# METHOD 519.5

# GUNFIRE VIBRATION

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# METHOD 519.5

# GUNFIRE VIBRATION

NOTE: 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.

## 1. SCOPE.

### 1.1 Purpose.

Gunfire vibration tests are performed to provide a degree of confidence that materiel can physically and functionally withstand the relatively infrequent, repetitive shock or transient vibration encountered in operational environments during the firing of a low caliber gun.

### 1.2 Application.

Use this method to evaluate the physical and functional performance of materiel likely to be exposed to a gunfire environment in its lifetime. This test method is applicable where materiel is required to demonstrate its adequacy to resist repetitive gunfire environment without unacceptable degradation of its functional performance and/or structural integrity. In general, the gunfire environment may be considered to be a repetitive shock or transient vibration produced by (1) gun muzzle blast pressure impinging on a materiel surface, (2) structure-borne repetitive shock or transient vibration due to actuation of the gun mechanism, and/or a combination of (1) and (2). The closer the materiel surface is to pressure pulse exposure, the more the measured environment appears as a repetitive shock producing high rise time and rapid decay of materiel response, and the less role the structure-borne vibration contributes to the overall materiel response environment. The farther the materiel surface is from the pressure pulse exposure, the more the measured environment appears as a structure-borne repetitive shock or transient vibration that has been filtered by structure intervening between the gun source and the materiel. In general, repetitive shock or transient vibration applied to a complex multi-modal materiel system will cause the materiel to respond to (1) forced frequencies imposed on the materiel from the external excitation environment, and (2) the materiel's resonant natural frequencies either during or immediately after application of the excitation. Such response may cause:

a. materiel failure as a result of increased or decreased friction between parts, or general interference between parts;

b. changes in materiel dielectric strength, loss of insulation resistance, variations in magnetic and electrostatic field strength;

c. materiel electronic circuit card malfunction, electronic circuit card damage, and electronic connector failure. (On occasion, circuit card contaminants having the potential to cause short circuits may be dislodged under materiel response to gunfire environment);

d. permanent mechanical deformation of the materiel as a result of overstress of materiel structural and non-structural members;

e. collapse of mechanical elements of the materiel as a result of the ultimate strength of the element being exceeded;

f. accelerated fatiguing of materials (low cycle fatigue);

g. potential piezoelectric activity of materials; and

h. materiel failure as a result of cracks and fracture in crystals, ceramics, epoxies, or glass envelopes.

### 1.3 Limitations.

It may not be possible to replicate some operational service gunfire materiel response environments because of impedance mismatches. In particular, laboratory fixture limitations or other physical constraints may prevent the satisfactory application of the gunfire induced excitation to a test item in the laboratory. In addition:

a. This method does not include the repetitive shock or transient vibration effects experienced by very large extended materiel, e.g., airframe structural systems, over which varied parts of the materiel may experience different and uncorrelated external excitation. For this type of repetitive shock or transient vibration, specialized tests based on experimental data must be devised.

b. This method does not include special provisions for performing gunfire vibration tests at high or low temperatures. This includes the extreme temperature environments directly related to the gunfire pressure wave emission and materiel absorption of thermal energy. Perform tests at ambient temperature unless otherwise specified. Guidelines found in this section of the standard, however, may be helpful in setting up and performing gunfire vibration tests at high or low temperatures, but not at gun pressure wave temperatures.

c. This method is not intended to simulate blast pressure or acoustic effects as a result of exposure to gunfire environment.

d. This method does not include engineering guidelines related to unplanned test interruption as a result of test equipment or other malfunction. Generally, if interruption occurs during a gunfire vibration test input, repeat that gunfire vibration test input. Care must be taken to ensure stresses induced by the interrupted gunfire vibration test do not invalidate subsequent test results. It is incumbent on all test facilities that data from such interruptions be recorded and analyzed before continuing with the test sequence. In addition, the materiel must be inspected prior to test to ensure pre-gunfire vibration test materiel integrity.

## 2. TAILORING GUIDANCE.

### 2.1 Selecting the Gunfire Vibration Method.

After examining requirements documents and applying the tailoring process in Part One of this standard to determine where exposure to a gunfire environment is foreseen in the life cycle of the materiel, use the following to confirm the need for this method and to place it in sequence with other methods.

#### 2.1.1 Effects of a gunfire environment.

Exposure to a gunfire environment has the potential for producing adverse effects on the physical and functional integrity of all materiel. In general, the level of adverse effects increases with the caliber of the gun, proximity of the materiel to the gun, and the duration of the gunfire environment. The gunfire firing rate and the duration of gunfire environment exposure that correspond with natural frequencies of the materiel (along with its subharmonics and superharmonics) will magnify the adverse effects on the materiel's overall physical and functional integrity.

#### 2.1.2 Sequence among other methods.

a. General. See Part One, paragraph 5.5.

b. Unique to this method. Sequencing among other methods will depend upon the type of testing i.e., developmental, qualification, endurance, etc. and the general availability of test items. Normally, schedule gunfire vibration tests early in the test sequence, but after any vibration and shock tests.

(1) If the gunfire environment is deemed particularly severe and the chances of materiel survival without major structural or functional failure are small, perform the gunfire vibration test first in the test

sequence. This provides the opportunity to redesign the materiel to meet the gunfire vibration requirement before testing to the more benign environments.

(2) If the gunfire environment is deemed severe but the chances of the materiel survival without structural or functional failure is good, perform the gunfire vibration test after vibration, thermal and shock tests, allowing the stressing of the test item prior to gunfire vibration testing to uncover combined, vibration, temperature shock, and gunfire vibration environmental failures. (There are often advantages to applying gunfire vibration tests before climatic tests, provided this sequence represents realistic service conditions. Climate-sensitive defects often show up more clearly after the application of severe gunfire environments. However, internal or external thermal stresses may permanently weaken materiel resistance to vibration, shock, and gunfire that may go undetected if gunfire vibration tests are applied before climatic tests.)

(3) In cases in which the gunfire vibration test levels are deemed less severe than the vibration test levels, the gunfire vibration tests may be deleted from the testing sequence.

(4) The gunfire environment may affect materiel performance when materiel is tested simultaneously to other environmental conditions such as vibration, shock, temperature, humidity, pressure, etc. If materiel is known to be sensitive to a combination of environments, test to those environments simultaneously. If it is impractical to test to a combination of environments simultaneously, and where it is necessary to evaluate the effects of the gunfire environment together with other environments, expose a single test item to all relevant environmental conditions in turn. In general, gunfire may occur at any time during the specified operational conditions, so sequence it as close as practical to the life cycle environmental profile. If in doubt, conduct it immediately after completing any vibration and shock testing.

### 2.2 Selecting a Procedure.

This method includes a set of three Pulse Procedures and one Vibration Procedure.

a. Pulse Procedures.

(1) Procedure I: Direct Reproduction of Measured Materiel Response Data.

(2) Procedure II: Statistically Generated Repetitive Pulse – Mean (Deterministic) Plus Residual (Stochastic) Pulse.

(3) Procedure III: Repetitive Pulse Shock Response Spectrum (SRS).

b. Vibration Procedure.

Procedure IV: High Level Random Vibration/Sine-on-Random Vibration / Narrowband Random-on-Random Vibration.

### 2.2.1 Procedure selection considerations.

Based on the test data requirements, determine which test procedure, combination of procedures, or sequence of procedures is applicable. In many cases, one or more of the procedures will apply. Consider all gunfire environments anticipated for the materiel during its life cycle, both in its logistic and operational modes. When selecting procedures, consider:

a. Materiel response. Materiel response to a substantial gunfire environment is characterized by a high level repetitive shock or transient vibration. Such an environment has principal frequency components at the firing rate of the gun and its harmonics. In addition, there exists comparatively low level random vibration energy distributed at other frequencies from DC to 2 kHz. The gunfire environment is considered to be non-stationary because it usually has a time varying root-mean-square (rms) level that is substantially above the ambient or aircraft-induced environmental vibration level for a short period of time. Because of the nature of the measured response data, the analysis is usually not easily interpreted in terms of either stationary measures of the environment such as autospectral density estimates, or transient measures of the environment in terms of shock response spectra. In this case select one of the

Pulse Procedures. Materiel response to a benign gunfire environment is characterized by a slight increase in the ambient vibration level with no readily distinguishable pulse characteristics. Stationary random vibration analysis techniques may be used to specify the test, and Procedure IV may be used. The choice of test procedures is also governed by the in-service gunfire environment and the availability of measured data. It is assumed in applying these procedures that the dynamics of the materiel are well known, in particular, the resonances of the materiel and the relationship of these resonances to the gunfiring rate and its harmonics. Improper test procedure selection may result in either an unconservative materiel undertest or a substantial materiel overtest. These procedures can be expected to cover the entire range of testing related to materiel exposed to gunfire environment. In summary,

(1) for severe materiel response to gunfire environment with measured data, use Procedures I, II, or III.

(2) for benign materiel response to aircraft gunfire with or without measured data use Procedure IV.

b. T<u>he operational purpose of the materiel</u>. From requirement documents, determine the operations or functions to be performed by the materiel before, during, and after exposure to the gunfire environment.

c. <u>The natural exposure circumstances</u>. Materiel response to a gunfire environment is heavily dependent upon the caliber of the gun and the physical relationship between the gun and the materiel.

d. <u>Data required</u>. The test data required to document the test environment and to verify the performance of the materiel before, during, and after the test.

e. <u>Procedure sequence</u>. Refer to paragraph 2.1.2.

**2.2.2 Difference among procedures.**

a. <u>Procedure I - Direct Reproduction of Measured Materiel Response Data</u>. In-service gunfire environment materiel response is replicated under laboratory exciter waveform control to achieve a near exact reproduction of the measured gunfire environment materiel response time history. Use the guidelines provided in Annex A.

b. <u>Procedure II - Statistically Generated Repetitive Pulse – Mean (Deterministic) Plus Residual (Stochastic) Pulse</u>. This procedure is based upon a statistical fitting of a model to in-service response data. Statistical characteristics of the in-service gunfire environment materiel response are modeled (usually by creating a pulse ensemble and obtaining a time varying mean pulse and its associated residuals via nonstationary data processing techniques). The statistical model of the gunfire environment response is replicated under laboratory exciter waveform control to achieve a statistical reproduction of the measured gunfire environment materiel response time history. Use the guidelines provided in Annex B.

c. <u>Procedure III – Repetitive Pulse Shock Response Spectrum (SRS)</u>. The measured in-service gunfire environment materiel response time history is decomposed into individual pulses for analysis. Maximax shock response spectra are computed over the individual pulses to characterize the gunfire environment materiel response by an SRS. A response time history is composed that has a duration equivalent to an individual measured gunfire materiel environment response pulse and that exhibits the characteristic gunfire SRS. The derived gunfire pulse is repeated at the gunfiring rate. Use the guidelines provided in Annex C.

d. <u>Procedure IV: High Level Random Vibration/Sine-on-Random Vibration/Narrowband Random-on-Random Vibration</u>. If no pulse form is indicated by the measured in-service gunfire environment materiel response time history (in general the firing rate of the gun cannot be determined from an examination of the field measured materiel response time history), or the materiel is distant from the gun and only high level structure-borne random vibration is exhibited, use the guidelines provided for (1) vibration in method 514.5, (2) sine-on-random or narrowband random-on-random vibration, or (3) short duration transient vibration in method 516.5, Procedure VIII. In the absence of measured data, use the guidelines provided in Annex D.

### 2.3 Determine Test Levels and Conditions.

Having selected this method and relevant procedures (based on the materiel's requirements documents and the tailoring process), complete the tailoring process by identifying appropriate parameter levels, applicable test conditions, and test techniques for the selected procedures. Base these selections on the requirements documents, the Life Cycle Environmental Profile, Operational Environment Documentation (see Part One, figure 1-1), and information provided with this procedure. Consider the following when selecting test levels.

#### 2.3.1 General considerations.

Establish the test severities using available data or data acquired directly from an environmental data measurement program. When these data are not available, test severities and guidance may be found in Annex D. Annex D is to be used for aircraft gunfire vibration only. Test guidance is provided in Annexes A through C for cases in which measurement data are available and a precise replication is desired. The test selected may not necessarily be an adequate simulation of the complete environment; thus, a supporting assessment may be necessary to compliment the test results.

#### 2.3.2 Test conditions.

In all cases care must be taken to replicate the measured environmental materiel response data which may require establishing the correct interface impedances. When measured data is not available, the materiel response must be in accordance with that defined in Procedure IV.

#### 2.3.3 Test axes and number of gunfire events.

The test axes should be in accordance with the physical configuration for the in-service environment. Material response to gunfire pressure pulses will generally involve testing in axes normal to the pressure direction. Material response to structure-borne vibration will generally involve testing in all axes. The number of gunfire events should be in accordance with the Environmental Life-Cycle Profile Document.

### 2.4 Test Item Configuration.

(See Part One, paragraph 5.8.) Configure the test item for gunfire vibration testing as would be anticipated during in-service use including particular attention to the details of the mounting of the materiel to the platform. Gunfire response vibration can be sensitive to the details of the materiel/platform configuration and input impedances.

### 2.5 Controls.

The dynamic excitation is controlled to within specified bounds by sampling the dynamic response of the test item at specific locations. These locations may be at or in close proximity to the materiel fixing points (controlled input tests) or at defined points on the materiel (controlled response tests). The dynamic motions may be sampled at a single point or at several locations (multi-point).

a. For Procedures I, II, and III the electrodynamic or electrohydraulic vibration exciter is operated in an open loop waveform control configuration with materiel response replication at a single point.

b. For Procedure IV, either single or multi-point control may be used.

#### 2.5.1 Control options.

##### 2.5.1.1 Open loop.

The Pulse Procedures tests are of short duration and performed in an open loop mode after appropriate compensation of the analog voltage input waveform.

#### 2.5.1.2 Single point control.

Single point control is a minimum requirement for Procedure IV. Select a single point to represent, as close as possible, the materiel hard point from which the field-measured data were obtained or upon which predictions are based.

#### 2.5.1.3 Multiple point control.

For Procedure IV where the materiel is distant from the gunfire input environment and the measured response data at appropriate hard points indicate no more than a random vibration environment slightly above ambient conditions, multiple point control may be desirable. Multiple point control will be based on the specified control strategy that may include the average of the ASD's of the control points selected.

### 2.5.2 Control methods.

#### 2.5.2.1 Waveform control.

Application of the techniques for Procedures I, II, and III will generally involve a computer with digital-to-analog interface and analog-to-digital interface with the compensated analog output going directly to drive the exciter. This form of control is termed waveform control where the actual form of the time history (nonstationary or stationary) is preserved in the laboratory replication. Perform signal processing off-line where the resulting properly compensated vibration exciter drive signal will be stored as a digital signal. Certain modern control systems make specific provisions for waveform control.

