levels are shown in Annex C, figure 514.5C-17 for general use, and on figure 514.5C-18 for helicopter materiel. Note that 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).

e. Exposure durations. Test durations are shown in Annex C, figure 514.5C-17 for general use and on figure 514.5C-18 for helicopter materiel.

2.4.2 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 reference y, Chapter 7 and reference z, section 3.6 and chapters 5 and 6.

(1) Flutter is a mechanism where the vibrations of a "wing" in a flow are such as to produce lift forces and moments that reinforce and amplify the vibration. A "wing" is a cantilever beam with slender cross section (i.e., the dimension parallel to the airflow is much larger than the dimension perpendicular to the flow). Flutter is not the result of an environmental forcing function. It is a mechanism inherent in a design and once started it needs no further environmental excitation to sustain and amplify the motion. Flutter is a separate engineering specialty and should be handled by

flutter engineers. The vibration engineer needs to recognize flutter and the difference between flutter and other vibrations. Many artificial problems have been generated when other types of vibrations have been mislabeled as flutter. Conversely, flutter problems will not be solved until recognized as such and treated by flutter engineers.

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

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

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

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

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

$$f = 0.22\ V/D$$

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

f = frequency
V = velocity
D = cantilever cross section diameter
F = force
ρ = density

t = time
L = the exposed length (perpendicular to the cross section)

(For non-circular cross sections, D becomes the dimension perpendicular to the flow in the frequency equation and the dimension parallel to the flow in the force equation. See reference y, section 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 effect 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 down stream of a flow disturbance such as a cockpit canopy, a radome that projects into the air stream, or a cavity in the aircraft skin. Severe broadband flow turbulence carries downstream behind the disturbing element for a distance of three to five times the maximum cross sectional dimension of the disturbing element.

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

(2) Helicopters and external stores.

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

(b) Flight speeds of helicopters are lower than fixed wing aircraft and streamlining is not as important. Thus, blunt cross section cantilevers are more likely to be used. When blunt cross sections are used, care should be exercised to insure 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 effect large, low frequency structures. The low frequency turbulence produced by large trucks effects 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 reference z, section 6.1.) Dynamic absorbers are often useful in changing modal properties (see reference y, sections 3.2 and 3.3).

(2) Vortex shedding driven vibration also generally leads to rapid fatigue or wear failure. This problem typically involves a single mode of vibration of the materiel. If possible, the problem should be eliminated by separating the shed frequency and the resonant frequency (ideally by a factor of 2). If this is not practical, it may be possible to survive this mechanism for useful periods of time with good design. Good design consists of using materials with good fatigue properties, elimination of high stress points, and adding damping. In order to define exposure levels, it is necessary to measure the motions of the cantilever on the platform in the operating environment. These measurements are used to define modal responses. When laboratory tests are required, response control is necessary. This is because the primary energy input is directly from the fluid flow. Response of the cantilever to this input is greater than the response to the vibration environment at the mount.

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

d. Exposure durations. As discussed above, problems should be solved by eliminating instability mechanisms or by moving materiel away from turbulence. If it is necessary to define exposure durations, take them from the life cycle profile. Note that 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.

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ANNEX B

ENGINEERING INFORMATION

1. SCOPE.

1.1 Purpose.

This Annex provides information intended to be useful in interpreting the main body and Annex A of method 514.5.

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. Reference aa is recommended as a starting point.

2. ENGINEERING INFORMATION.

2.1 Vibration Test Types.

The following presents discussions of general types of vibration tests. The nomenclature and descriptions are based on U. S. Air Force aircraft practices. 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. It should be assumed that a qualification test, a durability test, or a reliability test consumes the test article such that it is not suitable for field deployment. Development tests and worthiness tests may or may not consume a complete life depending on the specific test goals. It is important to insure that 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, requirements, and success or failure criteria 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 that developed materiel is compatible with the environmental life cycle and that formal testing does not result in failure. The tests have a variety of specific objectives. Therefore, allow considerable freedom in selecting test vibration levels, excitation, frequency ranges, and durations. Typical programs might include modal analysis to verify analytical mode shapes and frequencies, and sine dwell, swept sine, transient, or random excitation transient vibration to evaluate function, fatigue life, or wear life. The test types, levels, and frequencies are selected to accomplish specific test objectives. Levels may be lower than life cycle environments to avoid damage to a prototype, higher to verify structural integrity, or raised in steps to evaluate performance variations and fragility.

2.1.2 Qualification test.

Qualification testing is conducted to determine compliance of a materiel with specific environmental requirements. Note that these tests are a simplified, shortened expression of the environmental life cycle. For most items, this consists of a functional test and an endurance test (sometimes combined). The functional test represents the worst case vibration (or envelope of worst case conditions) of the environmental life cycle. The endurance test is an accelerated fatigue test representing an entire life cycle. Typically, vibration is not combined with other environmental stresses although part of the vibration test may be at high temperature and part at low temperature. An exception might be the transportation of large assemblies where a production assembly is subjected to the test environment and then fielded.

2.1.3 Functional test.

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

2.1.4 Endurance test.

In the past, endurance test duration was normally set at one hour per axis. This approach has serious shortcomings.

a. Conventional approach. In the past, test levels were usually established by raising functional levels to account for equivalent fatigue damage. Another approach was to assume that if enough stress cycles (usually assumed to be 10^6 cycles) were accumulated without failure, that this demonstrated that the stresses were below the material endurance limit. Each of these approaches has serious shortcomings. The first requires testing at vibration levels well above levels seen in service. This ignores nonlinearity of material properties, joint friction, isolator performance, heat buildup, etc. The second ignores the fact that many materials (particularly those typical of electrical/electronic devices) do not exhibit endurance limits and that 10^6 stress cycles may not be sufficient for those that do.

b. Recommended approach. Use the simplified fatigue relationship below (see Annex B, paragraph 2.2, below) to determine the time at maximum service levels (functional levels) that is equivalent to a vibration lifetime (levels vary throughout each mission). Use the equivalent time as the functional test duration, thereby combining functional and endurance tests. There may be cases when this test duration is too long to be compatible with program restraints. In these cases, use as long of a test duration as is practical and use the fatigue relationship to define the test level. While this approach does not completely eliminate nonlinearity questions, it does limit levels to more realistic maximums.

2.1.5 Durability test.

Durability testing is a 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 Annex B, 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.

2.1.6 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. Multiple test items are often exposed to segments of a life cycle rather than one materiel test item exposed to a complete life cycle. The environmental simulation is established to fit these requirements and is generally similar to the durability testing discussed above.

2.1.7 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.

2.1.8 Environmental Stress Screen (ESS).

ESS is not an environmental test. It is a production or maintenance acceptance inspection technique. 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. Qualification tests should include maximum lifetime ESS exposure. Worthiness safety tests should include the maximum ESS exposure appropriate to the particular materiel. When materiel is to be subjected to worthiness test and then used in the field, it may be wise to substitute a worthiness test for ESS. This subjects the materiel to the minimum amount of vibration while showing field worthiness. Durability tests should include maximum ESS events in the correct positions in the life cycle simulation. For reliability tests, it may be appropriate to vary the ESS exposures between minimum and maximum.

2.2 Fatigue Relationship.

The following relationship may be used to determine vibratory fatigue equivalency between vibration exposures, to sum vibratory fatigue damage of separate vibration exposures, and to define accelerated test levels for vibration endurance tests:

$$(W_0 / W_1) = (T_1 / T_0)^{1/4} \quad \text{or} \quad (g_0 / g_1) = (T_1 / T_0)^{1/6}$$

W = random vibration level (acceleration spectral density, g^2/Hz)
g = sinusoidal vibration level (peak acceleration, g)
T = Time

This relationship is a simplified expression of linear fatigue damage accumulation. The exponent is the material constant (slope of a log/log fatigue or S/N curve). The values given are widely used for Air Force avionics. Other values are used for other types of materiel. For example, missile programs have used exponents ranging from 1/3.25 to 1/6.6. Space programs sometimes use 1/2. Many materials exhibit exponents between 1/6 and 1/6.5. This wide variation is based on degree of conservatism desired as well as material properties. More sophisticated analyses based on fatigue data (S/N curves) for specific materials should be used when practical. Note that using material S/N curves results in different equivalencies for different parts in a given materiel 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 mixed random and periodic. Usually, random vibration best simulates these environments. Situations do occur where combined sinusoidal and random vibration and sinusoidal alone are appropriate. Most vibration tests run with steady state excitation. Steady state vibration is appropriate at times in simulation of transient events. However, there are cases where transient events can only be satisfactorily represented by transient vibration excitation.