#### 2.5.2.2 Random vibration control.

Whether the control console is digital or analog, use closed loop control. Because the loop time for the vibration procedure depends on the desired number of degrees of freedom and on the analysis and overall bandwidths, it is important to select these parameters so that test tolerances and control accuracy can be maintained.

## 3. INFORMATION REQUIRED.

### 3.1 Pretest.

The following information is required to conduct a gunfire vibration test.

a. General. Information listed in Part One, paragraphs 5.7, 5.8, 5.9, and 5.11 and Appendix A, Tasks 405 and 406 of this standard.

b. Specific to this method.

(1) Knowledge of the test fixture, test item and combined test fixture/test item modal frequencies, and their relationship to the gunfiring rate. Ideally this would consist of an experimental modal survey related to the test configuration. If this is not practical, a supporting analytical assessment of the modal characteristics of the test configuration needs to be supplied by a trained analyst.

(2) Gunfire environment. Either:

(a) measured data that are input as a compensated waveform into a exciter system under direct waveform control (Procedure I).

(b) measured data that have been statistically processed and a stochastically generated, compensated waveform developed as input into a exciter system under direct waveform control (Procedure II).

(c) measured data that have been statistically processed and a complex shock pulse SRS synthesis form of time history generated (superposition of damped sinusoids, amplitude modulated sine waves, or other) and compensated that matches a SRS specifying spectrum shape, peak spectrum values, spectrum break points, pulse duration and gunfiring rate (Procedure III).

(d) measured high level random or transient vibration (methods 514.5 or 516.5, Procedure VIII), predicted sine-on-random spectrum; or predicted narrowband random-on-random (Procedure IV).

(3) Techniques used in the processing of the input and the materiel response data.

### 3.2 During Test.

Collect the following information during conduct of the test:

a. General. Information in Part One, paragraph 5.10, and in Part One, Appendix A, Tasks 405 and 406 of this standard.

b. Specific to this method. Information related to failure criteria. Other environmental conditions at which testing is to be carried out if other than standard laboratory conditions, and the specific features of the test assembly (exciter, fixture, interface connections, etc.). For test validation purposes, record achieved test parameters, deviations from pre-test procedures including parameter levels, and any procedural anomalies and any test failures.

### 3.3 Post-test.

Record the following post-test information.

a. General. Information listed in Part One, paragraph. 5.13, and in Appendix A, Tasks 405 and 406 of this standard.

b. Specific to this method.

(1) Duration of each exposure and number of exposures.

(2) Functional and physical integrity of the test item after each test based upon functional testing and visual examination.

(3) Response time histories and the information processed from these time histories. In general, under processed information, for

(a) Procedure I. Data that correspond to the analysis performed on the measured data. This processing may include an autospectral density (ASD) estimate, an average Fourier spectra (FS) or energy spectral density (ESD) estimate, in cases of very short time history records an SRS estimate or some form of nonstationary processing with a time varying spectra.

(b) Procedure II. Data that correspond to the analysis performed on the measured data, which will generally require the creation of an ensemble of short time history (pulse) records. This processing may include an average FS or ESD estimate, an average SRS estimate or some form of nonstationary processing with a time varying spectra over the ensemble of collected data.

(c) Procedure III. Data that correspond to the analysis performed on the measured data that will generally require the creation of an ensemble of short time history (pulse) records. Since the input is the repetition of a fixed waveform, the analysis of one input pulse by way of FS, ESD, or SRS will suffice to define the input. For the measured materiel response output, this processing may include an average FS or ESD estimate, an average SRS estimate, or a single SRS estimate computed over several pulses.

(d) Procedure IV. Data will be processed to display the frequency spectra defining the event. In general, this will be an ASD estimate over the duration of the event and displayed by the software used to control the exciter.

(4) Results of operational checks.

(5) Test item and/or fixture modal analysis data.

## 4. TEST PROCESS.

### 4.1 Test Facility.

Use a test facility, including all auxiliary equipment, capable of providing the specified gunfire materiel response environments within the tolerances stated 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 gunfire vibration tests and take measurements at standard ambient conditions as specified in Part One, paragraph 5.1.

### 4.2 Controls.

All measurement devices are to be calibrated in accordance with standard calibration procedures. The complete test parameter control chains (checking, compensation, servoing, recording, etc.) should not produce uncertainties exceeding one third of the tolerances specified in paragraphs 4.2.1 through 4.2.4. Because of the nature of the gunfire environment, tolerances may be given in the time, amplitude, and frequency domain according to the processing requirements of the procedure. In Procedures I, II, and III it is assumed that the test item response measurement data collected is representative of the true environment and not a function of the local materiel configuration, e.g., local resonances which may not be controllable to the tolerances in paragraphs 4.2.1 through 4.2.4.[1]

#### 4.2.1 Direct reproduction of measured materiel response data.

a. Time domain. Ensure the duration of one pulse is within 2.5% of the duration obtained from the measured gunfiring rate.

b. Amplitude domain. Ensure materiel time history major positive and negative response peaks are within ±10% of the measured gunfire time history peaks.

c. Frequency domain. Compute an average ESD estimate over the ensemble created from the materiel time history response that is within ± 3dB of the average ESD estimate computed over the ensemble created from the measured gunfire time history over at least 90% of the frequency range. In cases in which an ensemble from the data cannot be created, compute an ASD estimate of the time history records for comparison provided the data is appropriately windowed to reduce spectral leakage. The tolerances for the ASD analysis are ± 3dB over at least 90% of the frequency range.

#### 4.2.2 Statistically generated repetitive pulse – mean (deterministic) plus residual pulse (stochastic).

a. Time domain. Ensure the duration of one pulse is within 2.5% of the duration obtained from the measured gunfiring rate.

b. Amplitude domain. Ensure materiel time history major positive and negative response peaks are within ±10% of the measured gunfire time history peaks.

c. Frequency domain. Compute an average ESD estimate over the ensemble created from the materiel time history response that is within ± 3dB of the average ESD estimate computed over the ensemble created from the measured gunfire time history over at least 90% of the frequency range.

#### 4.2.3 Repetitive pulse shock response spectra.

a. Time domain. Ensure the duration of one pulse is within 5% of the duration obtained from the measured gunfiring rate.

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[1] Use text fixturing that will ensure test item response in other axes does not exceed 25% of the test item response in the test axis when measured in the time, amplitude, or frequency domain.

b. Amplitude domain. Ensure materiel time history major positive and negative response peaks are within ±10% of the measured gunfire time history peaks.

c. Frequency domain. Ensure the shock response spectrum (SRS) computed over the materiel time history response from one simulated gunfire pulse is within –1dB and +3dB from the mean SRS computed over the ensemble of field measured gunfire materiel response data over at least 90% of the frequency range. Use an SRS analysis of at least 1/6 octave frequency spacing.

**4.2.4 High level random vibration/sine-on-random vibration/narrowband random-on-random vibration.**

a. Time domain. Ensure the root-mean-square (RMS) value of the amplitude measured at the control point in the test axis is within ± 5% of the preset RMS value. Likewise, ensure the maximum variation of the RMS value at the fixing points in the test axis is ± 10% of the preset RMS value.

b. Amplitude domain. Ensure the amplitude distribution of the instantaneous values of the random vibration measured at the control point is nominally Gaussian. Use an amplitude distribution that contains all occurrences up to 2.7 standard deviations. Keep occurrences greater than 3.5 standard deviations to a minimum.

c. Frequency domain. Ensure an ASD analysis of the materiel time history response is within ±3 dB of an ASD analysis computed over the field measured gunfire data or the predicted gunfire environment. Allow local exceedances up to ± 6 dB above 500 Hz, but limit the accumulation of all local exceedances to 5% of the overall test frequency range. Use a maximum analysis filter bandwidth of 5 Hz and attempt to have the number of independent statistical degrees of freedom (DOF) for control greater than 100.

**4.3 Instrumentation.**

In general, acceleration will be the quantity measured to meet specification with care taken to ensure acceleration measurements can be made that provide meaningful data (reference a). Give special consideration to the measurement instrumentation amplitude and frequency range specifications in order to satisfy the measurement and analysis requirements. All measurement instrumentation must be calibrated to traceable national calibration standards (see Part One, paragraph 5.3.2). In addition, instrumentation to measure test item function may be required. In this case, obtain suitable calibration standards and adhere to them.

a. Accelerometer.

(1) Transverse sensitivity of less than or equal to 5%.

(2) An amplitude linearity within 10% from 5% to 100% of the peak acceleration amplitude required for testing.

(3) For all gunfire vibration procedures, a flat frequency response within ±10% across the frequency range 5 – 2 kHz. The measurement devices may be of the piezoelectric or piezoresistive type.

(4) For cases in which response below 2 Hz is desired, piezoresistive accelerometer measurements are required with a flat frequency response within ±10% across the frequency range DC-2 kHz.

(5) The measurement device and its mounting will be compatible with the requirements and guidelines provided in reference a.

b. Other measurement devices. Any other measurement devices used to collect data must be demonstrated to be consistent with the requirements of the test, in particular, the calibration and tolerances provided in paragraph 4.2.

c. Signal conditioning. Use signal conditioning compatible with the instrumentation requirements on the materiel. In particular, filtering will be consistent with the response time history requirements. Use signal conditioning requirements in accordance with the guidelines provided in reference a. Use extreme care in filtering the acceleration signals at the amplifier output. Do not filter the signal into the amplifier for fear of filtering bad measurement data and the inability to detect the bad measurement data. The signal from the signal conditioning must be anti-alias filtered before digitizing.

**4.4 Data Analysis.**

a. An analog anti-alias filter configuration will be used that will

(1) not alias more than a 5 percent measurement error into the frequency band of interest (1 Hz to 2 kHz).

(2) have linear phase-shift characteristics in the data passband.

(3) have a passband uniform to within one dB across the frequency band of interest (see paragraph 4.3).

b. In subsequent processing of the data, use any additional filtering that is compatible with the anti-alias analog filtering. In particular, additional digital filtering must maintain phase linearity for processing gunfire time histories for Procedures I, II, and III.

c. It is suggested for Procedures I, II and III that the time history data be over-sampled by a factor of 10. Ideally, for 2 kHz data, a sample rate of 20,480 (with a linear phase anti-alias filter set at 2.5 kHz) will be suitable. A maximum 5 Hz analysis filter bandwidth is recommended.

d. Analysis procedures will be in accordance with those requirements and guidelines provided in reference a. In particular the test item response acceleration time histories will be qualified according to the procedures in reference a. In severe cases of response acceleration it may be necessary that each time history be integrated to detect any anomalies in the measurement system e.g., cable breakage, amplifier slewrate exceedance, data clipped, unexplained accelerometer offset, etc. The integrated amplitude time histories will be compared against criteria given in reference a.

**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 gunfire environment.

**4.5.1 Preparation for test.**

**4.5.1.1 Preliminary guidelines.**

Prior to initiating any testing, review the pretest information in the test plan to determine test details (e.g., procedure, calibration load (if any), test item configuration, measurement configuration, gunfire level, gunfire duration, number of repetitions of gunfire event to be applied). Note in particular all details of the test validation procedures. Use fixturing that simulates actual in-service mounting attachments (including vibration isolators and fastener torque, if appropriate). Install all the connections (cables, pipes, etc.) in a way that they impose stresses and strains on the test item similar to those encountered in service. In certain cases consider the suspension of the test item at low frequency to avoid complex test fixture resonances that may coincide with measured materiel gunfire response resonant frequencies.

**4.5.1.2 Pretest checkout.**

After appropriate compensation of the excitation input device and prior to conducting the test, perform a pretest checkout of the test item at standard ambient conditions to provide baseline data. Conduct the checkout as follows:

Step 1. Conduct a complete visual examination of the test item with special attention to stress areas or areas identified as being particularly susceptible to damage and document the results.

Step 2. Install the test item in its test fixture.

Step 3. Conduct a test item operational check in accordance with the approved test plan along with simple tests for ensuring the response measurement system is responding properly. Document the results for compliance with information contained in Part One, paragraph 5.

Step 4. If the test item integrity has been verified, proceed to the first test. If not, resolve the problem and restart at Step 1.

#### 4.5.1.3 Procedure overview.

Paragraphs 4.5.2 through 4.5.5 provide the basis for collecting the necessary information concerning the test item in a gunfire vibration environment. For failure analysis purposes, in addition to the guidance provided in Part One, paragraph 5.14, each procedure contains information to assist in the evaluation of the test results. Analyze any failure of a test item to meet the requirements of the system specifications based on the guidelines in Part One, paragraph 5.14.

#### 4.5.1.4 Test item considerations.

Test items can vary from individual materiel items to structural assemblies containing several items of materiel of different types.

a. General. Unless otherwise specified in the individual test plan, attach the materiel to the vibration exciter by means of a rigid fixture capable of transmitting the vibration conditions specified. Ensure the fixture inputs vibration to racks, panels, and/or vibration isolators to simulate as accurately as possible the vibration transmitted to the materiel in service. When required, ensure materiel protected from vibration by racks, panels and/or vibration isolators also passes the appropriate test requirements with the test item hard-mounted to the fixture. (Refer to method 514.5 for further guidance relative to field/laboratory impedance mismatches.)

b. Stores. Where practical, perform testing in three mutually perpendicular axes with the mounting lugs in the normal carriage position. Suspend the store from a structural frame by means of its normal mounting lugs, hooks, and sway braces, that simulate the operational mounting apparatus. Use a test setup such that the rigid body modes (translation and rotation) of vibration for the store/frame/suspension system are between 5 and 20 Hz. Apply compensated materiel response excitation to the store by means of a rod or other suitable mounting device running from a vibration exciter to a hard, structurally supported point on the surface of the store. Alternatively, hard-mount the store directly to the exciter using its normal mounting lugs and a suitable fixture. Ensure the stiffness of the mounting fixture is such that its induced resonant frequencies are as high as possible and do not interfere with the store response. For both configurations, use launcher rails as part of the test setup, where applicable. Refer to method 514.5 for further guidance relative to field/laboratory impedance mismatches.

c. Subsystem testing. When identified in the test plan, subsystems of the materiel may be tested separately. The subsystems can be subjected to different gunfire levels. In this case, ensure the test plan stipulates the gunfire levels specific to each subsystem.

d. Test item operation. Refer to the test plan to determine whether the test item is or is not in operation. Because continuous gunfire vibration testing can cause unrealistic damage of the test item (e.g., unrealistic heating of vibration isolators), interrupt the excitations by periods of rest, defined by the test plan. For additional details, refer to Annexes A, B, C, and D.