2.3.1 Random vibration.

Random vibration is expressed as acceleration spectral density (also referred to as power spectral density, or PSD) spectra. The acceleration spectral density at a given frequency is the square of the root mean square (rms) value of the acceleration divided by the bandwidth of the measurement. This gives a value expressed in terms of a one Hertz bandwidth centered on the given frequency. 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 $1/(BT)^{1/2}$, 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, with 1 Hz being ideal. In most cases, 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.

a. Frequency range. Acceleration spectral density is defined over a relevant frequency range. This range is between the lowest and highest frequencies at which the materiel may be effectively excited by mechanical vibration. Typically, the low frequency is one half the frequency of the lowest resonance of the materiel or the lowest frequency at which significant vibration exists in the environment. The high frequency is two times the highest materiel resonant frequency, the highest frequency at which significant vibration exists in the environment, or the highest frequency at which vibration can be effectively transmitted mechanically. It is generally accepted that the highest frequency for mechanically transmitted vibration is 2000 Hz, although practically it is often lower. (When frequencies around and above 2000 Hz are needed, it is generally necessary to augment the vibration with acoustic noise - see method 523.2.)

b. Rms values. The use of rms values to specify random vibration is not valid. 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 an 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 that the frequency range of the sinusoidal exposure is representative of the platform environment.

2.3.3 Mixed broadband and narrowband vibration.

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

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 Annex B, paragraph 2.4.3).

b. Sinusoid(s) over broadband random background. Ensure that the random spectrum is continuous over the frequency range and that it envelops all of the environment except for the amplitude(s) to be represented by the sinusoid(s). The sinusoid(s) amplitude(s) should envelop 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 Annex B, paragraph 2.4.3).

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 open loop waveform control. Verification of the laboratory test is provided by (1) display of the laboratory measured amplitude time history; (2) an optimally smooth estimate of the amplitude time history time-varying root-mean-square, and (3) either an energy spectral density estimate or a Shock Response Spectrum (SRS) estimate for comparatively short environments (transient vibration duration less than the period of the first natural mode of the test item) or a time-varying autospectral density estimate of longer duration environments, e.g., 2.5 to 7.5 seconds. In general, since the environment is being replicated in the laboratory under open loop waveform control, if the impulse response function of the system is correctly determined and correctly applied, then the replication should be near 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 references c, bb, and method 516.5.)

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 utilize 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 Annex B, paragraph 2.3.2). Random rms is the square root of the area under a spectral density curve (see Annex B, paragraph 2.3.1). These are not equivalent!

2.4 Platform/Materiel and Fixture/Test Item Interaction.

Generally, it is assumed that the vibration environment of the materiel is not affected by the materiel itself. That is, the vibration of the platform at the materiel attachment point would be the same whether or not the materiel is attached. Since the entire platform, including all materiel, vibrates as a system, this is not strictly correct. However, when the materiel does not add significantly to the mass or stiffness of the platform, the assumption is correct within reasonable accuracy. The following sections discuss the limitations of this assumption. Note that 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 Annex B, 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 A, paragraph 2.3.1 for materiel mounted in jet aircraft. Note that due to differences in environments, relative sizes, and structural methods, the factor defined in Annex C, table 514.5C-III is only applicable to materiel mounted in full sized jet aircraft.

d. Large item size relative to platform. When materiel is large in size or mass relative to the platform, always consider these effects. This is imperative for aircraft and aircraft stores. Catastrophic failure of the aircraft is possible. It is also imperative to consider these effects in design of vibration test fixtures. Otherwise, the vibration transmitted to the test materiel 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 (factor of two minimum) 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. Note: 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 life cycle, include the appropriate minimum integrity exposures in materiel (Annex A, paragraph 2.4.1).

2.4.3 Materiel resonant frequency variation.

The installed resonant frequencies of materiel varies 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 effect 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 criterion, add an allowance to narrow band spectral elements. Plus and minus five per cent has been chosen for the propeller aircraft criteria of Annex A, paragraph 2.3.2. This was chosen because it seemed to be a reasonable number, and because enveloped C-130 and P-3 aircraft data (references p through t) in g^2/Hz form exhibited approximately this bandwidth.

2.5 Modal Test and Analysis.

Modal test and analysis is a technique for determining the structural dynamic characteristics of materiel and test fixtures. Modal tests, (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 (references dd and ee).

2.5.1 Modal test techniques.

Modal analysis may be accomplished in various ways. The simplest method consists of inputting sine vibration with a shaker, adjusting the frequency and amplitude output of the shaker to excite a structural mode, measuring outputs with a roving accelerometer, and hand plotting the results. This process is repeated for each structural mode of interest. A more sophisticated approach would utilize multi-shaker wide band random excitation, simultaneous measurement of signals from an accelerometer and force gage array, and computer computation and storage of frequency response functions (FRF). Techniques such as random burst and instrumented hammer excitation are available. Select methodology that will result in well-understood usable data, and that will provide the level or detail needed for the specific test goals.

2.5.2 Material non-linear behavior.

Dynamic inputs should be at as realistic levels as possible and at as many levels as practical because materiel response is generally nonlinear with amplitude.

2.6 Aerodynamic Effects.

A primary source of vibration in aircraft and aircraft stores is the aerodynamic flow over the vehicle. Oscillating pressures (turbulence) within the flow drive vibration of the airframe surfaces. These pressures and thus the vibration are a linear function of dynamic pressure and a non-linear function of Mach number. When a flow becomes supersonic, it smoothes out and turbulence drops off. Then, as speed increases, further turbulence builds up again. This phenomenon is well illustrated in the vibration data contained in reference k. The Mach corrections given in Annex C, table 514.5C-V are based on an average of this data. The following definitions and the values and the formulas of Annex C, table 514.5C-VI are provided for use in calculating airspeeds and dynamic pressures. The formulas are somewhat complex and in the past it was common to use simplified graphical equivalents. With the availability of modern computers and programmable calculators these simplifications are no longer justified. The source of the formulas is reference ff and the source of the atmospheric values is reference gg.

2.6.1 Dynamic pressure.

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

2.6.2 Airspeed.

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

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

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

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

d. True airspeed. This is the actual airspeed. To calculate true airspeed with an aircraft air data system, local atmospheric properties must be accurately known. This was not practical until recent years and aircraft generally do not use true airspeed in handbooks nor to navigate. True airspeed may be expressed in various units but it is usually seen as knots true airspeed (Ktas).

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

2.6.3 Altitude.

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

2.7 Similarity.

It is often desirable to use materiel in an application other than that for which it was developed. Also, changes are made to existing materiel or the environmental exposures of an application change. The question arises as to how to verify that the materiel is suitable for the application. This is usually accomplished through a process called "qualification by similarity." Unfortunately, this process has never had a generally accepted definition. In practice it sometimes devolves to a paper exercise that provides traceability but has no engineering content. The following is 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 (items that have not been changed in any way) 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 is exceeded by application requirements by no more than 6 dB in maximum test level, and by no more than 50% in fatigue damage potential at each frequency. In addition, vibration response at critical resonances is such that materiel life and function will be acceptable in the application.

2.7.2 Modified materiel.

Qualify modified materiel (items that have been changed in any way) 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 test(s) or other vibration exposure(s) 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.

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) is no more than 3.0 dB below the application requirement at any frequency and was at or above the requirement for at least 80% of the total bandwidth.

d. The fatigue damage potential of the exposure(s) is not less than 50% 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% of the frequency range. State fatigue damage potentials as totaled equivalent exposure times at maximum application levels. Base summations and equivalencies on the following relationships.

$$W_1/W_2 = (T_2/T_1)^{1/4}$$

W_1 = Acceleration spectral density of exposure 1 (g^2/Hz)
W_2 = Acceleration spectral density of exposure 2 (g^2/Hz)
T_1 = Duration of exposure 1 (hours)
T_2 = Duration of exposure 2 (hours)

$$g_1/g_2 = (T_2/T_1)^{1/6}$$

g_1 = Peak sinusoidal acceleration of exposure 1 (g)
g_2 = Peak sinusoidal acceleration of exposure 2 (g)
T_1 = Duration of exposure 1 (hours)
T_2 = Duration of exposure 2 (hours)

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, the first natural frequency of each sub assembly, and the first natural frequency of each circuit card 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 Annex B, paragraph 2.7.3 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:

a. The total change in mass of the unit and of each subassembly is within ±10%.
b. The unit center of gravity is within ±10% 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% of the original frequencies.
f. The first natural frequency of each circuit board is within ±10% 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.

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ANNEX C

TABLES AND FIGURES

1. SCOPE.

1.1 Purpose.
This Annex provides tables and figures associated with the main body, Annex A, and Annex B of method 514.5.

2. TABLES.

TABLE 514.5C-I. Typical mission / field transportation scenario.