### 4.5.2 Procedure I - Direct reproduction of measured materiel response data.

#### 4.5.2.1 Controls.

This procedure assumes that measured materiel response data are available in digital form and this response data will be replicated in the laboratory on the test item.

#### 4.5.2.2 Test tolerances.

Ensure test tolerances are in accordance with those specified in paragraph 4.2.

#### 4.5.2.3 Procedure steps.

Step 1. Precondition in accordance with paragraphs 4.2 and 4.5.1.

Step 2. Choose control strategy and control and monitoring points in accordance with paragraph 2.5.

Step 3. Perform operational checks in accordance with paragraph 4.5.1.

Step 4. Mount the test item on the vibration exciter or utilize some other means of suspension in accordance with paragraph 4.5.1.

Step 5. Determine the time history representation of the vibration exciter drive signal required to provide the desired gunfire materiel acceleration response on the test item. (Refer to Annex A).

Step 6. Apply the drive signal as an input voltage and measure the test item acceleration response at the selected control/monitoring point.

Step 7. Verify that the test item response is within the allowable tolerances specified in paragraph 4.2.1.

Step 8. Apply gunfire simulation for on and off periods and total test duration in accordance with the test plan. Perform operational and functional checks in accordance with the test plan.

Step 9. Repeat the previous steps along each of the other specified axes.

Step 10. In all cases, record the information required.

#### 4.5.2.4 Analysis of results.

Refer to the guidance in Part One, paragraph 5.14, to assist in the evaluation of the test results. In addition, a display of the measured test item response time history and analysis called for in paragraph 4.2.1 to satisfy the test tolerances.

### 4.5.3 Procedure II - Statistically generated repetitive pulse – mean (deterministic) plus residual (stochastic) pulse.

#### 4.5.3.1 Controls.

This procedure assumes that measured response data is available in digital form, has been statistically modeled, and the generated sample function response data will be replicated in the laboratory on the test item.

#### 4.5.3.2 Test tolerances.

Ensure test tolerances are in accordance with those specified in paragraph 4.2.

#### 4.5.3.3 Procedure steps.

Step 1. Generate a statistical representation of the field measured materiel response data. In general this will involve an off-line procedure designed to generate an ensemble of pulses based on measured data for input to the vibration exciter (refer to Annex B).

Step 2. Precondition in accordance with paragraphs 4.2 and 4.5.1.

Step 3. Choose control strategy and control and monitoring points in accordance with paragraph 2.5.

Step 4. Perform operational checks in accordance with paragraph 4.5.1.

Step 5. Mount the test item on the vibration exciter (or use some other means of suspension) in accordance with paragraph 4.5.1.

Step 6. Determine the time history representation of the vibration exciter drive signal required to provide the desired gunfire materiel acceleration response on the test item. (Refer to Annex B).

Step 7. Apply the drive signal as an input voltage and measure the test item acceleration response at the selected control/monitoring point.

Step 8. Verify that the test item response is within the allowable tolerances specified in paragraph 4.2.2.

Step 9. Apply gunfire simulation for on and off periods and total test duration in accordance with the test plan. Perform operational and functional checks of the test item in accordance with the test plan.

Step 10. Repeat the previous steps along each of the other specified axes.

Step 11. In all cases, record the information required.

**4.5.3.4 Analysis of results.**

Refer to the guidance in Part One, paragraph 5.14, to assist in the evaluation of the test results. In addition, a display of the measured test item response time history and analysis called for in paragraph 4.2.2 to satisfy the test tolerances.

**4.5.4 Procedure III – Repetitive pulse shock response spectrum (SRS).**

**4.5.4.1 Controls.**

This procedure assumes that measured response data are available in the digital form of a pulse and an associated SRS. The test pulse is generated as in the case of SRS shock synthesis testing and replicated at the firing rate of the gun.

**4.5.4.2 Test tolerances.**

Ensure test tolerances are in accordance with those specified in paragraph 4.2.

**4.5.4.3 Procedure steps.**

Step 1. Separate the measured field data into individual pulses and compute Shock Response Spectra over the individual pulses using damping factors of 5%, 2%, 1%, and 0.5% (Q = 10, 25, 50, and 100). (See Annex C.)

Step 2. Based upon the SRS estimates determined in Step 1, compare the mean shock spectra for each of the damping factors to determine the predominant frequencies and to obtain an estimate of the duration or half cycle content comprising the individual predominant frequencies. An individual selected pulse may be used instead of utilizing the mean SRS for each of the damping factors. (Refer to Annex C.)

Step 3. Characterize the SRS time history using the results of Step 2 for specification of the complex transient duration, and choose a mean SRS or individual pulse from Step 2 for amplitude characterization.

Step 4. Precondition in accordance with paragraphs 4.2 and 4.5.1.

Step 5. Choose control strategy and control and monitoring points in accordance with paragraph 2.5.

Step 6. Perform operational checks in accordance with paragraph 4.5.1.

Step 7. Mount the test item on the vibration exciter (or use some other means of suspension) in accordance with paragraph 4.5.1.

Step 8. After proper vibration exciter drive signal compensation, input the SRS transient through the exciter control system at the firing rate of the gun, and measure the test item acceleration response at the selected control monitoring point.

Step 9. Verify that the test item response is within the allowable tolerances specified in paragraph 4.2.3.

Step 10. Apply gunfire simulation on and off periods and total test duration in accordance with the test plan. Perform operational and functional checks of the test item in accordance with the test plan.

Step 11. Repeat the previous steps along each of the other specified axes.

Step 12. In all cases, record the information required.

#### 4.5.4.4 Analysis of results.

Refer to the guidance in Part One, paragraph 5.14, to assist in the evaluation of the test results. In addition, a display of the measured test item response time history and SRS analysis called for in paragraph 4.2.3 to satisfy the test tolerances.

### 4.5.5 Procedure IV - High level random vibration/sine-on-random vibration/narrowband random-on-random vibration.

#### 4.5.5.1 Controls.

This procedure assumes that either the gunfire environment is to be predicted or measured response data is available in the form of an ASD estimate. This response data will be replicated in the laboratory by way of vibration control or special software for gunfire vibration testing.

#### 4.5.5.2 Test tolerances.

Ensure test tolerances are in accordance with those specified in paragraph 4.2.

#### 4.5.5.3 Procedure steps.

Step 1. Compute an autospectral density analysis over the measured gunfire data using an analysis overall bandwidth of at least 2 kHz at a suitable processing analysis bandwidth (not to exceed 5 Hz), or compute a combination discrete sine component and 2 kHz autospectral density prediction (refer to Annex D).

Step 2. Based upon the guidance to follow, generate time history corresponding to a (1) high level time domain windowed random vibration test spectrum, (2) sine-on-random vibration test spectrum, or (3) narrowband random-on-random vibration test spectrum.

a. if the ASD spectral estimate is computed from field measured materiel response data and appears as a continuous spectra with no discrete components at harmonic frequencies then generate a high level random vibration time history having the same spectral content and proceed to generate a transient vibration time history by appropriate time domain windowing with a boxcar shaped window. The window on/off durations being functions of the in-service gunfire schedule.

b. if the ASD spectral estimate is computed from field measured materiel response data and appears as a continuous spectra with discrete components at harmonic frequencies then generate either a sine-on-random or narrowband random-on-random vibration time history having the same spectral content according to the knowledge of the in-service use. If the in-service use anticipates a fixed firing rate gun then sine-on-random is the selected test method. If the in-service use anticipates a variable firing rate gun or several guns with fixed firing (or variable firing) rate then the narrowband random-on-random is the selected test method. Selection of the test parameters for narrowband random-on-random (e.g., sweep rate and sweep bandwidth) is left to the discretion of an experienced analyst for specification using the in-service gunfire schedule. The testing should not be limited by the software test capability. The on/off gunfire durations are selected as functions of the in-service gunfire schedule.

NOTE: It is important to realize for any ASD estimate with apparent discrete harmonic components the amplitude of the discrete harmonic components is sensitive to the way in which the stationary random time history is processed. The amplitude of the discrete harmonic components is sensitive to (1) relationship between the “true” discrete frequency (gunfiring rate and harmonics) and the resolution analysis bandwidth selected in the processing and (2) the form of windowing and overlap used in the processing. Make every effort to process the time history data for the combined discrete and continuous spectra estimate for the (1) measured field materiel response and (2) measured laboratory test item response, in exactly the same way.

c. if the ASD spectral estimate is predicted for materiel response as a continuous spectra with discrete components at harmonic frequencies, then generate either a sine-on-random vibration or narrow band random-on-random time history having the same spectral content according to the knowledge of the in-service use and the experience of an analyst. In general, narrow band random-on-random will be used for gun configurations other than a single gun with a fixed firing rate. The on/off gunfire durations are selected as functions of the in-service gunfire schedule.

Step 3. Precondition the test item in accordance with paragraphs 4.2 and 4.5.1.

Step 4. Choose control strategy and control and monitoring points in accordance with paragraph 2.5.

Step 5. Perform operational checks in accordance with paragraph 4.5.1.

Step 6. Mount the test item on the vibration exciter (or use some other means of suspension) in accordance with paragraph 4.5.1.

Step 7. Input the vibration profile through the exciter control system, and measure the test item acceleration response at the selected control monitoring point or points.

Step 8. Verify that the test item response is within the allowable tolerances specified in paragraph 4.2.4.

Step 9. Apply gunfire simulation on and off periods and total test duration in accordance with the test plan. Perform operational and functional checks of the test item in accordance with the test plan.

Step 10. Repeat the previous steps along each of the other specified axes.

Step 11. In all cases, record the information required.

#### 4.5.5.4 Analysis of results.

Refer to the guidance in Part One, paragraphs 5.14 and 5.17 and Part One, Appendix A, Tasks 405 and 406 to assist in the evaluation of the test results. In addition a display of the measured test item response time history and analysis as called for in paragraph 4.2.4 to satisfy the test tolerances.

## 5. REFERENCE/RELATED DOCUMENTS.

a. Handbook for Dynamic Data Acquisition and Analysis, IEST-RP-DTE012.1, Institute of Environmental Sciences and Technology, 940 East Northwest Highway, Mount Prospect, IL 60056.

b. Harris, C., and C. E. Crede, eds., Shock and Vibration Handbook, 2nd Edition, NY, McGraw-Hill, 1976.

c. Piersol, A.G., Analysis of Harpoon Missile Structural Response to Aircraft Launches, Landings and Captive Flight and Gunfire. Naval Weapons Center Report #NWC TP 58890. January 1977.

d. Piersol, Allan G., Determination of Maximum Structural Responses From Predictions or Measurements at Selected Points, Proceedings of the 65th Shock and Vibration Symposium, Volume I, SAVIAC, 1994.

e. Bendat, J. S. and A. G. Piersol, Random Data: Analysis and Measurement Procedures, John Wiley & Sons Inc., NY, 1986.

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# ANNEX A

# DIRECT REPRODUCTION OF MEASURED MATERIEL RESPONSE DATA

## 1. SCOPE.

### 1.1 Purpose.

This Annex provides guidance and a basis for direct reproduction (in a laboratory test) of measured materiel response data on a vibration exciter under waveform control in an open loop mode.

### 1.2 Application.

This technique is useful for the reproduction of single point materiel response that may be characterized as nonstationary or as a transient vibration (see Part One, Appendix D). Acceleration is considered the variable of measurement in the discussion to follow although other variables could be used, provided the dynamic range of the measured materiel response is consistent with the dynamic range of the electrodynamic exciter used as an input device to reproduce the materiel response.

## 2. DEVELOPMENT.

### 2.1 Basic Considerations for Environment Determination.

It is assumed that an in-service test is performed with properly instrumented materiel where the measurements are made at pre-selected points on the materiel. The measurement points exhibit minimum local resonances, yet the measurement locations will allow the detection of significant overall materiel resonances. The measurement locations may be determined prior to making an in-service test by examination of random vibration data on the materiel using various accelerometer mounting locations and fixturing configurations (the same as those to be used in laboratory testing). In processing, ensure the field measured data is DC coupled (not high pass filtered) and sampled at ten times the highest frequency of interest with appropriate anti-alias filtering techniques. Examine the measured data time history traces for any indication of clipping, or any accelerometer performance anomalies such as zero shifting. If there is indication of accelerometer measurement anomalies, examine a potentially corrupted acceleration time history carefully according to the procedures used in qualifying pyrotechnic shock data, e.g., time history integration to examine velocity and displacement characteristics, sample probability density function (PDF) estimates computed. (For further details refer to method 517 or to reference a. in paragraph 5.) If there are no indications of accelerometer anomalies, high pass filter the in-service measured data at a very low frequency, e.g., 1 Hz, and place it in a digital file for manipulation. An example of gunfire simulation using Procedure I is discussed below. This procedure is performed with a personal computer (PC) with signal processing capability and analog-to-digital and digital-to-analog interfaces.

### 2.2 Test Configuration.

A specially instrumented test item is installed in a laboratory vibration fixture and mounted on an electrodynamic exciter. The test item employed during the laboratory simulation is the same materiel configuration used to collect the gunfire vibration materiel response data during an in-service test, including accelerometer response measurement locations.

### 2.3 Creating a Digital File of the Gunfire Vibration Materiel Response.

The first step in the environment replication process is to digitize the measured in-service data to obtain a materiel response amplitude time history (figure 519.5A-1). Digital processing of the analog data is performed using a 2,000 Hz, 48dB/octave linear phase anti-alias filter and a sample rate of 20,480 samples per second for good time history resolution.

**2.4 Characterization of Vibration Exciter Drive Signal/Test Item Inverse Frequency Response Function.**

Definition of the inverse frequency response function between the exciter drive signal and the acceleration response of the test item installed on the exciter is achieved by subjecting the test item to a low level burst of swept sine excitation. The swept sine excitation is generated on the PC using a sample rate of 20,480 samples per second and a block size of 2,048 points for a duration of approximately 0.1 second. The swept sine input utilizes a start frequency of 10 Hz and a stop frequency of 2,000 Hz. The swept sine excitation is input through the vibration exciter power amplifier using the digital-to-analog interface of the PC. Figure 519.5A-2 presents the swept sine exciter input along with the resulting test item response. Subsequently, the swept sine exciter input and the test item response are digitized using the PC analog-to-digital interface with a sample rate of 20,480 samples per second and a block size of 2,048 points. The inverse frequency response function (IH (f)) is estimated as follows.

$$IH\ (f) = E_{dd}(f) \,/\, E_{dx}(f)$$

where

$E_{dd}$ = the input energy spectral density of the swept sine exciter drive signal, d(t) – units of (volts$^2$-sec)/Hz

$E_{dx}$ = the energy spectral density cross spectrum between the acceleration response of the test item, x(t) and the swept sine exciter drive signal, d(t) – units of (volt-g-sec)/Hz

Figure 519.5A-3 presents the modulus and phase of the inverse frequency response function. To reduce the noise in IH(f) three or more IH(f) estimates may be averaged. Under laboratory conditions, usually the signal-to-noise ratio is so high that averaging to reduce noise levels in the estimate is unnecessary. (See references a and b in paragraph 2.10 below.)