<table>
<tr><th colspan="2">PORT STAGING AREA (PSA)</th><th colspan="2">CORPS STAGING AREA (CSA)</th><th colspan="2">FORWARD SUPPLY POINT (FSP)</th><th colspan="2">USING UNIT (USU)</th><th colspan="2">EXPENDITURE</th></tr>
<tr><td></td><td colspan="2">600 km (375 miles) ⟷</td><td colspan="2">200 km (125 miles) ⟷</td><td colspan="2">26 km (16 miles) ⟷</td><td colspan="2">26 km (16 miles) ⟷</td><td></td></tr>
<tr><td></td><td colspan="4">Trucks, Semitrailers ⟷</td><td colspan="2">Two-Wheeled Trailers ⟷</td><td colspan="2">Two-Wheeled Trailers or M548 Cargo Carrier ⟷</td><td></td></tr>
</table>

TABLE 514.5C-II. Propeller aircraft vibration exposure.

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

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

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

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

4/ C-130 Aircraft
3 blade propeller - f_0 = 51 Hz
4 blade propeller - f_0 = 68 Hz
6 blade propeller - f_0 = 102 Hz (C-130J)

TABLE 514.5C-III. Jet aircraft vibration exposure.

$$W_0 = W_A + \sum_1^n (W_J)$$

W_0, W_A, W_J - Exposure levels in acceleration spectral density (g^2/Hz).

Aerodynamically induced vibration

$$W_A = a \times b \times c \times (q)^2$$

Jet engine noise induced vibration

$$W_J = \{[0.48 \times a \times d \times \cos^2(\theta)/R] \times [D_c \times (V_c / V_r)^3 + D_f \times (V_f / V_r)^3]\}$$

a - Platform / Materiel interaction factor (see Annex B, paragraph 2.4). Note that this factor applies to W_o and not to the low frequency portion (15 Hz to break) of figure 514.5C-14.
 = 1.0 for materiel mounted on vibration isolators (shock mounts) and materiel weighing less than 36 kg.
 = $1.0 \times 10^{(0.6 - W/60)}$ for materiel weighing between 36 and 72.12 kg.(w = weight in kg)
 = 0.25 for materiel weighing 72.12 kg or more.

b - Proportionality factor between vibration level and dynamic pressure (SI units). = 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.	$\sum_1^n$ - Jet noise contribution is the sum of the W_J values for each engine. d - Afterburner factor. = 1.0 for conditions where afterburner is not used or is not present. = 4.0 for conditions where afterburner is used. R - Vector distance from center of engine exhaust plane to materiel center of gravity, m (ft). 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 to TBD Hz at 0.04 g^2/Hz) of figure 514.5C-8. (Annex A, paragraph. 2.3.1) = 1.0 for $0 \leq$ Mach ≤ 0.9 = $(-4.8M + 5.32)$ for $0.9 \leq$ Mach ≤ 1.0 (where M = Mach number) = 0.52 for Mach number greater than 1.0	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 V_c - Engine core exhaust velocity Engine core exhaust velocity (without afterburner), m/sec (ft/sec). V_f - Engine fan exhaust velocity (without afterburner), m/sec (ft/sec).
q - Flight dynamic pressure, kN/m^2 (lb/ft^2). (See Annex B, para. 2.6.1 and table 5145C-VI)	

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

TABLE 514.5C-IV. Helicopter vibration exposure.

MATERIEL LOCATION	RANDOM LEVELS	SOURCE FREQUENCY (f_x) RANGE (Hz)	PEAK ACCELERATION (A) 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 Specific Helicopter or from Table (below).			Drive Train Component Rotation Frequency (Hz) Determine 1S from Specific Helicopter and Component.	
f_1 = 1P	f = 1T	fundamental	f = 1S	fundamental
f = n × 1P	f = m × 1T	blade passage	f = 2 × 1S	1st harmonic
f = 2 × n × 1P	f = 2 × m × 1T	1st harmonic	f = 3 × 1S	2nd harmonic
f = 3 × n × 1P	f = 3 × m × 1T	2nd harmonic	f = 4 × 1S	3rd harmonic

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

TABLE 514.5C-V. Jet aircraft external store vibration exposure.

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

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

$$M \le 0.90, \; K = 1.0; \qquad 0.90 \le M \le 1.0, \; K = -4.8 \times M + 5.32; \qquad M \ge 1.0, \; K = 0.52 \quad \underline{2}/$$

$$f_1 = C\,(t/R^2), \quad (Hz) \quad \underline{3}/, \underline{4}/, \underline{5}/ \qquad f_2 = f_1 + 1000, \quad (Hz) \quad \underline{3}/$$

$$f_0 = f_1 + 100, \quad (Hz) \quad \underline{6}/, \underline{7}/$$

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		
Behind other store(s)	1	2	fin / tailcone unit	8	16
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 = 2.54×10^3 (metric units) ($= 1.0 \times 10^5$ English units).
q – Flight dynamic pressure (see table 514.5C-VI) – kN/m^2 (lb/ft^2).
ρ – Store weight density (weight/volume) - kg/m^3 (lb/ft^3).
Limit values of ρ to $641 \le \rho \le 2403$ kg/m^3 ($40 \le \rho \le 150$ lb/ft^3).
t – Average thickness of structural (load carrying) skin - m (in).
R – Store characteristic (structural) radius m (in) (Average over store length).
= Store radius for circular cross sections.
= Half or major and minor diameters for elliptical cross section.
= Half or longest inscribed chord for irregular cross sections.

1/ – When store parameters fall outside limits given, consult references.
2/ – Mach number correction (see Annex B, 2.6)
3/ – Limit f_1 to $100 \le f_1 \le 2000$ Hz
4/ – Free fall stores with tail fins, $f_1 = 125$ Hz
5/ – Limit (t/R^2) to: $0.0010 \le (t/R^2) \le 0.020$
6/ – $f_o = 500$ Hz for cross sections not circular or elliptical
7/ – If $f_o > 200$ Hz then use $f_o = 2000$ 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

TABLE 514.5C-VI. Dynamic pressure calculation.

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

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

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

$$q = {}^1/_2\ \rho_o \sigma V_a^2 M^2 \qquad q = {}^1/_2\ \rho_o V_{eas}^2 \qquad q = {}^1/_2\ \rho_o \sigma V_{tas}^2$$

	$h \le 11000$ m	$11000 \le h \ge 20056$ m	($h \le 36\,089$ ft)	$36089 \le h \ge 65800$ ft
θ	$1 - 2.2556 \times 10^{-5}\ h$	0.75189	$1 - 6.8750 \times 10^{-6} \times h$	0.75189
δ	$\theta^{5.2561}$	$0.2234\ e^{\phi}$	$\theta^{5.2561}$	$0.2234\ e^{\phi}$
σ	$\theta^{4.2561}$	$0.2971\ e^{\phi}$	$\theta^{4.2561}$	$0.2971\ e^{\phi}$
V_a	$V_{ao} \times \theta^{1/2}$	295.06	$V_{ao} \times \theta^{1/2}$	968.03
λ	-------	$(11000 - h) / 6342.0$	------	$(36089 - h) / 20807$
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)
V_{ias} – Indicated airspeed, m/sec (ft/sec)
V_{eas} – Equivalent airspeed, m/sec (ft/sec)
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)
V_{ias} – Local speed of sound, m/sec (ft/sec)
M – Mach number
q – Dynamic pressure, kN/m^2 (lb/ft^2)
h – Pressure altitude, m (ft), (standard atmosphere)
T_o – Sea level atmospheric temperature °K (°R)

ρ_o – Sea level atmospheric density kg/m^3 ($slugs/ft^3$ or $lb\ sec^2/ft^4$)
δ – Ratio of local atmospheric pressure to sea level atmospheric pressure
σ – Ratio of local atmospheric density to sea level atmospheric density (standard atmosphere)
θ – Ratio of temperature at altitude to sea level temperature (standard atmosphere)
λ – Stratospheric altitude variable

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 Check Cases

Airspeed	h = 3048 m	(h = 10000 ft)	h = 15240 m	(h = 50000 ft)
500 V_{kcas}	$q = 38.5\ kN/m^2$	($q = 804\ lb/ft^2$)	$q = 23.8\ kN/m^2$	($q = 497\ lb/ft^2$)
500 V_{ktas}	$q = 30.0\ kN/m^2$	($q = 626\ lb/ft^2$)	$q = 6.18\ kN/m^2$	($q = 129\ lb/ft^2$)
M = 0.8	$q = 31.2\ kN/m^2$	($q = 652\ lb/ft^2$)	$q = 5.20\ kN/m^2$	($q = 109\ lb/ft^2$)
500 V_{keas}	$q = 40.6\ kN/m^2$	($q = 848\ lb/ft^2$)	at all altitudes	

TABLE 514.5C-VII. Break points for curves of figures 514.5C-1 through 514.5C-3.

U. S. highway truck vibration exposures figure 514.5C-1					
vertical		transverse		longitudinal	
Hz	g^2/Hz	Hz	g^2/Hz	Hz	g^2/Hz
10	0.01500	10	0.00013	10	0.00650
40	0.01500	20	0.00065	20	0.00650
500	0.00015	30	0.00065	120	0.00020
1.04	g rms	78	0.00002	121	0.00300
		79	0.00019	200	0.00300
		120	0.00019	240	0.00150
		500	0.00001	340	0.00003
		0.204	g rms	500	0.00015
				0.740	g rms

Composite two-wheeled trailer vibration exposures figure 514.5C-2					
vertical		transverse		longitudinal	
Hz	g^2/Hz	Hz	g^2/Hz	Hz	g^2/Hz
5	0.2252	5	0.0474	5	0.0563
8	0.5508	6	0.0303	6	0.0563
10	0.0437	7	0.0761	8	0.1102
13	0.0253	13	0.0130	13	0.0140
15	0.0735	15	0.0335	16	0.0303
19	0.0143	16	0.0137	20	0.0130
23	0.0358	21	0.0120	23	0.0378
27	0.0123	23	0.0268	27	0.0079
30	0.0286	25	0.0090	30	0.0200
34	0.0133	28	0.0090	33	0.0068
36	0.0416	30	0.0137	95	0.0019
41	0.0103	34	0.0055	121	0.0214
45	0.0241	37	0.0081	146	0.0450
51	0.0114	46	0.0039	153	0.0236
95	0.0266	51	0.0068	158	0.0549
111	0.0166	55	0.0042	164	0.0261
136	0.0683	158	0.0029	185	0.0577
147	0.0266	235	0.0013	314	0.0015
185	0.0603	257	0.0027	353	0.0096
262	0.0634	317	0.0016	398	0.0009
330	0.0083	326	0.0057	444	0.0027
360	0.0253	343	0.0009	500	0.0014
500	0.0017	384	0.0018	2.40	g rms
3.85	g rms	410	0.0008		
		462	0.0020		
		500	0.0007		
		1.28	g rms		

Composite wheeled vehicle vibration exposures figure 514.5C-3					
vertical		transverse		longitudinal	
Hz	g^2/Hz	Hz	g^2/Hz	Hz	g^2/Hz
5	0.2308	5	0.1373	5	0.0605
8	0.7041	9	0.0900	6	0.0577
12	0.0527	12	0.0902	8	0.0455
16	0.0300	14	0.0427	12	0.0351
20	0.0235	16	0.0496	15	0.0241
22	0.0109	18	0.0229	16	0.0350
24	0.0109	119	0.0008	19	0.0092
26	0.0154	146	0.0013	25	0.0159
69	0.0018	166	0.0009	37	0.0041
79	0.0048	201	0.0009	41	0.0060
87	0.0028	273	0.0053	49	0.0017
123	0.0063	289	0.0021	105	0.0006
161	0.0043	371	0.0104	125	0.0004
209	0.0057	382	0.0019	143	0.0013
224	0.0150	402	0.0077	187	0.0013
247	0.0031	422	0.0027	219	0.0028
278	0.0139	500	0.0016	221	0.0068
293	0.0037	1.60	g rms	247	0.0325
357	0.0028			249	0.0098
375	0.0052			270	0.0026
500	0.0011			293	0.0094
2.18	g rms			336	0.0120
				353	0.0247
				379	0.0085
				431	0.0224
				433	0.0092
				500	0.0014
				1.96	g rms

TABLE 514.5C-VIII. Break points for figure 514.5C-6.

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

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

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

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

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

C-141		
Hz	g^2/Hz	dB/Oct
15	0.002	
39.086	0.002	
		4
300	0.03	
700	0.03	
		-9
2000	0.0013	
rms = 5.01g		

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

General Exposure		
Hz	g^2/Hz	dB/Oct
15		
105.94	0.01	
		6
150	0.02	
500	0.02	
		-6
2000	1.3E-3	
rms = 3.54 g		

3. FIGURES

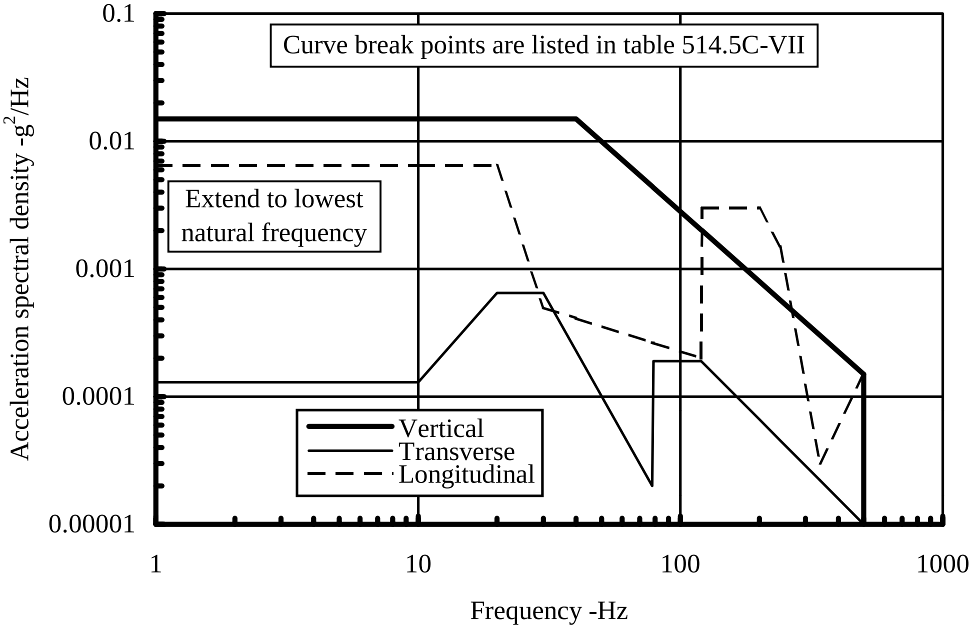

FIGURE 514.5C-1. U. S. highway truck vibration exposure.

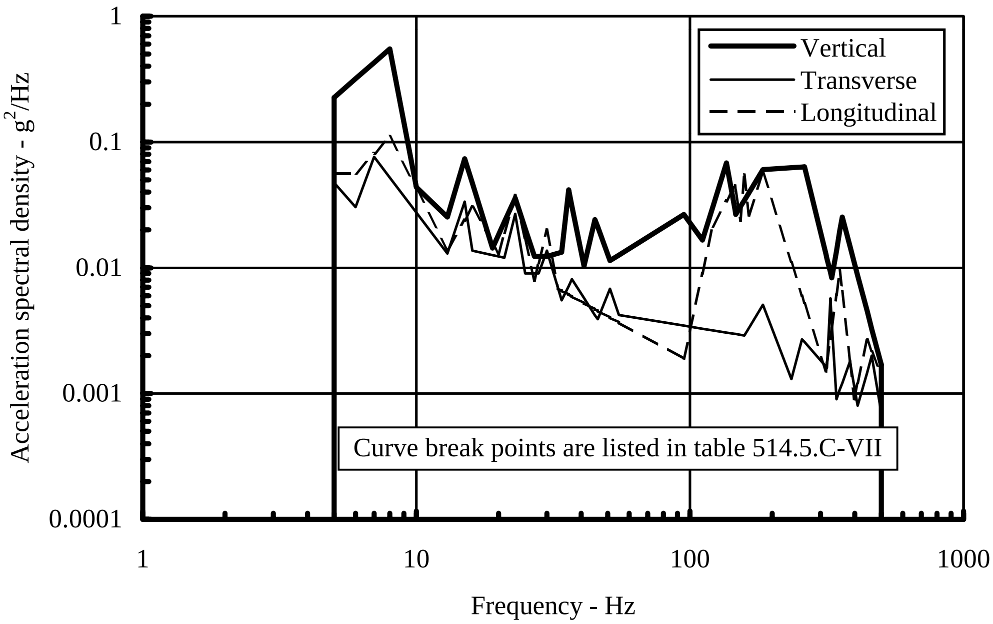

FIGURE 514.5C-2. Composite two-wheeled trailer vibration exposure.