**2.5 Tapering the Inverse Frequency Response Function.**

Because the signal processing software computes the inverse frequency response function out to the Nyquist frequency, which is far above the frequency range of interest, a tapering function is applied to the inverse frequency response function. The tapering function removes the unwanted frequency content (noise) beyond the frequency band of interest (10 - 2000 Hz). The modulus is reduced to zero from 2,000 Hz over a bandwidth of approximately 200 Hz; whereas, the phase remains constant beyond 2,000 Hz. The modulus and phase of the tapered inverse frequency response function is presented on figure 519.5A-4. Some experimentation with the tapering configuration may be needed at this point on behalf of the tester to optimize the information preserved in the 10 - 2000 Hz frequency domain and reduce excessive noise.

**2.6 Computing the Impulse Response Function.**

The impulse response function is generated by computing the inverse Fourier transform of the tapered inverse frequency response function, IH(f). See figure 519.5A-5.

**2.7 Computing the Compensated Vibration Exciter Drive Signal.**

The compensated vibration exciter voltage drive signal is generated by convolution of the impulse response function (figure 519.5A-5) in units of volts/(g-sec) with the measured gunfire materiel response (figure 519.5A-1) in units of (g). This may also be accomplished in the frequency domain by multiplying transforms i.e., IH(f) by the transform of an unwindowed block of time history using either overlap-and-save or overlap and add procedures. The compensated vibration exciter voltage drive signal is plotted in the top portion of figure 519.5A-6.

**2.8 Reproducing the Gunfire Materiel Response.**

Using the digital-to-analog interface of the PC, the compensated vibration exciter voltage drive signal is input through the vibration exciter power amplifier to obtain the desired gunfire materiel response from the test item. The vibration exciter is under waveform control in an open-loop mode of operation. For the short duration of the nonstationary record or transient vibration, this is an adequate mode of vibration exciter control. Figure 519.5A-6 presents the compensated exciter voltage drive signal along with the resulting materiel response. Figure 519.5A-7 provides a comparison of the overall in-service measured gunfire materiel response with the laboratory simulated gunfire test item response.

### 2.9 Conclusion.

For single point materiel response measurements on comparatively simple dynamic materiel, the method of direct reproduction of in-service measured materiel response is near "optimal." The main advantage of this technique is that it permits reproduction of materiel responses (nonstationary or transient vibration) that are difficult, if not impossible, to completely specify and synthesize for input to a vibration exciter control system. The main disadvantage of this technique is that there is no obvious way to statistically manipulate the measured materiel response data to ensure a conservative test. However, conservativeness could be introduced into the testing by performing the manipulation at a reduced level of vibration exciter power amplifier gain and then testing at the higher gain. The assumption behind this scenario is that the test item response resulting from the vibration exciter input is a linear function of the power amplifier gain.

### 2.10 Reference/Related Documents.

a. Merritt, R.G. and S.R. Hertz, Aspects of Gunfire, Part 1- Analysis, Naval Weapons Center, China Lake, CA 93555-6100, NWC TM 6648, Part 1, October 1990.

b. Merritt, R.G. and S.R. Hertz, Aspects of Gunfire, Part 2- Simulation, Naval Weapons Center, China Lake, CA 93555-6100, NWC TM 6648, Part 2, September 1990.

## 3. RECOMMENDED PROCEDURES.

### 3.1 Recommended Procedure.

For single point materiel response measurements on comparatively simple dynamic materiel, this procedure is to be used in cases in which laboratory replication of the response environment is absolutely essential to establish materiel operational and structural integrity under gunfire environment.

### 3.2 Uncertainty Factors.

The only significant uncertainty in this procedure results in the degree to which the measured environment differs from the actual in-service environment. It is usually not possible to obtain the measured environment under every conceivable in-service condition.