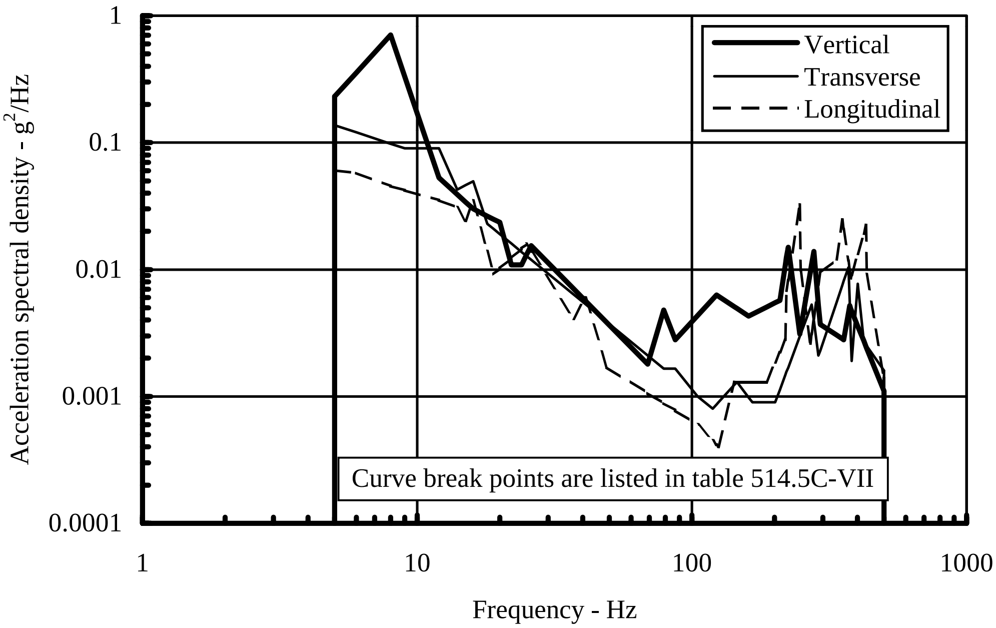

FIGURE 514.5C-3. Composite wheeled vehicle vibration exposure.

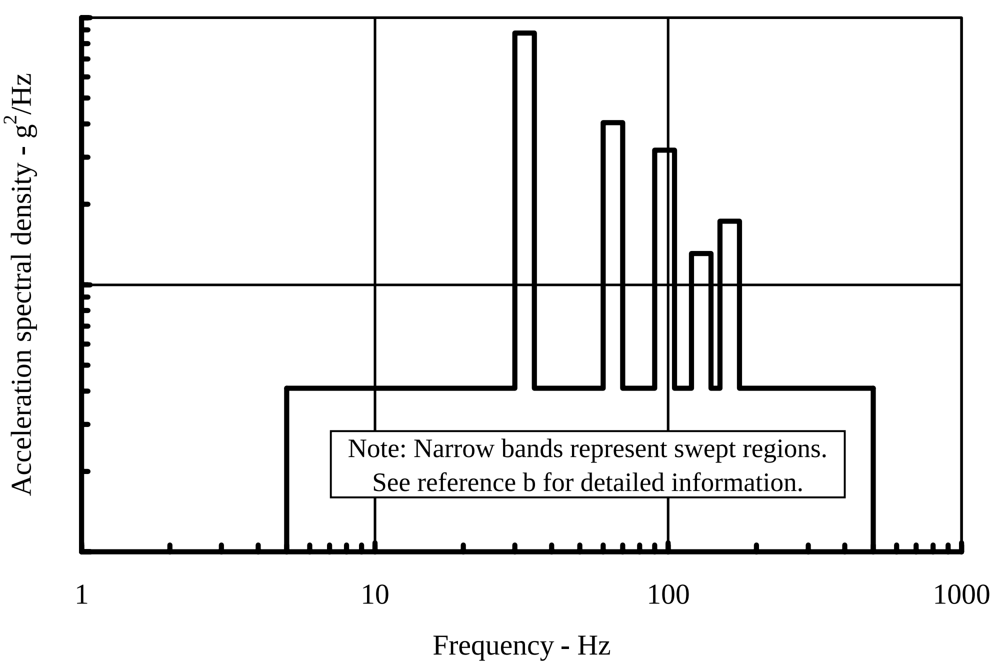

FIGURE 514.5C-4. Tracked vehicle representative spectral shape.

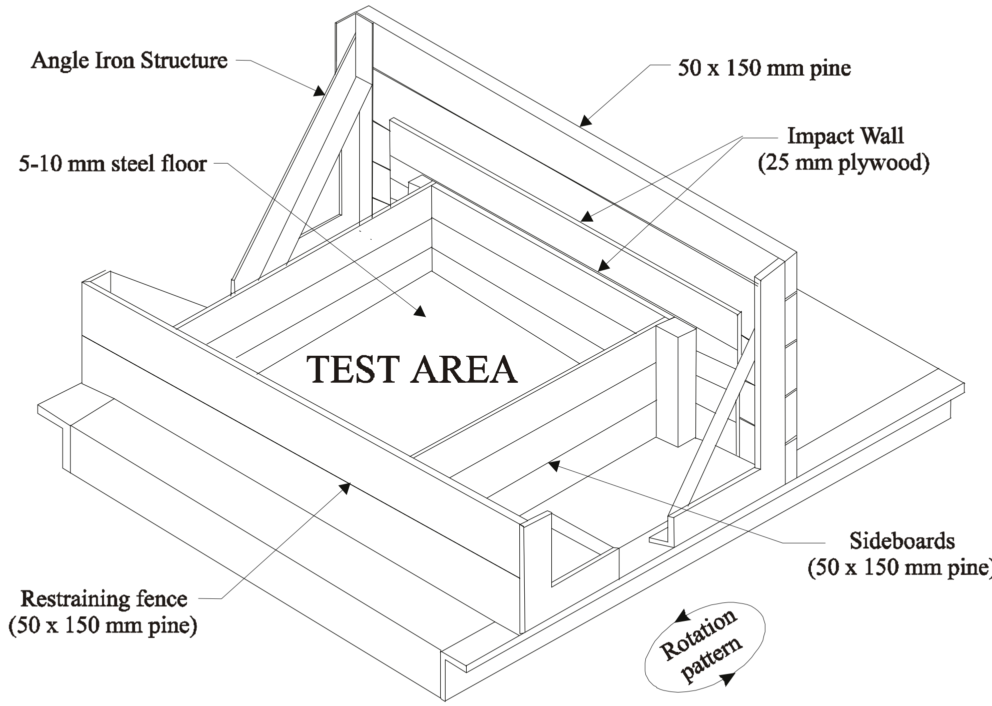

FIGURE 514.5C-5. Loose cargo test setup.

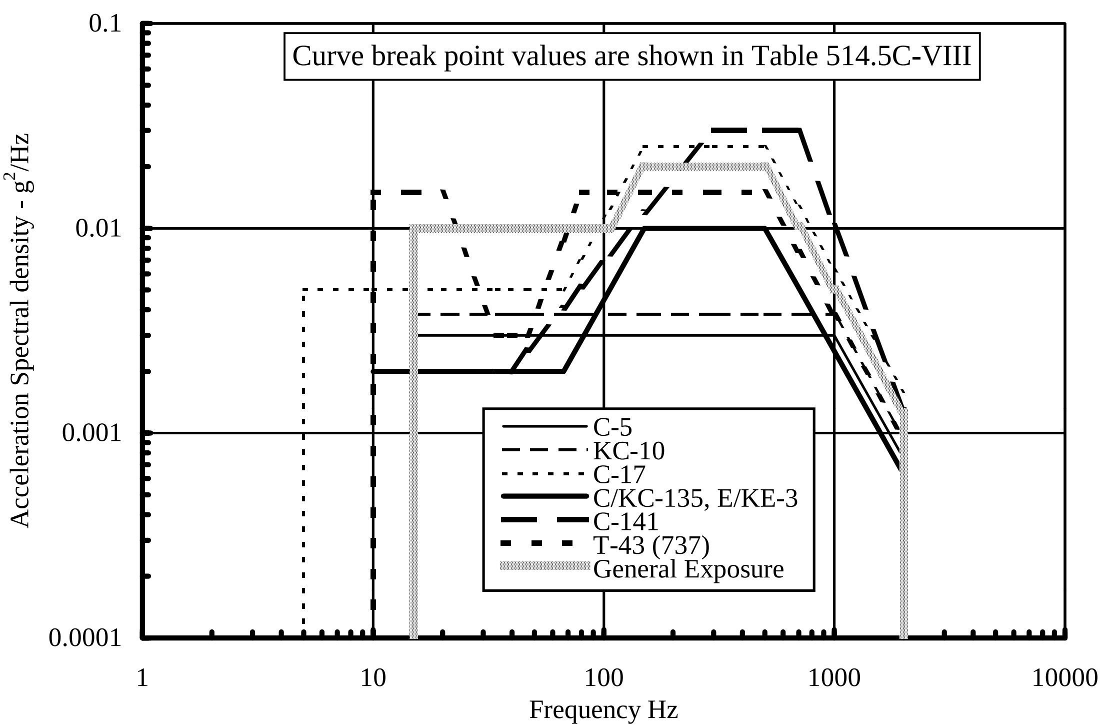

FIGURE 514.5C-6. Jet aircraft cargo vibration exposure.

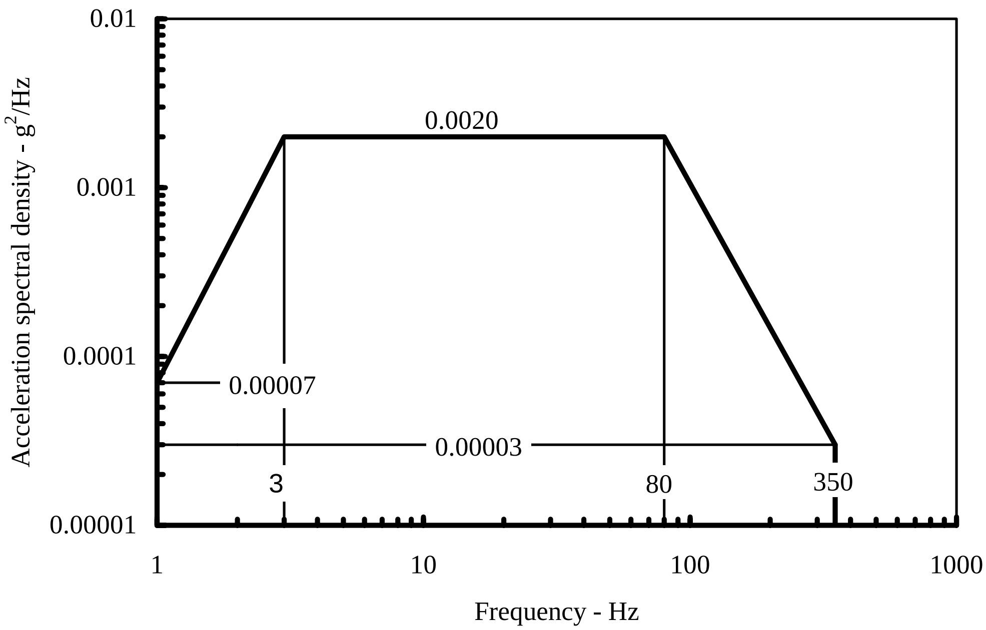

FIGURE 514.5C-7. Rail cargo vibration exposure.

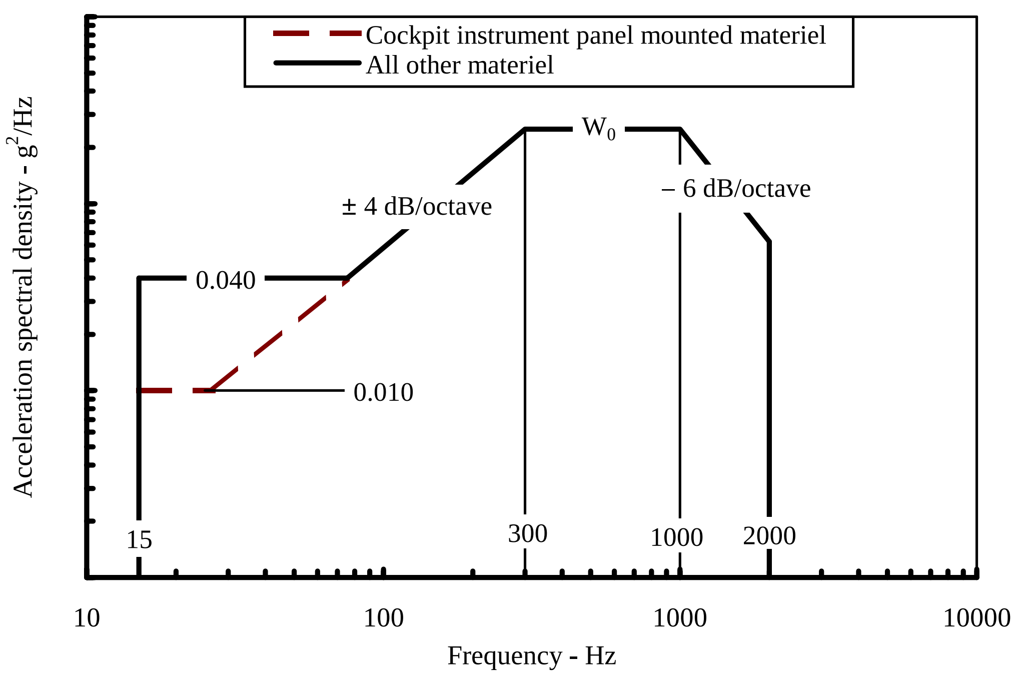

FIGURE 514.5C-8. Jet aircraft vibration exposure.

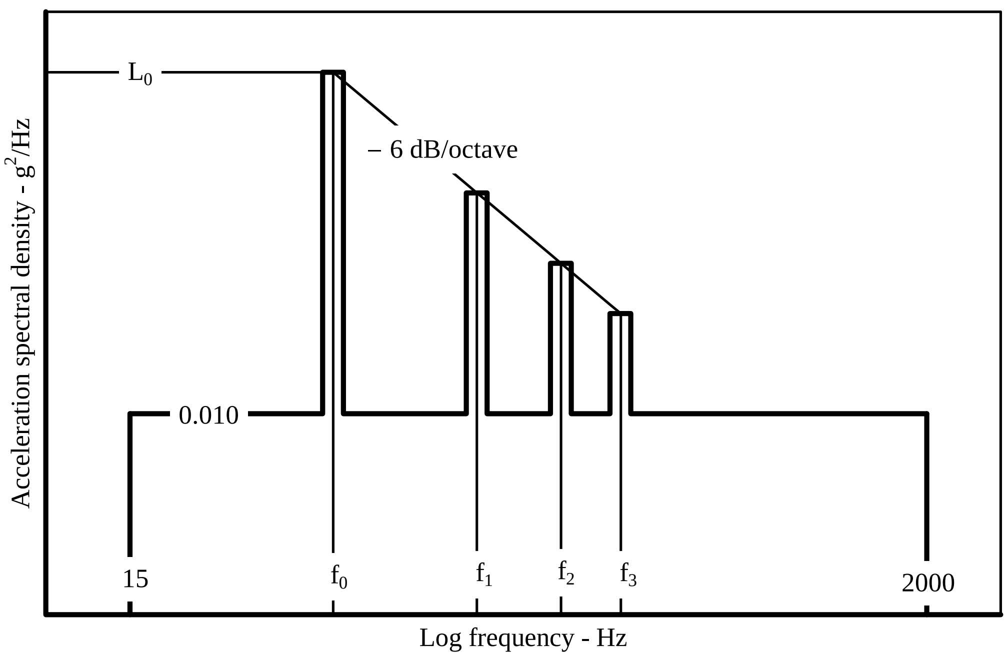

FIGURE 514.5C-9. Propeller aircraft vibration exposure.

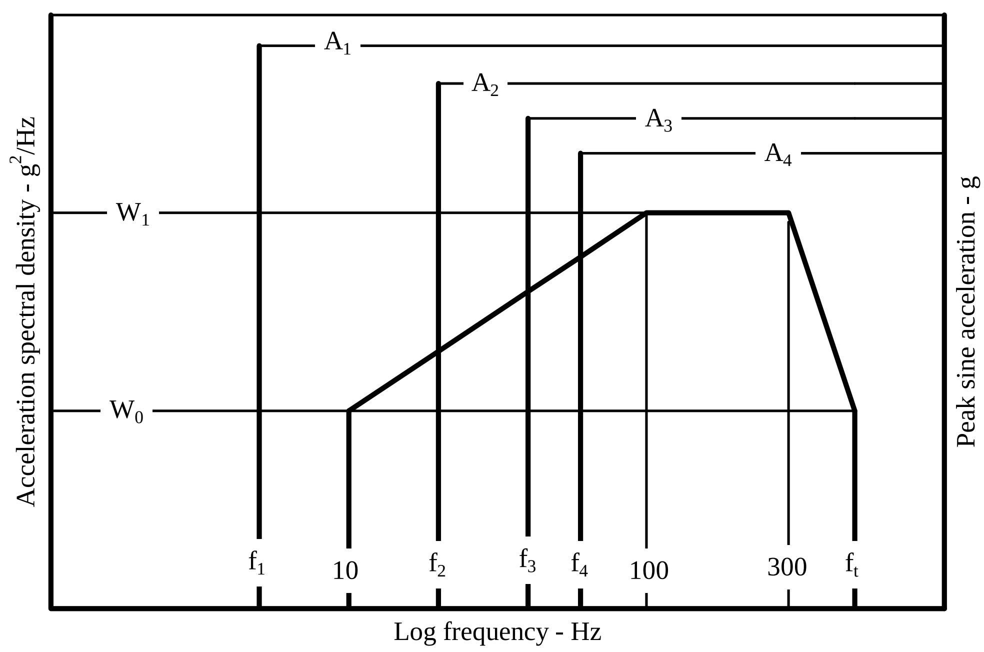

FIGURE 514.5C-10. Helicopter vibration exposure.