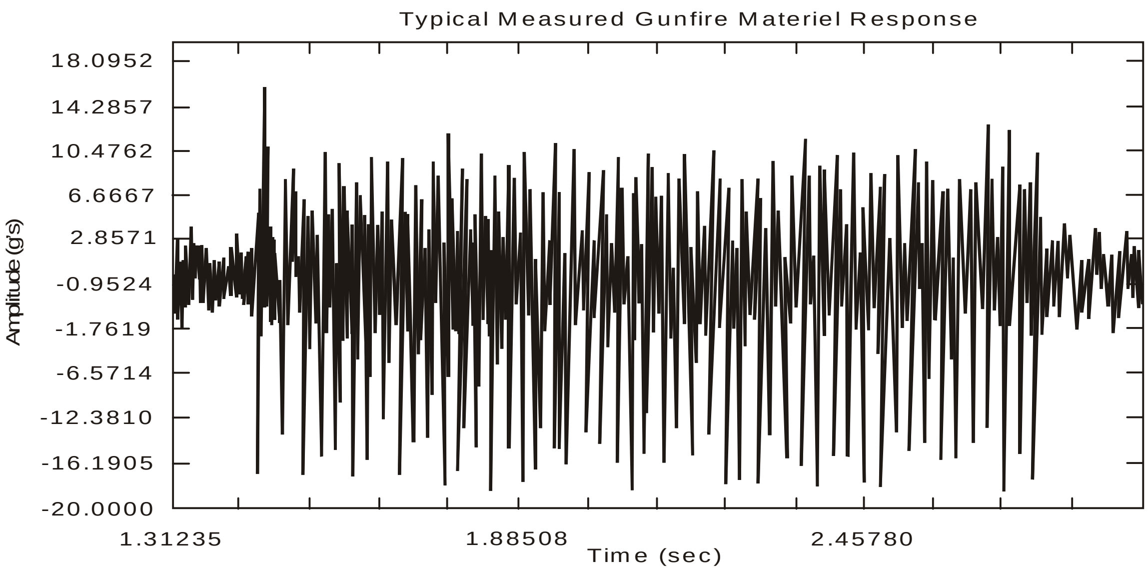


**FIGURE 519.5A-1. Digital flight data.**

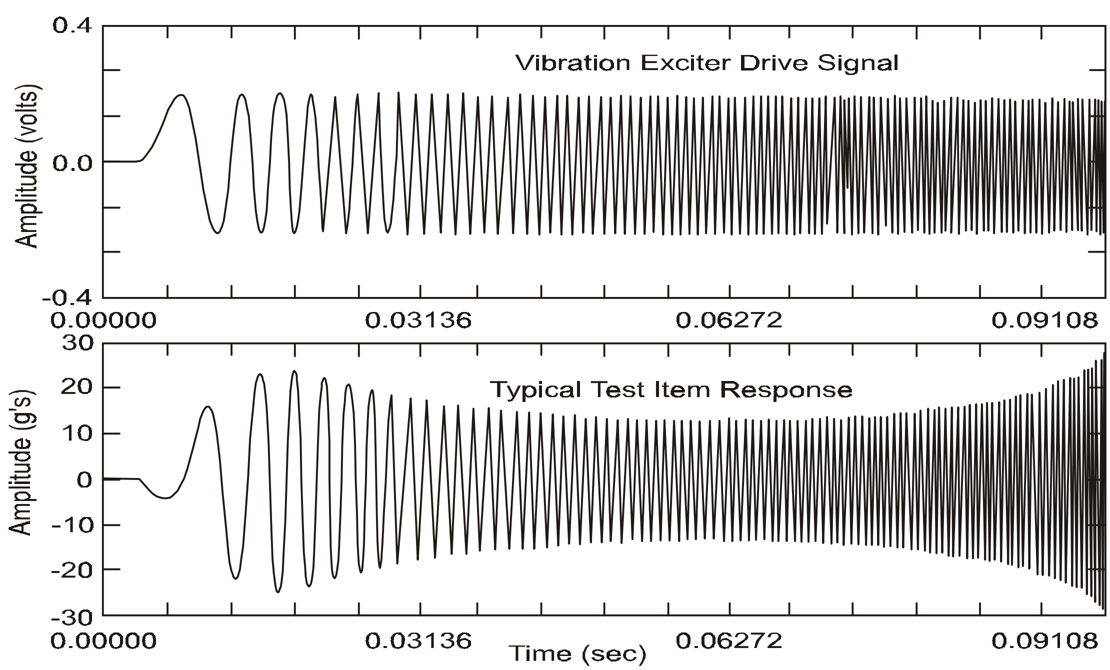


**FIGURE 519.5A-2. Swept sine vibration exciter input with resulting test item response.**

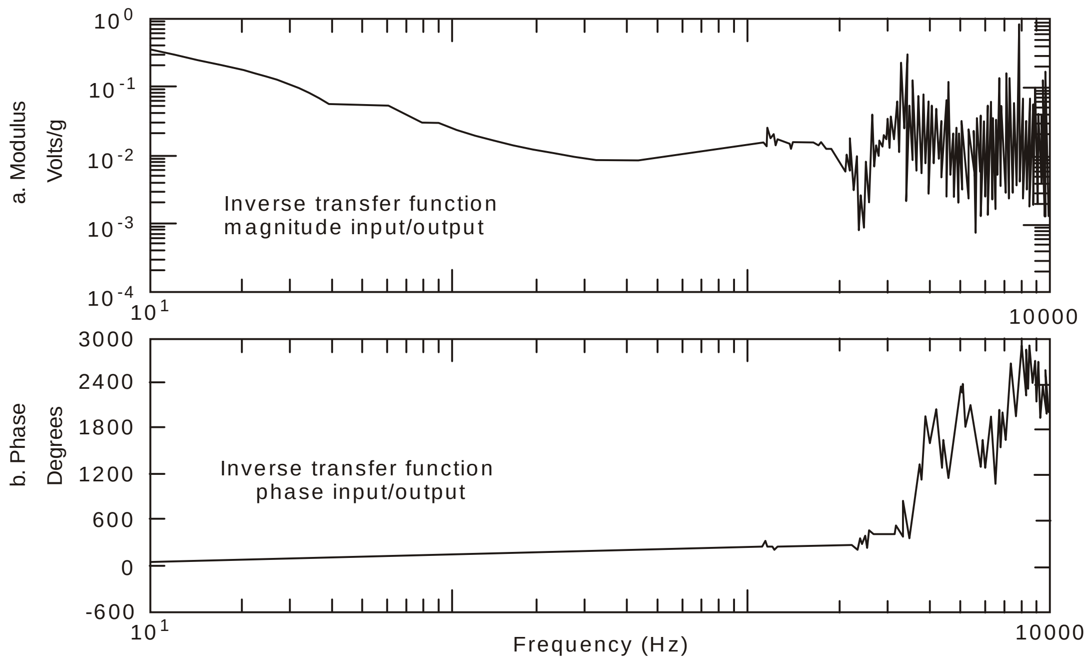


**FIGURE 519.5A-3. Modulus and phase of inverse frequency response function.**

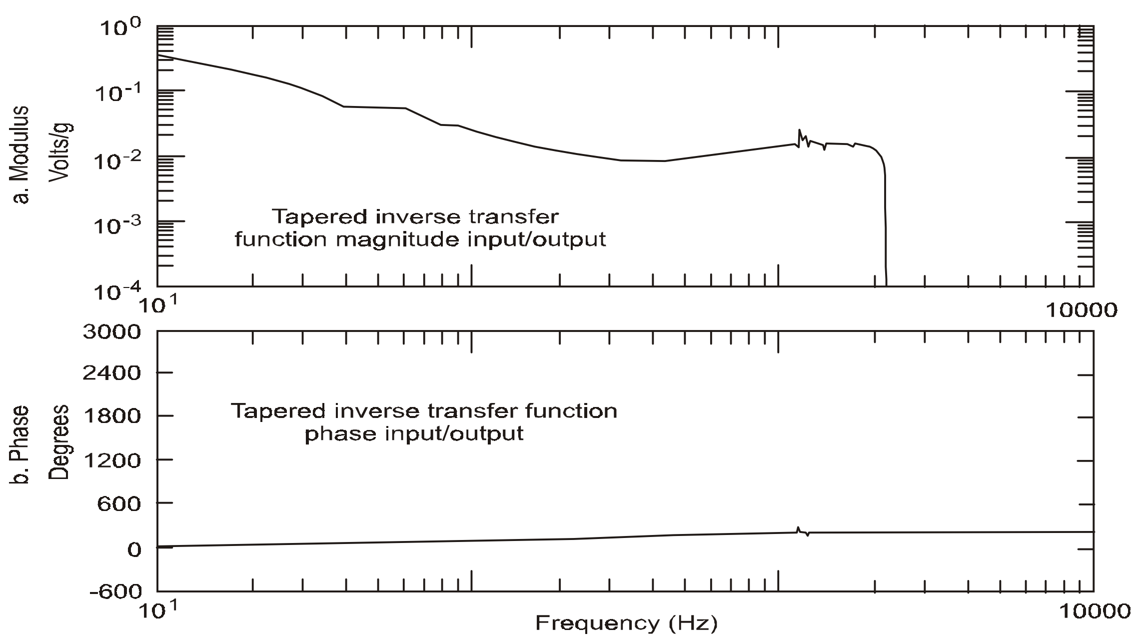


**FIGURE 519.5A-4. Modulus and phase of tapered inverse frequency response function.**

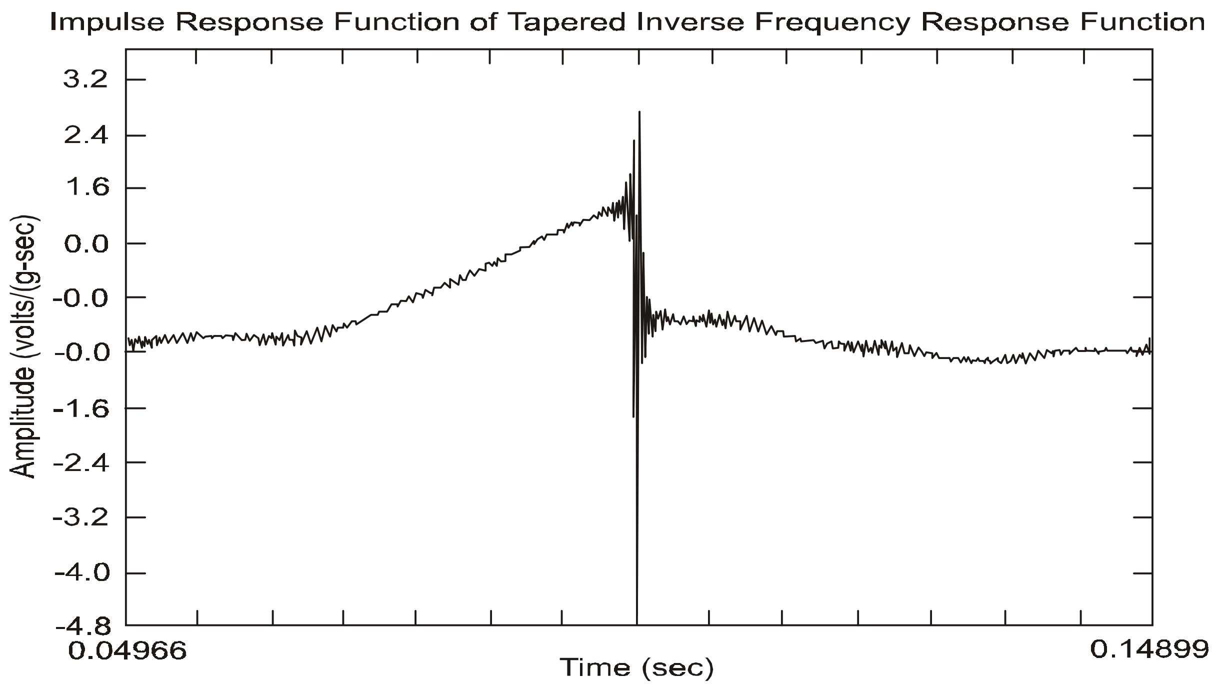


**FIGURE 519.5A-5. Impulse response function.**

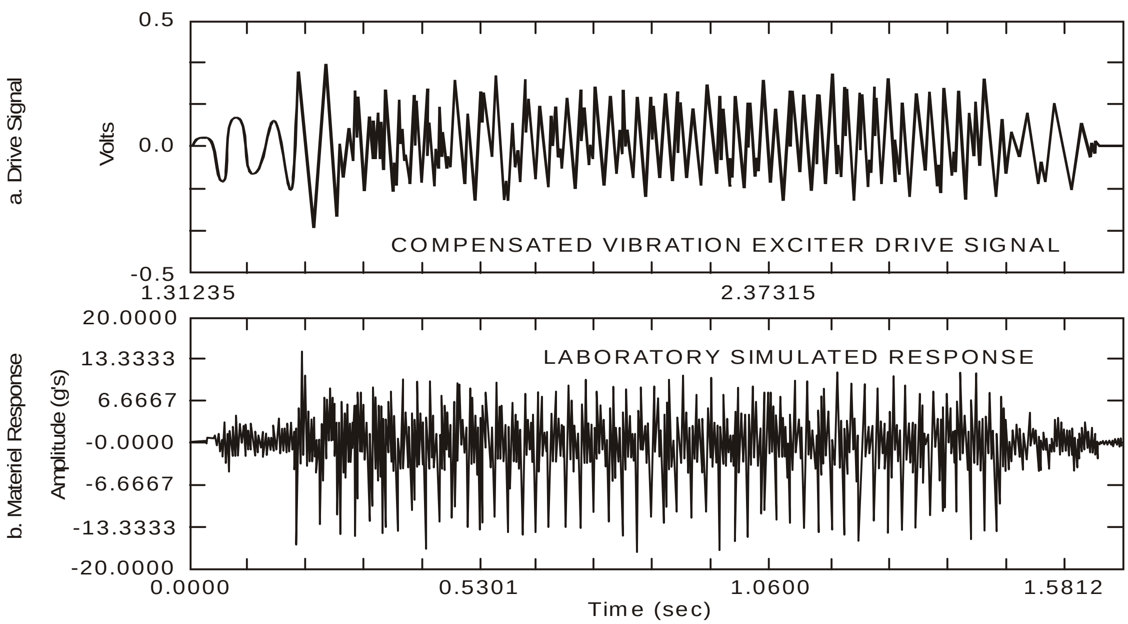


**FIGURE 519.5A-6. Compensated vibration exciter drive signal along with resulting test item response.**

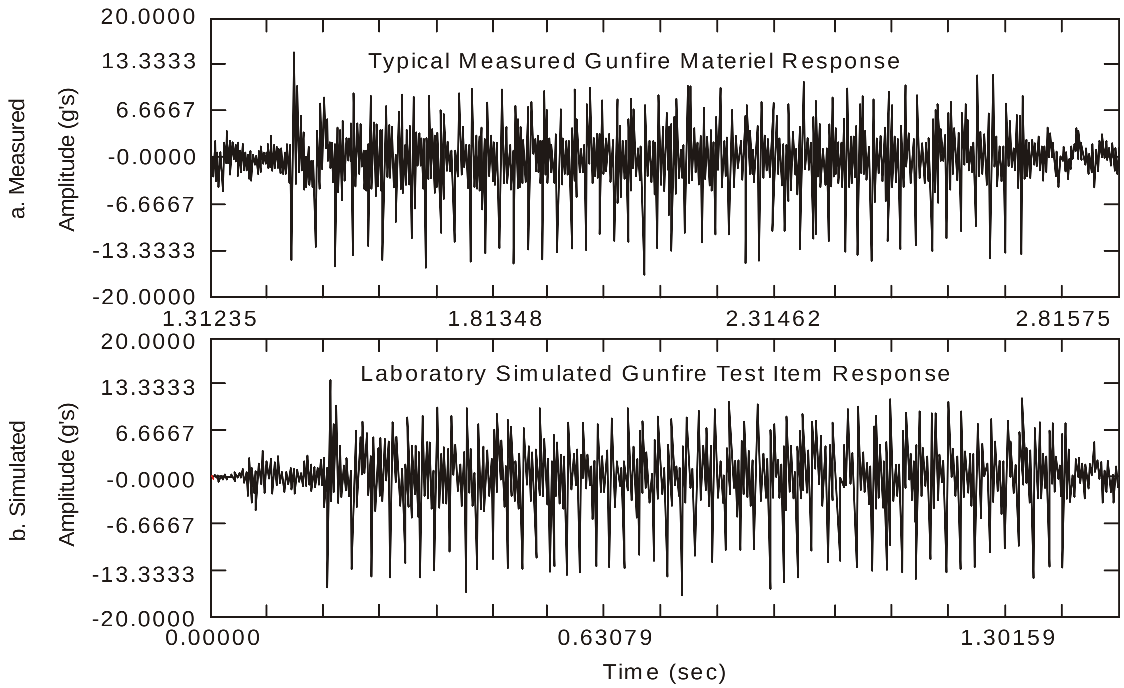


**FIGURE 519.5A-7. Comparison of measured gunfire materiel response with laboratory simulated gunfire test item response.**

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# ANNEX B

## STATISTICALLY GENERATED REPETITIVE PULSE – MEAN (DETERMINISTIC) PLUS RESIDUAL (STOCHASTIC) PULSE

## 1. SCOPE.

### 1.1 Purpose.

This annex provides an overview of a technique for simulation of a time-varying random process given a sample function for the process that can be used to generate ensemble statistics describing the time-varying character of the process.

### 1.2 Application.

Details for the technique are found in reference a, other aspects of the technique are found in references c and d, more recent developments are found in references f, g, and h of this annex. The stochastic simulation technique to be described here is for a single unknown time-varying random process for which a single sample function from the process is available. This single sample function is representative of a single gunfire physical configuration for which extrapolation to other configurations is undetermined. This technique:

a. is convenient to implement on a personal computer (PC) used to control a vibration exciter system;

b. has many features analogous to that of traditional stationary time history vibration exciter simulation based on autospectral density estimate specification;

c. is very flexible in terms of the length of statistically equivalent records it can generate for laboratory test replication of an in-service measured response environment;

d. has statistics that are easy to interpret and that approximate the true statistical variation in the unknown underlying random process;

e. can be generalized to other forms of time-varying random processes with ensemble representation easily;

f. abandons a minimal number of higher order features of the measured response ensemble not considered essential to conservative in-service measured response data replication by way of laboratory test item response simulation testing.

The following paragraphs are directed toward an overview of this method of test item response simulation along with its limitations.

## 2. DEVELOPMENT.

### 2.1 Nomenclature for Annex B.

| | |
|---|---|
| E [ ] | expected value of the quantity within the brackets |
| N, Np | number of pulses in an ensemble |
| P (x, t) | probability distribution function for a nonstationary random process |
| Rxx ($\tau$, t) | auto-correlation function for a non-stationary random process |
| $\{x_i(t)\}$ | random process |
| $x_i(t)$ | ith sample function for the random process |
| $X_T(f)$ | finite Fourier transform of x(t) over a finite interval of time, T |
| $\mu_X(t)$ | true time–varying mean |

$\hat{\mu}_x(t)$ time-varying mean estimate

$\sigma_x(t)$ true time-varying standard deviation

$\hat{\sigma}_x(t)$ time-varying standard deviation estimate

$\Psi_x^2(t)$ true time-varying mean square

$\hat{\Psi}_x^2(t)$ time-varying mean square estimate

$T_p$ period in seconds of a stationary sample record

$f_1=1/T_p$ fundamental frequency of a stationary sample record in Hertz

$T$ sampling time interval

$f_c=1/(2T)$ Nyquist cutoff frequency

**2.2 Introduction.**

In all that follows, the term "ensemble" is taken to mean a collection of sample time history records defined over a specified time interval. In the case of a nonstationary environment, the only complete description of the environment, is given through (1) statistical estimates of all the probabilistic moments of the process as a function of amplitude and time from the specification of P(x,t), or (2) a statistical estimate of the time-varying autocorrelation function, R(τ,t). Generally, P(x,t) and R(τ,t) are not available either directly in an analytic form or through accurate estimates based on the limited in-service measured response data. For practical purposes, for an in-service measured environment estimating the (1) time-varying mean, (2) time-varying standard deviation, (3) time-varying root mean square, (4) overall average energy spectral density, and (5) time-varying autocorrelation, assist in characterizing the nonstationary random process from which the sample ensemble is taken. Replication of at least (1) - (4) or all of these measured ensemble estimates in the simulation process will provide a satisfactory nonstationary test simulation of the in-service environment.

**2.3 Assumptions.**

To assist in deciding if the procedures described in this annex are applicable to particular measurement/test objectives, the following basic assumptions are made. (In what follows it is assumed that acceleration is the materiel response measurement variable. However, other measurement variables, e.g., strain, may be just as useful, provided they are capable of capturing the characteristic amplitude/frequency range of interest.)

a. The in-service measured materiel response is obtained from measurements at "hard points" on the materiel to be tested. The term “hard points” implies that (a) local materiel response peculiar to the location of the measurement instrumentation (including structural nonlinearity) is not dominant in the materiel response measurement, and (b) measured materiel response at the selected point is representative of the overall materiel response.

b. A sample time history trace of the measured in-service materiel response shows a distinct time-varying quality that repeats in a time interval correlated with the firing rate of the gun.

c. A sample time history of the measured in-service materiel response may be decomposed into an ensemble of shorter time history records (or pulses) having similar time-varying characteristics at equal time intervals from the beginning of each of the shorter time history records (the exact method of decomposition of the sample time history record is left to the discretion of the analyst - this usually can be accomplished by examining the measured “timing” or “firing” pulse for a repeated event or by way of cross-correlation methods as applied to the sample time history).

d. For testing, configuration information for the test item similar to that configuration for which the measured in-service materiel response data is available.

e. Use of the procedures outlined in Annex A for Direct Reproduction of Measured Materiel Response Data for determination of the test frequency response function for an electrodynamic or electrohydraulic vibration exciter.

f. Application of the test frequency response function to the simulated amplitude time history may be accomplished through (a) an energy spectral density function formulation whereby each short time history or pulse is individually compensated by way of the convolution of the pulse time history with the system impulse response function, and the pulses concatenated into one long output voltage time history for input to the digital-to-analog interface, or (b) a long time history convolution, whereby the uncompensated long output time history is first generated and then convolved with the system impulse response function to provide the compensated voltage drive signal for input to the digital-to-analog interface. Both of these techniques assume generation of a long compensated voltage waveform to be run in an open-loop mode on a vibration exciter system. For this open-loop run configuration, it is suggested that the length of the compensated waveform not exceed five seconds and the appropriate abort limits are active on the vibration exciter system. (As sophistication in vibration exciter control systems increases, the energy spectral density formulation with waveform compensation on individual pulses and closed loop control will become the norm for operation. At this time, practicality of this procedure is limited by the speed of processors in input and output to the vibration exciter system. In addition, (1) a rationale for quantitatively judging the “adequacy” of the simulation in “real time,” based on the time-varying statistical estimates, and (2) a means of “real time” compensation of “inadequate” simulation in real time has not been developed.)

g. The adequacy of the simulation in meeting the specification on the error between the measured in-service materiel response statistics and the measured test item response from the test simulation is based on utilizing equivalent sample sizes or correcting the error measure based on sample size differences.

h. In summary, at the time of this writing, the test simulation of a measured in-service materiel response is based on

   (1) pretest generation of the uncompensated test sample time history;

   (2) compensation of the test sample time history;

   (3) open-loop waveform control for the vibration exciter system;

   (4) off line processing of the test item response sample time history for direct comparison with the measured in-service materiel response sample time history.

### 2.4 Modeling and Statistics for Description of a Materiel Response Time-varying Random Process.

A very general model for modeling time-varying random processes is the “product model,” which assumes that the time-varying characteristics of a random process can be separated from the frequency characteristics of the random process (see reference b). For materiel response to a gunfire environment, a form of product model can be used to adequately describe this response. The procedures used in constructing the model require some experience. Unfortunately, this modeling does not provide for parameterized predictions of materiel response in other measured data configurations. The basic statistics to be used to characterize a measured response environment with an ensemble representation are the following:

a. the time-varying mean;

b. time-varying standard deviation;

c. time-varying root mean square;

d. average energy spectral density function (may be time dependent).

Error statistics for the simulation may be based on the error expressions for a. through d.