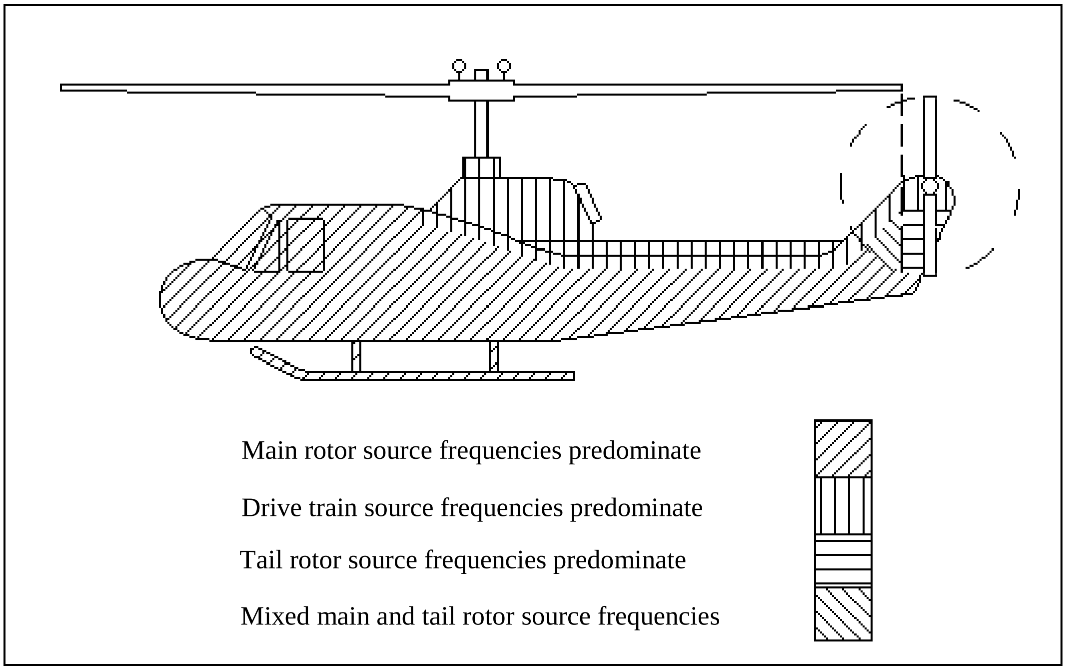

FIGURE 514.5C-11. Helicopter vibration zones.

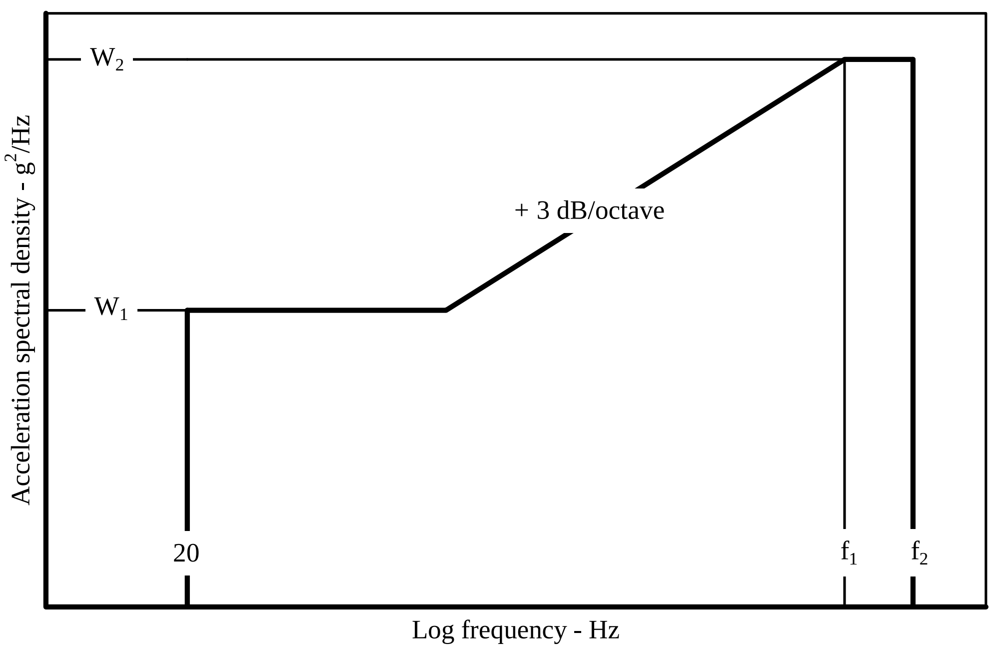

FIGURE 514.5C-12. Jet aircraft store vibration response.

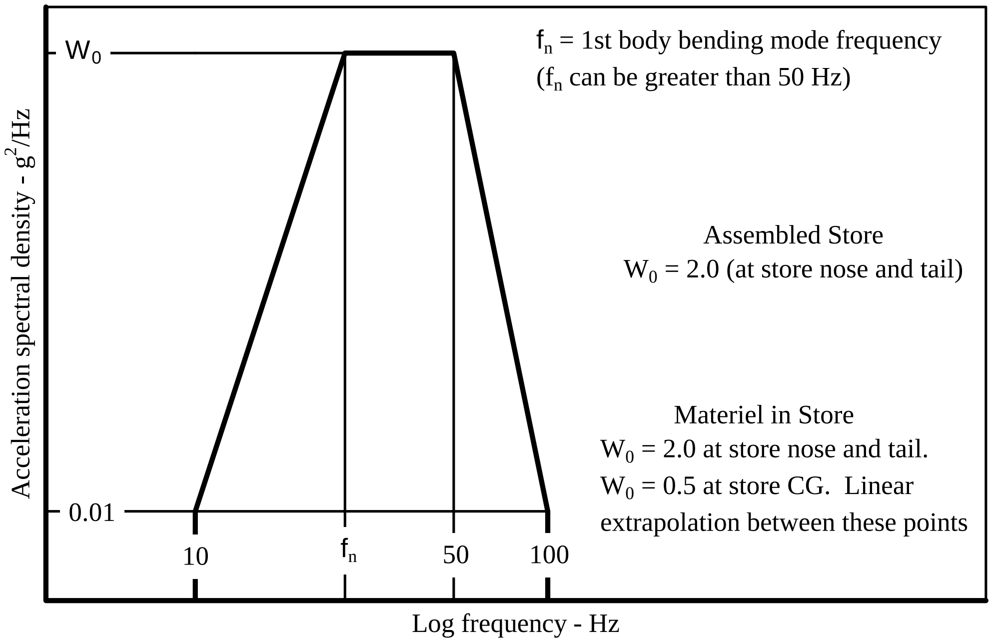

FIGURE 514.5C-13. Jet aircraft store buffet response.

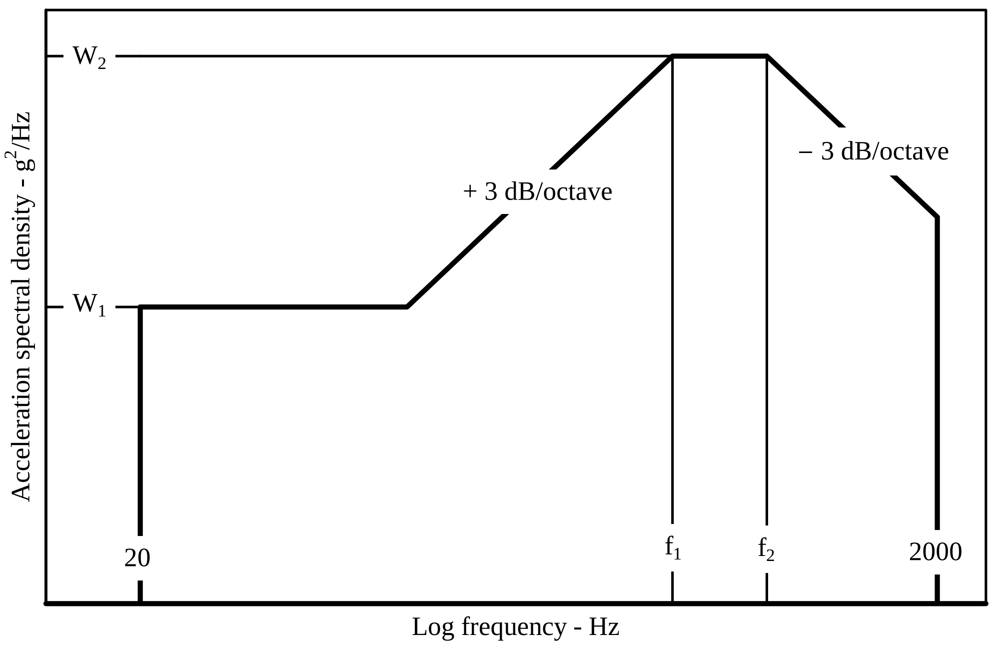

FIGURE 514.5C-14. Jet aircraft store equipment vibration exposure.