The following is a definition of the product model used in this development. Consideration is given to the time-varying frequency character over discrete time intervals, which can be explored in more detail through the nonstationary autocorrelation function. References/Related Documents (paragraph 2.7) consider this issue in more detail. Using the notation and terminology from reference b, for u(t) a sample time history from a stationary random process, {u(t)}, and both $a_1(t)$ and $a_2(t)$ deterministic time histories, then a general time-varying random process, {x(t)}, can be modeled as

$$x(t) = a_1(t) + [a_2(t)\, u(t)]_f \qquad \text{(B-1)}$$

$a_1(t)$ is a deterministic time history defined in terms of the in-service time-varying ensemble mean estimate. $a_2(t)$ is a deterministic time history defined in terms of the in-service time-varying ensemble standard deviation estimate. $a_2(t)$ shapes (in the time domain) the root mean square level of the residuals from the in-service ensemble after $a_1(t)$ has been removed from the in-service ensemble. The "f" following the bracket indicates that the residual information is a function of frequency content and in the description below, f, represents the time-varying frequency content in four discrete equal length time intervals. For this model $a_1(t)$ - the time-varying mean of the ensemble will be referred to as the "signal" and $[a_2(t)\ u\ (t)]_f$ - the shaped residual or "noise." If the time-varying random process is heavily dominated by the deterministic time-varying mean or "signal," i.e., the amplitude of $a_1(t)$ is large in comparison with the residual $[a_2(t)\ u(t)]_f$, then one should expect comparatively small time domain errors in the time-varying mean, standard deviation, and root mean square. The frequency content should also be easily replicated. The residual ensemble constructed by subtracting the time-varying mean from each sample time history of the original ensemble is defined in terms of the in-service measured ensemble as follows:

$$\{r(t)\} = \{x(t)\} - \hat{\mu}_x(t) \qquad \text{(B-2)}$$

This residual ensemble has the following two properties:

a. time-varying mean of {r(t)} is zero

b. time-varying root mean square of {r(t)} is the time-varying standard deviation of the ensemble {x(t)}

Time domain criterion for testing the validity of the simulation is given as the variance of the time domain estimators of the time-varying mean, time-varying standard deviation and the time-varying root mean square. Expressions for these estimators and their variance are provided in equations (B-3) through (B-8). The notation and terminology from reference b is employed. The unbiased time-varying mean estimate for an ensemble {x(t)} of N time history samples, each of duration $T_P$, is given by

$$\hat{\mu}_x(t) = \frac{1}{N}\sum_{i=1}^{N} x_i(t) \quad 0 \le t \le T_P \qquad \text{(B-3)}$$

and the variance of this estimator is given as

$$E\left[\left(\hat{\mu}_x(t) - \mu_x(t)\right)^2\right] \qquad 0 \le t \le T_P \qquad \text{(B-4)}$$

where $\mu_x(t)$ is the true nonstationary time-varying mean of the process.

The unbiased time-varying standard deviation estimate for an ensemble {x(t)} is given by

$$\hat{\sigma}_x(t) = \sqrt{\frac{\sum_{i=1}^{N}\left(x_i(t) - \hat{\mu}_x(t)\right)^2}{N-1}} \qquad 0 \le t \le T_P \qquad \text{(B-5)}$$

and the variance of this estimator can be given in its theoretical form as

$$E\left[\left(\hat{\sigma}_x(t) - \sigma_x(t)\right)^2\right] \qquad 0 \le t \le T_P \qquad \text{(B-6)}$$

where $\sigma_x(t)$ is the true nonstationary time-varying standard deviation of the process.

The unbiased time-varying mean square estimate for an ensemble {x(t)} is given by

$$\hat{\Psi}_x^2(t) = \frac{1}{N}\sum_{i=1}^{N} x_i^2(t) \qquad 0 \le t \le T_p \tag{B-7}$$

and the variance of this estimator is given as

$$E\left[\left(\hat{\Psi}_x^2(t) - \Psi_x^2(t)\right)^2\right] \qquad 0 \le t \le T_p \tag{B-8}$$

where $\Psi_x^2(t)$ is the true nonstationary time-varying mean square of the process.

In the frequency domain, the average energy spectral density function for an ensemble {x(t)}

$$\hat{E}_{xx}(f) = 2E\left[\left|X_{Tp}(f)\right|^2\right] \qquad 0 < f < f_c \tag{B-9}$$

and the variance of this estimator is given in theoretical form as

$$V\left[\hat{E}_{xx}(f)\right] = E\left[\left(\hat{E}_{xx}(f) - E_{xx}(f)\right)^2\right] \qquad 0 < f < f_c \tag{B-10}$$

The estimate $\hat{E}_{xx}(f)$ will also contain a bias error related to the Fourier analysis bandwidth. It is assumed here that total bias error can be minimized by proper selection of the Fourier analysis bandwidth. It is important to note that a wider analysis resolution bandwidth was required for demonstration of the time-varying frequency characteristics of the ensemble. The wider analysis resolution bandwidth will increase the bias error. In computing these estimates of error (or just quantitatively measuring how “close” the test simulation test item response is to in-service materiel response) the "true" quantities are unknown but can be taken as the processed in-service measured materiel response.

**2.5 Specific Application of the Model to the Measured Materiel Response.**

This portion of the annex provides a brief overview of the actual processing necessary to perform a successful stochastic test item response simulation to a measured in-service materiel response environment. Figures in this annex have been graphically enhanced over those contained in reference a. The in-service measured materiel response to be modeled is a fifty pulse ($N_p$=50) round 30 mm gunfire event depicted on figure 519.5B-1a. The gunfiring rate is approximately 40 rounds per second and the event lasts for about 1.25 seconds. This record is digitized at 20,480 samples per second with an anti-alias filter set at 2 kHz. It is clear just from visual inspection of the amplitude time history that it has periodic time-varying characteristics. This record is carefully decomposed into an ensemble of 50 pulses each of about 25 milliseconds length for which ensemble time-varying statistical techniques are applied. Figure 519.5B-2a contains the plot of a typical pulse of the ensemble (pulse 37) and figure 519.5B-3a contains its residual. Figure 519.5B-4a contains a plot of the mean estimate for this ensemble defined in equation (B-3). The standard deviation estimate of the ensemble of $N_P$ records defined in equation (B-5) is shown on figure 519.5B-5a. This is also the root mean square of the residual ensemble. Figure 519.5B-6a contains a plot of the root mean square for the ensemble. By subtracting the mean from each member of the ensemble as described in equation (B-4) a residual ensemble is obtained. This residual ensemble has zero mean and a non-zero time-varying root mean square the same as the standard deviation of the original ensemble. It is very important to understand the characteristics of this residual ensemble. It should be clear from the above figures that the measured ensemble has a time-varying mean, a time-varying mean square, and a time-varying frequency with higher frequencies in the initial portion of the record. An energy spectral density computed on the original measured ensemble and the measured residual ensemble reveals the effect of removal of the time varying mean from the original ensemble and the differing frequency characteristics of the two ensembles. Figure 519.5B-7a provides a superposition of both of these

ESD estimates. The Fourier analysis filter bandwidth for the ESD estimates is 5 Hz. An even more dramatic depiction of the time-frequency character of the original ensemble is given on figure 519.5B-8a, T1 through T4. In this analysis the pulse length is divided into four equal time segments of 6.25 milliseconds each and the average ESD computed for each segment retaining a 20 Hz filter bandwidth. The estimates are averaged over the ensemble with no time domain tapering applied. When all four spectra are superimposed upon one another, it is clear that the variation of frequency with time is substantial both for the original ensemble and for the residual ensemble (figure 519.5B-9a). The residual ensemble is studied for its second order or correlation properties in references a, c and d. The actual steps used to perform the simulation according to the model outlined in equation (B-1) and to estimate the error in the time-varying mean, standard deviation, root mean square, and the residual and overall energy spectrum estimate are contained in reference a. Figures 519.5B-10a and 10b depict the estimated deterministic functions $a_1(t)$ and $a_2(t)$, respectively. Figure 519.5B-11a displays the residual information before the residual is filtered, and figure 519.5B-11b the residual after filtering is applied. Using information from references a and b only, Fourier based processing (FFT and inverse FFT) is used to determine the simulated test ensemble. Segmentation in time in order to simulate the time-varying frequency characteristics of the ensemble did provide for some minor discontinuity at the time interval boundaries in the simulation. From Reference c it can be noted that it is also possible to segment the time-varying characteristics in the frequency domain which also results in some minor discontinuities in the frequency domain. The results of the simulation are displayed on the figures below in order to note the general fidelity in the simulation. Figure 519.5B-1b represents a simulated ensemble with $N_p$ pulses to give an overall qualitative assessment of the simulation. Figure 519.5B-2b and figure 519.5B-3b provide plots of a typical pulse (pulse number 37) and its residual from this simulated ensemble, respectively. Figure 519.5B-4b is the mean for the ensemble with figure 519.5B-5b the standard deviation, and figure 519.5B-6b the root mean square. Figures 519.5B-7 through 519.5B-9 display measured information with corresponding simulated ESD information. Figure 519.5B-12 contains the maximum, the median time-varying root variance estimates for the time-varying mean for sample sizes of 10, 25, and 50 pulses. This represents the error that might be expected at each time point as a result of the simulation for the three sizes of ensembles. Corresponding information is provided on figure 519.5B-13 for the time-varying standard deviation and on figure 519.5B-14 for the time-varying root mean square. In general for an ensemble with Np = 50 sample time histories, the maximum root variance is less than 2.5 g's with the median being, in general, below 0.75 g's.

**2.6 Implementation.**

The technique outlined above may be implemented by pre-processing the data and generating the simulated materiel response ensemble on a mainframe computer or a PC. In either case the simulated digital waveform must be appropriately compensated by the procedure described in Appendix A before the analog voltage signal to the vibration exciter is output. This technique of stochastic simulation is quite elaborate in detail but does provide for a true stochastic time-varying laboratory simulation of materiel response based on measured in-service materiel response. The technique is flexible, in that it can produce an unlimited number of “pulses,” all slightly different, with testing limited only by the length of time a vibration exciter controller can provide an adequate simulation in an open-loop waveform mode of control. If it is assumed that vibration exciter output scales linearly with vibration exciter master gain, degrees of test conservativeness in the stochastic simulation may be introduced.

**2.7 References/Related Documents.**

a. R. G. Merritt, Simulation of Ensemble Oriented Nonstationary Processes, Part 2 Proceedings of 1994 IES 40th Annual Technical Meeting, Chicago, IL, May 1994.

b. J. S. Bendat and A. G. Piersol, Random Data: Analysis and Measurement Procedures, 2nd edition, John Wiley & Sons Inc., New York, 1986.

c. D. O. Smallwood, Gunfire Characterization and Simulation Using Temporal Moments, Proceedings of the 65th Shock and Vibration Symposium, Volume 1, San Diego, CA, November 1994.

d. R. G. Merritt, An Example of the Analysis of a Sample Nonstationary Time History, Proceedings of 1994 IES 40th Annual Technical Meeting, Chicago, IL, May 1994.

e. C. Lanczos, Discourse on Fourier Series, Hafner Publishing Company, New York, 1966.

f. D. O. Smallwood, Characterization and Simulation of Gunfire with Wavelets, Proceedings of the 69th Shock and Vibration Symposium, Minneapolis, MN, October 1998.

g. R.G. Merritt, A Note on Prediction of Gunfire Environment using the Pulse Method, Proceedings of 1999 IEST 45$^{th}$ Annual Technical Meeting, Ontario, CA, May 1999.

h. D. O. Smallwood, Characterization and Simulation of Gunfire with Wavelets, Shock and Vibration, Volume 6, November 2, 1998, IOS Press, The Netherlands.

## 3. RECOMMENDED PROCEDURES.

### 3.1 Recommended Procedure.

For single point materiel response measurements on comparatively simple dynamic materiel, use this procedure in cases in which laboratory replication of the response environment with potential statistical variation is absolutely essential to establish materiel operational and structural integrity in a gunfire environment.

### 3.2 Uncertainty Factors.

This procedure includes statistical uncertainty in addition to uncertainty in the degree to which the measured environment compares with the in-service environment. Uncertainty relative to the variety of in-service environment configurations is not accounted for in this procedure. This procedure cannot be used to determine gunfire environment prediction errors.