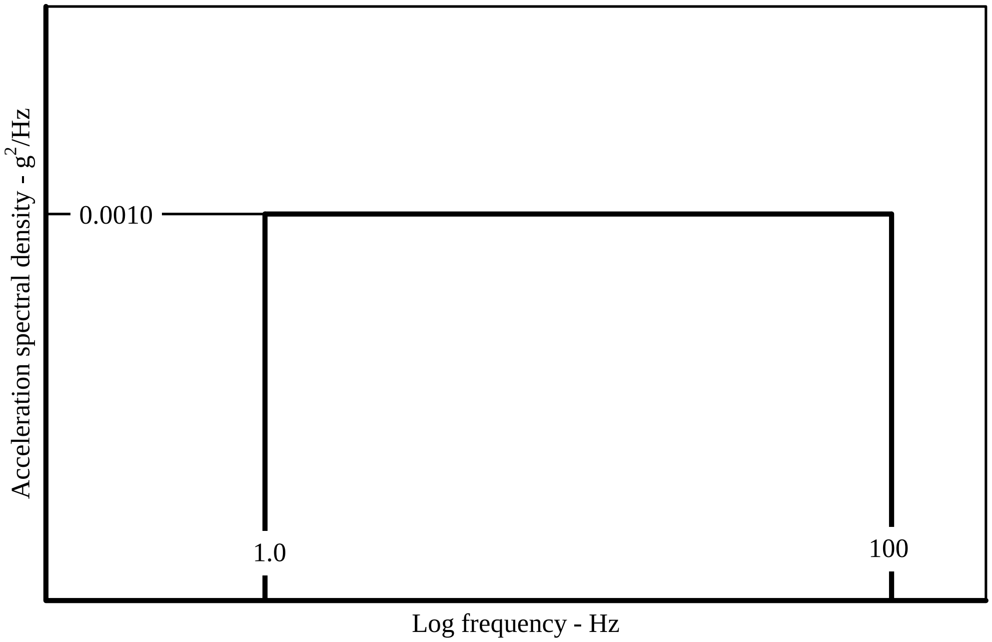

FIGURE 514.5C-15. Shipboard random vibration exposure.

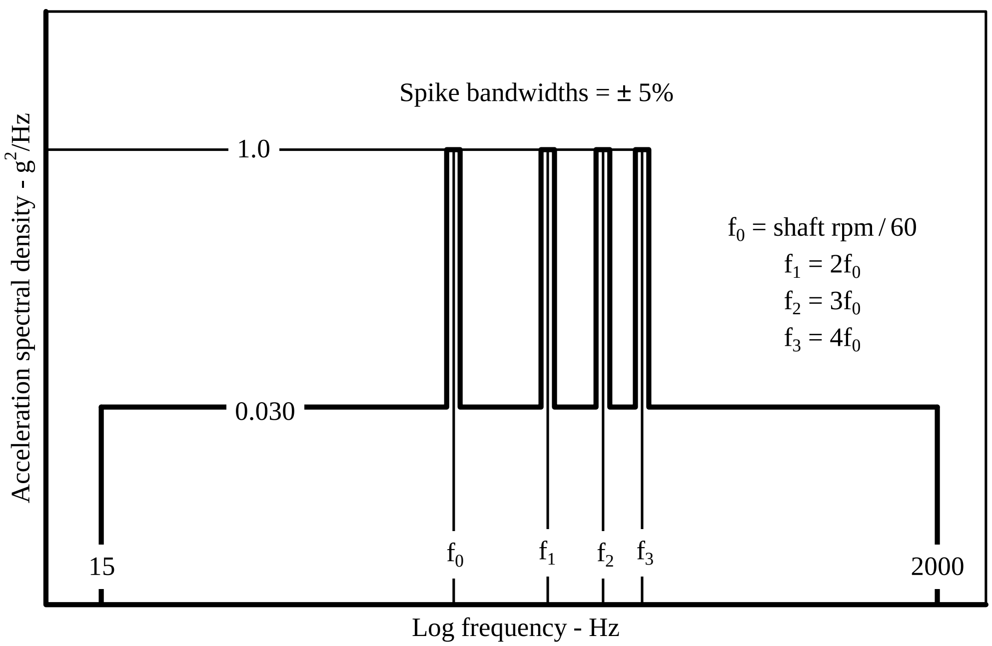

FIGURE 514.5C-16. Turbine engine vibration exposure.

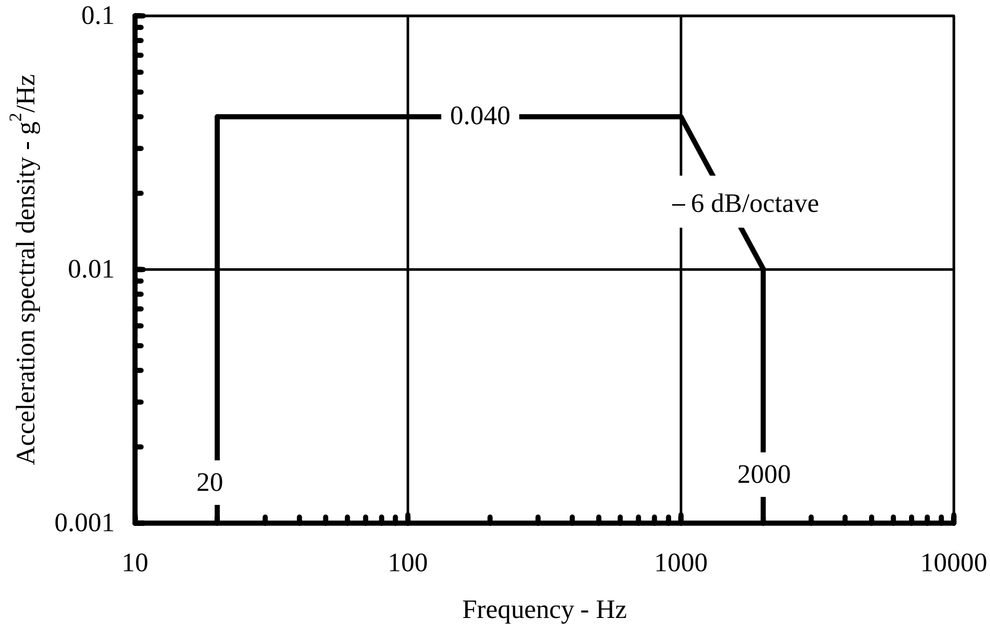

FIGURE 514.5C-17. General minimum integrity exposure.

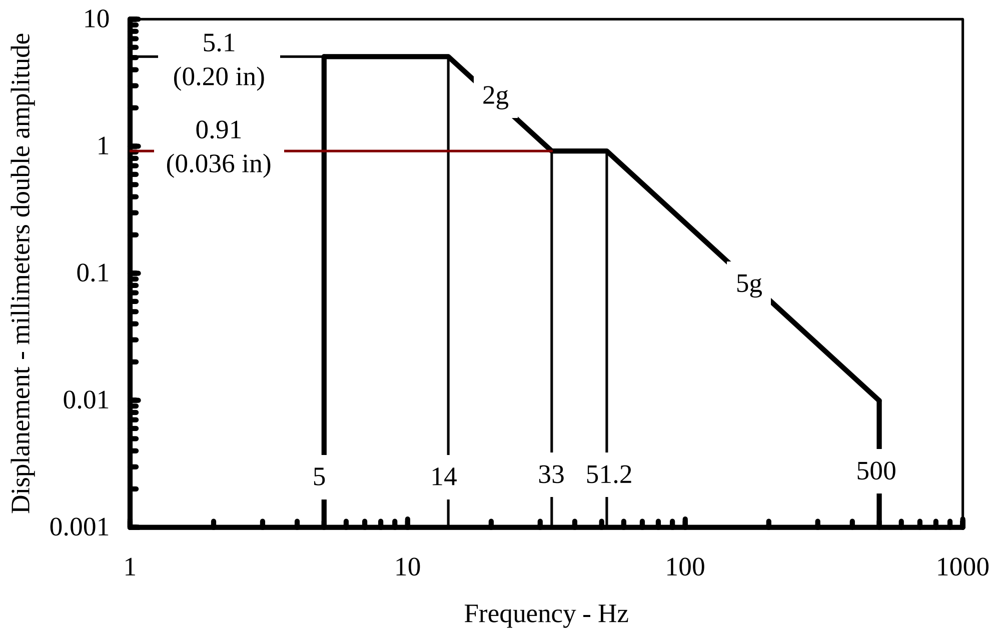

FIGURE 514.5C-18. Helicopter minimum integrity exposure.