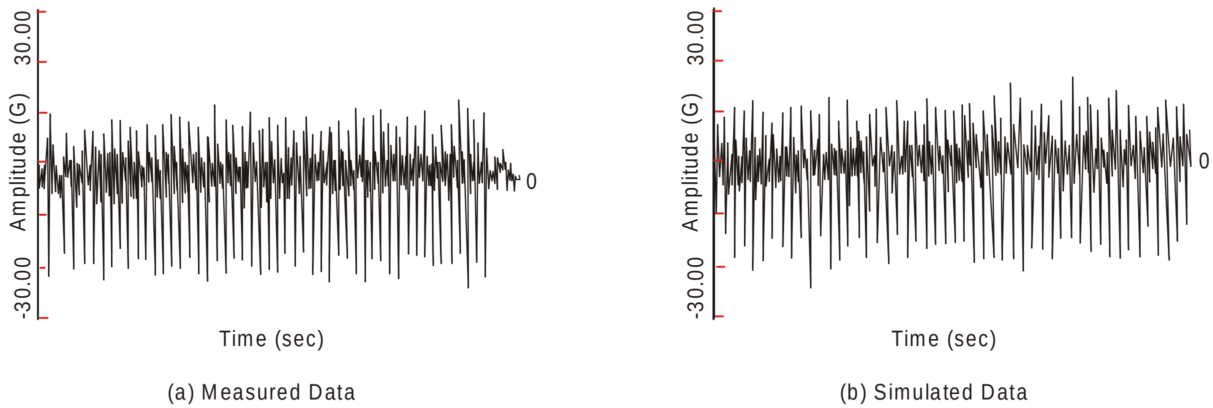



**FIGURE 519.5B-1. Fifty round 30mm gunfire event.**

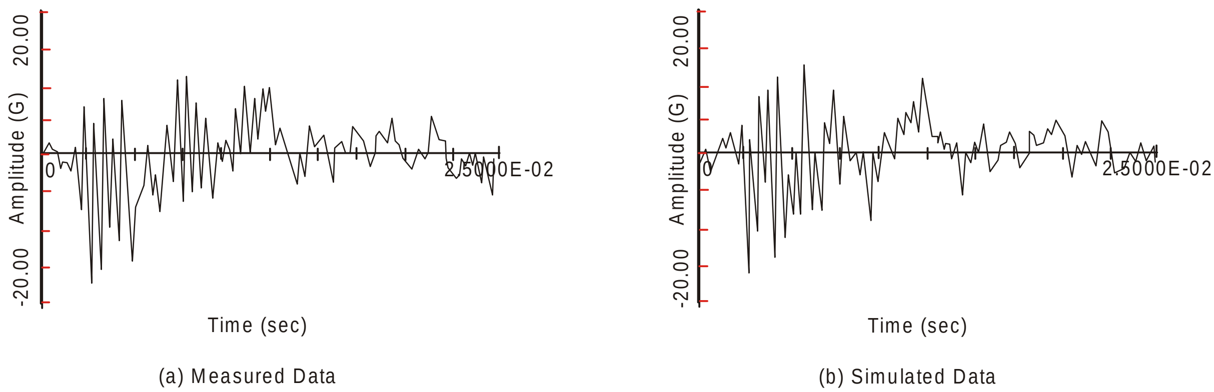



**FIGURE 519.5B-2. Ensemble sample time history pulse (pulse 37).**

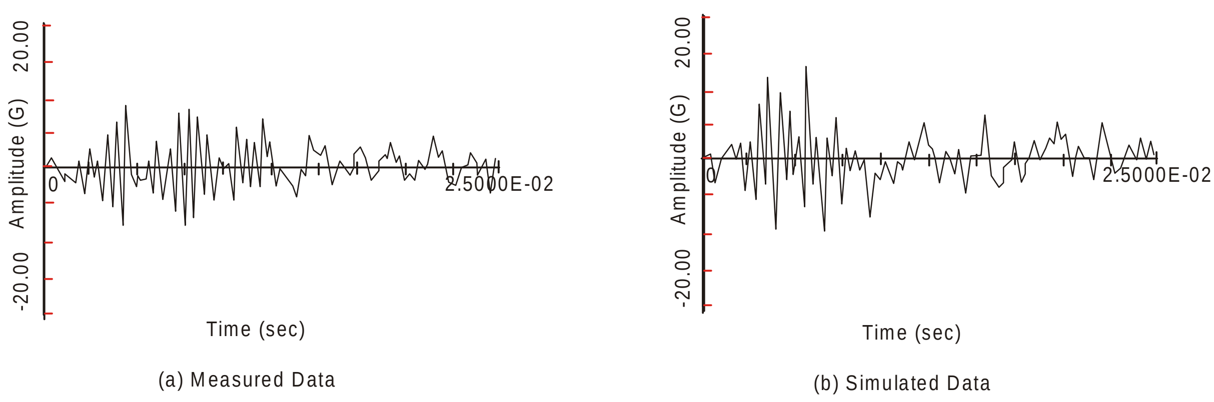
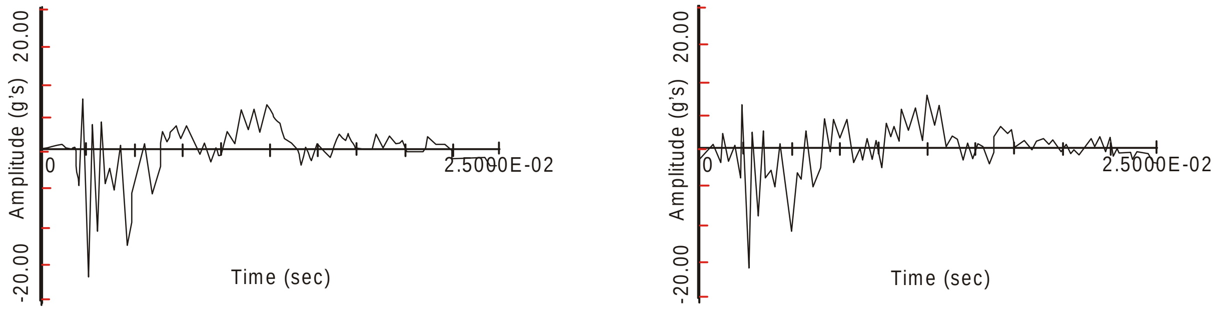
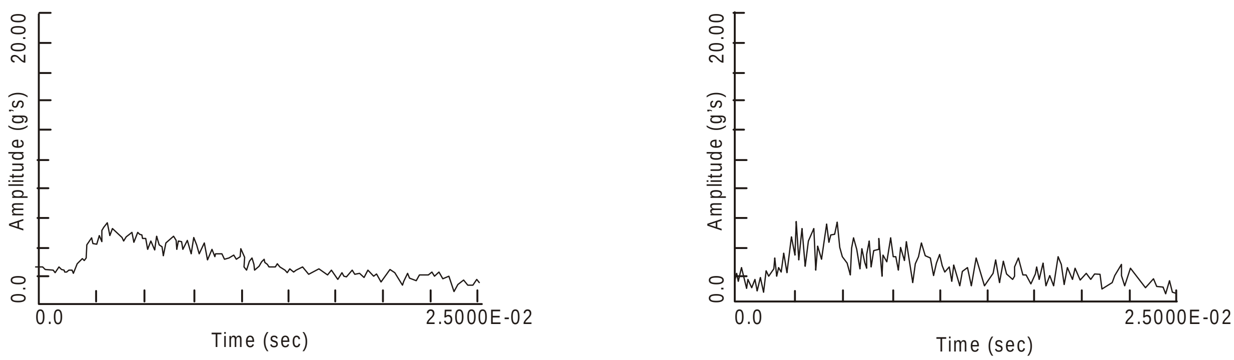



**FIGURE 519.5B-3. Ensemble residual sample time history pulse (pulse 37).**



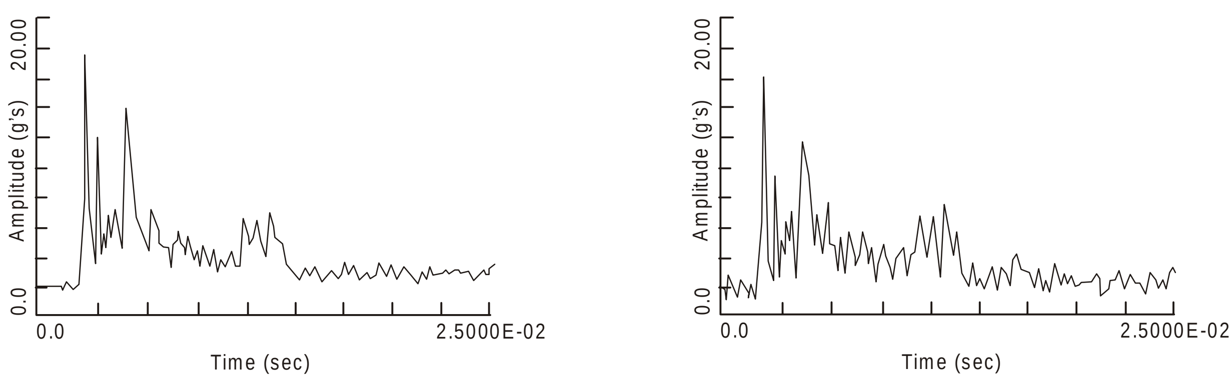

(a) Measured Data (b) Simulated Data

**FIGURE 519.5B-4. Ensemble time-varying mean estimate.**




(a) Measured Data (b) Simulated Data

**FIGURE 519.5B-5. Ensemble time-varying standard deviation estimate.**




(a) Measured Data (b) Simulated Data

**FIGURE 519.5B-6. Ensemble time-varying root mean square estimate.**

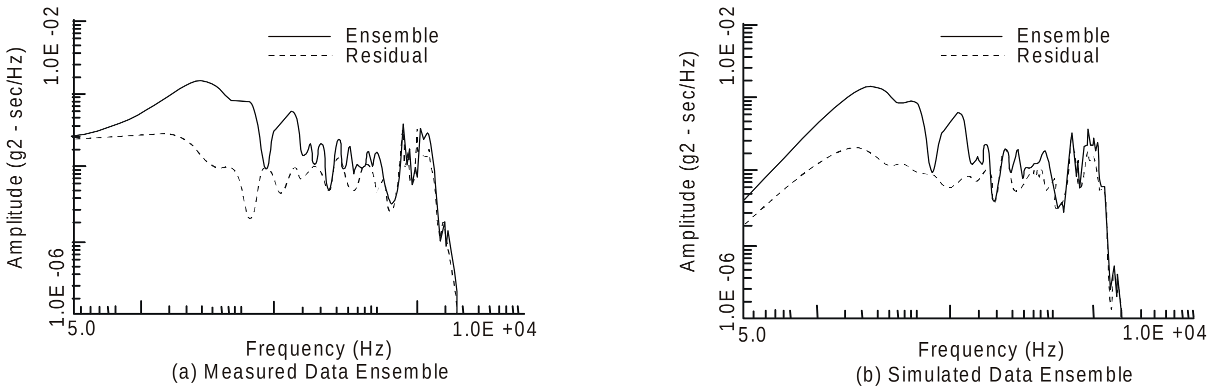



**FIGURE 519.5B-7. Energy spectral density function estimate.**

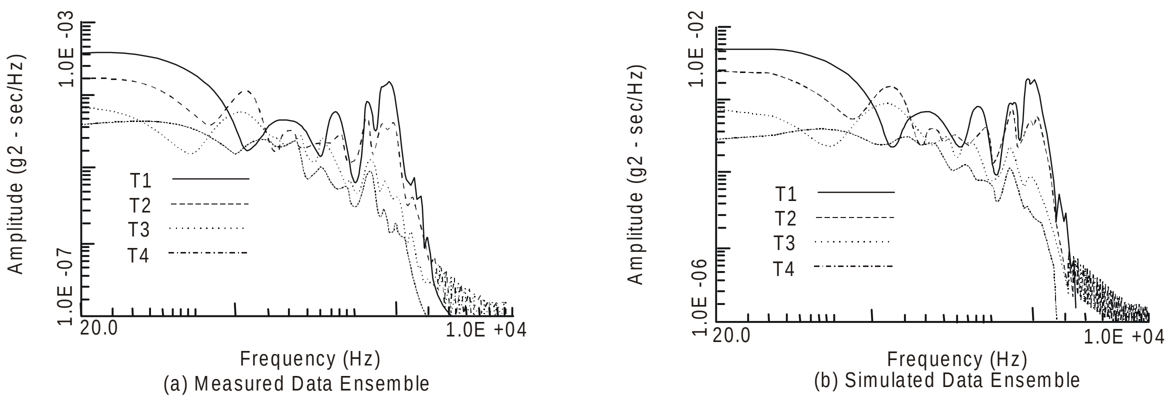



**FIGURE 519.5B-8. Short time energy spectral density function estimate (data).**

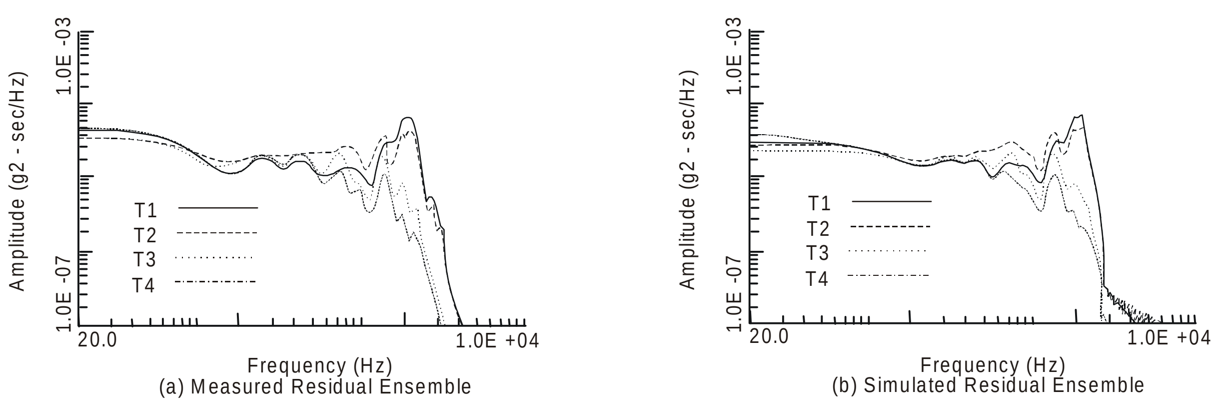
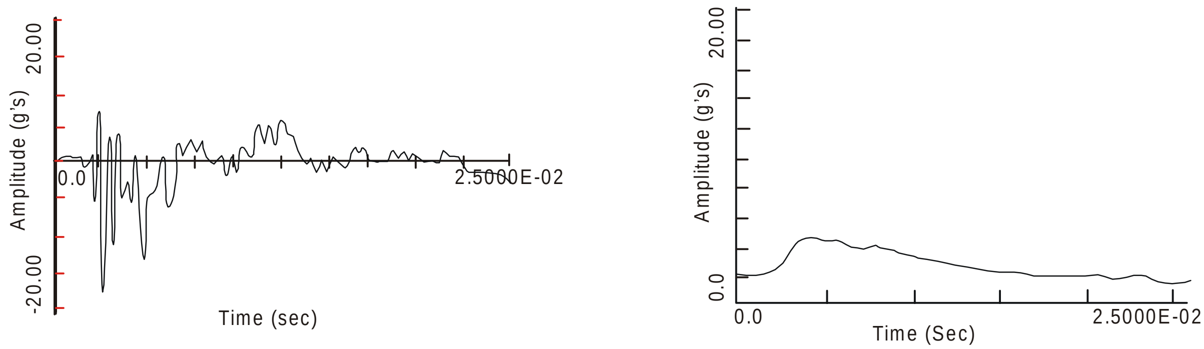


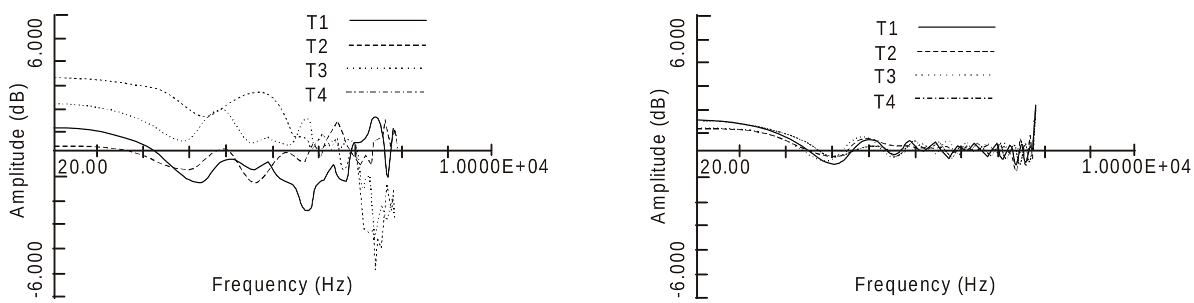

**FIGURE 519.5B-9. Short time energy spectral density function estimate (residual).**




a. $a_1(t)$ - Deterministic Signal

b. $a_2(t)$ - Estimate Smoothed Residual Window.

**FIGURE 519.5B-10. Non-stationary model deterministic functions.**




(a) Before Residual Filtering.

(b) After Residual Filtering.

**FIGURE 519.5B-11. Segmented ESD ratio.**

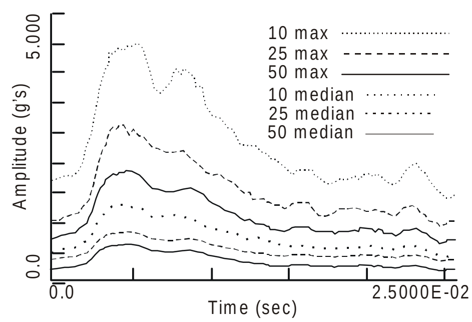



**FIGURE 519.5B-12. Smoothed simulation root variance estimate for the time-varying mean for simulated ensembles sample sizes of 10, 25, and 50. Sample time histories maximum and median.**

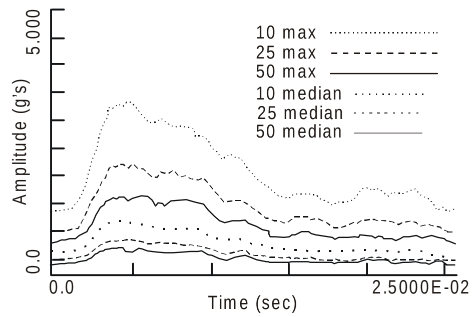



**FIGURE 519.5B-13. Smoothed simulation root variance esimtates for the time-varying standard deviation for simulated ensemble sample sizes of 10, 25, and 50 sample time histories maximum and median $N_p$ = 10, 25, and 50.**

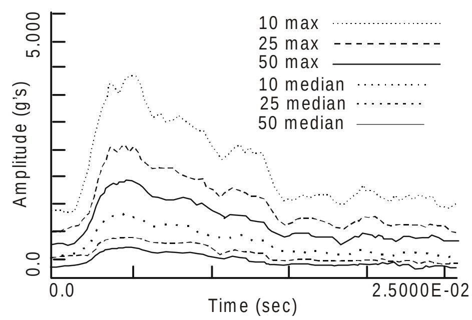



**FIGURE 519.5B-14. Smoothed simulation root variance estimate for the time-varying root mean square for simulated ensemble sample sizes of 10, 25 and 50. Sample time histories maximum and median.**

# ANNEX C

## REPETITIVE PULSE SHOCK RESPONSE SPECTRUM (SRS)

## 1. SCOPE.

### 1.1 Purpose.

This annex provides guidance and a basis for a technique for laboratory simulation of a measured materiel response of a gunfire environment. This technique is a form of the "Pulse Method" previously identified in MIL-STD-810E.

### 1.2 Application.

This technique is for a single unknown time-varying random process for which a single sample function from the process is available. This single sample function is representative of a single gunfire physical configuration for which extrapolation to other configurations is undetermined. This technique:

a. is convenient to implement on a vibration exciter control system with SRS capability;

b. has many features analogous to that of traditional SRS shock simulation based on SRS estimate specification;

c. is very flexible in terms of the length of statistically equivalent records it can generate for laboratory test replication of an in-service measured response environment;

d. is not restricted to one form of pulse, and

e. abandons a minimal number of higher order features of the measured response ensemble not considered essential to conservative in-service measured response data replication by way of laboratory test item response simulation testing.

The following paragraphs are directed toward an overview of this method of test item response simulation along with its limitations.

## 2. DEVELOPMENT.

### 2.1 Introduction.

The SRS method assumes that the measured materiel response time history can be decomposed into an ensemble of individual pulses. Maximax SRS are computed over the ensemble of pulses using various damping factors to assist in characterizing the frequency content of the individual pulses. The SRS mean is also computed over the ensemble of pulses for each damping factor to further characterize the materiel response pulses. Using the information from the SRS, an acceleration time history using amplitude modulated sine components or damped sinusoids is synthesized. The SRS time history is then used as the characteristic gunfire materiel response pulse, and input to the test item at the firing rate of the gun. (See references a and b in paragraph 2.8.)

#### 2.1.1 Advantages of this procedure are:

a. it makes use of standard laboratory shock test equipment;

b. the method reproduces the frequency characteristics of the measured materiel response data;

c. the SRS can be easily specified in documents and reproduced at various test facilities.

**2.1.2 Disadvantages of this procedure are:**

a. the character of the time history generated by the amplitude-modulated sine components or damped sinusoids is not well controlled and may not appear similar in form to the measured materiel response pulses;

b. little or no statistical variation can be easily introduced into the simulation;

c. reproducing the series of pulses at the firing rate of the gun may also present a problem for vibration exciter control systems not designed for this mode of operation.

A particular example of gunfire materiel response simulation using the Repetitive Pulse Shock Response Spectrum (SRS) technique is discussed below. This procedure, described in the following paragraphs, was performed using a digital vibration control system with SRS testing capability. (See reference b in paragraph 2.8.)

**2.2 Test Configuration.**

An instrumented test item is installed in a laboratory vibration fixture and mounted to the armature of an electrodynamic vibration exciter. The test item employed during the laboratory simulation is of the same configuration as the materiel used to measure the materiel response data. A piezoelectric accelerometer is installed internal to the test item for purposes of acceleration response measurement.

**2.3 Creating a Digital File of the Gunfire Environment Materiel Response Vibration.**

The first step in this simulation process is to digitize the measured in-service materiel response data to obtain an acceleration time history (figure 519.5C-1). Digital processing of the analog data is performed using a 2 kHz, 48 dB/octave low pass linear phase anti-alias filter (digital file was DC coupled and not high pass filtered) and a sample rate of 20,480 samples per second for good time history resolution.

**2.4 Computing the Shock Response Spectra.**

If examination of the individual measured response pulses indicates similar character between the pulses, a representative pulse is chosen for analysis. SRS are then computed over the representative pulse using a specified analysis Q of 10, 25, 50, and 100. To increase the statistical confidence in the results the pulse sequence may be ensemble averaged in time, the “mean” of the ensemble taken as the representative pulse, and the procedure above applied. If pulse characteristics are very dissimilar, then it may be necessary to run several tests from an analysis depending upon the judgement of an experienced analyst.

**2.5 Estimating Equivalent Half-Cycle Content of Representative Gunfire Environment Materiel Response Pulse.**

Figure 519.5C-2 indicates that the representative gunfire environment materiel response pulse contains seven predominant frequencies at near 80, 280, 440, 600, 760, 1,360, and 1,800 Hz. Because (2Q) half-cycles for a constant amplitude sine wave provides approximately 95% of the maximum amplitude given Q, an estimate of the equivalent half-cycle content that makes up the predominant frequencies contained in the measured gunfire materiel response can be determined by identifying the Q at which the peak acceleration for a particular frequency of the SRS begins to level off. A Q of 10 on figure 519.5C-2 characterizes the half-cycle content of the 80 Hz component. The half-cycle content of the other predominant frequencies, except at 1,800 Hz, is represented by a Q of 25. A Q of 50 quantifies the half-cycle content of the 1,800 Hz component.

**2.6 Generating SRS Transient for Representative Gunfire Environment Materiel Response Pulse.**

After estimating the frequency content of the representative gunfire environment materiel response pulse, an SRS transient time history pulse is generated (from a proprietary wave synthesis algorithm) using a digital vibration exciter control system. The SRS transient time history pulse is composed of 1/12-octave amplitude-modulated sine components, with the majority of the 1/12-octave components limited to three half-cycles that is the minimum allowed for the exciter control system. The seven predominant frequencies are restricted for half-cycle content by either the 25-millisecond duration of the gunfire response pulse (40 Hz gunfiring rate) or by the half-cycle estimation technique discussed in Annex C, paragraph 2.5. A Q of 10 is identified for the 80-Hz component; a Q of 25 for the 280-, 440-, 600-, 760-, and 1,360-Hz components; and a Q of 50 for the 1,800 Hz component. The SRS mean is computed over the ensemble of pulses for each damping factor (Q= 10, 25, 50, and 100) to characterize the SRS amplitudes. The mean SRS that is computed using an analysis Q of 50 is then selected to define the SRS amplitude for each frequency component of the simulated materiel response pulse. Zero time delay is specified for each of the 1/12-octave amplitude modulated sine components. See table 519.5C-I for the definition and figure 519.5C-3 for the SRS gunfire materiel response transient produced by the amplitude modulated sine component definition.

### 2.7 Simulating the Gunfire Materiel Response.

The final step in the gunfire materiel response simulation is to repeat the SRS response transient at the gunfiring rate of 40 Hz. Because of output pulse rate limitations of the vibration exciter control system being used, the 40 Hz firing rate could not be achieved. Figure 519.5C-4 is an acceleration time history that illustrates the repetitive character of the SRS gunfire environment simulation method without vibration exciter controller output pulse rate limitations. Note: Figure 519.5C-4 is generated for illustrative purposes by digitally appending the figure 519.5C-3 SRS materiel response transient pulse at the gunfiring rate. If the vibration exciter control system does not allow for such rapid repetition, the waveform control procedure defined in Annex A could be used on a digitally simulated and vibration exciter compensated series of materiel response pulses.

### 2.8 Reference/Related Documents.

a. Merritt, R.G. and S.R. Hertz, Aspects of Gunfire, Part 1- Analysis, Naval Weapons Center, China Lake, CA 93555-6100, NWC TM 6648, Part 1, October 1990.

b. Merritt, R.G. and S.R. Hertz, Aspects of Gunfire, Part 2- Simulation, Naval Weapons Center, China Lake, CA 93555-6100, NWC TM 6648, Part 2, September 1990.

## 3. RECOMMENDED PROCEDURES.

### 3.1 Recommended Procedure.

For single point materiel response measurements on comparatively simple dynamic materiel, use this procedure. This procedure is to be used in cases in which laboratory replication of the response environment is essential to establish materiel operational and structural integrity under gunfire environment.

### 3.2 Uncertainty Factors.

This procedure includes no statistical uncertainty in addition to no uncertainty in the degree to which the measured environment compares with the in-service environment.

**TABLE 519.5C-I. Amplitude modulated sine wave definition for SRS gunfire materiel response pulse.**[1]

| Frequency (Hz) | Amplitude (g's) | Half-cycles | Frequency (Hz) | Amplitude (g's) | Half-cycles |
|---|---|---|---|---|---|
| 78.75 | 11.995 | 3 | 445.45 | 34.995 | 21 |
| 83.43 | 11.803 | 3 | 471.94 | 26.455 | 3 |
| 88.39 | 11.628 | 3 | 500.00 | 19.999 | 3 |
| 93.64 | 11.455 | 3 | 529.73 | 21.232 | 3 |
| 99.21 | 11.285 | 3 | 561.23 | 22.568 | 3 |
| 105.11 | 11.117 | 3 | 594.60 | 23.988 | 29 |
| 111.36 | 10.952 | 3 | 629.96 | 18.323 | 3 |
| 117.98 | 10.777 | 3 | 667.42 | 13.996 | 3 |
| 125.00 | 10.617 | 3 | 707.11 | 20.448 | 3 |
| 132.43 | 10.459 | 3 | 749.15 | 29.992 | 37 |
| 140.31 | 10.304 | 3 | 793.70 | 31.225 | 3 |
| 148.65 | 10.151 | 3 | 840.90 | 32.509 | 3 |
| 157.49 | 10.000 | 3 | 890.90 | 33.845 | 3 |
| 166.86 | 10.814 | 3 | 943.87 | 35.237 | 3 |
| 176.78 | 11.708 | 3 | 1,000.00 | 36.728 | 3 |
| 187.29 | 12.662 | 3 | 1,059.46 | 38.238 | 3 |
| 198.43 | 13.709 | 3 | 1,122.46 | 39.811 | 3 |
| 210.22 | 14.825 | 3 | 1,189.21 | 41.448 | 3 |
| 222.72 | 16.051 | 3 | 1,259.91 | 43.152 | 3 |
| 235.97 | 17.358 | 3 | 1,334.84 | 44.975 | 49 |
| 250.00 | 18.793 | 3 | 1,414.21 | 37.325 | 3 |
| 264.87 | 20.324 | 3 | 1,498.31 | 31.010 | 3 |
| 280.62 | 22.004 | 13 | 1,587.40 | 50.003 | 3 |
| 297.30 | 18.275 | 3 | 1,681.79 | 80.631 | 3 |
| 314.98 | 16.901 | 3 | 1,781.80 | 130.017 | 89 |
| 333.71 | 14.825 | 3 | | 124.882 | |
| 353.55 | 13.002 | 3 | 1,887.75 | 119.950 | 3 |
| 374.58 | 16.653 | 3 | 2,000.00 | | 3 |
| 396.85 | 21.330 | 3 | | | |
| 420.45 | 27.321 | 3 | | | |

[1] Definition is based on the form in proprietary software (see reference b).

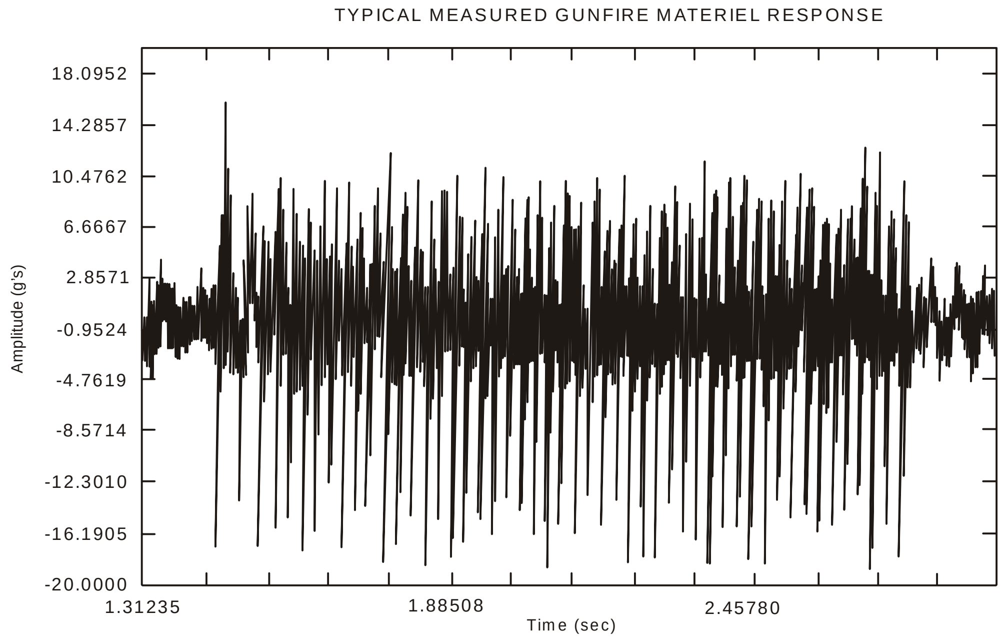



**FIGURE 519.5C-1. Digitized flight data.**

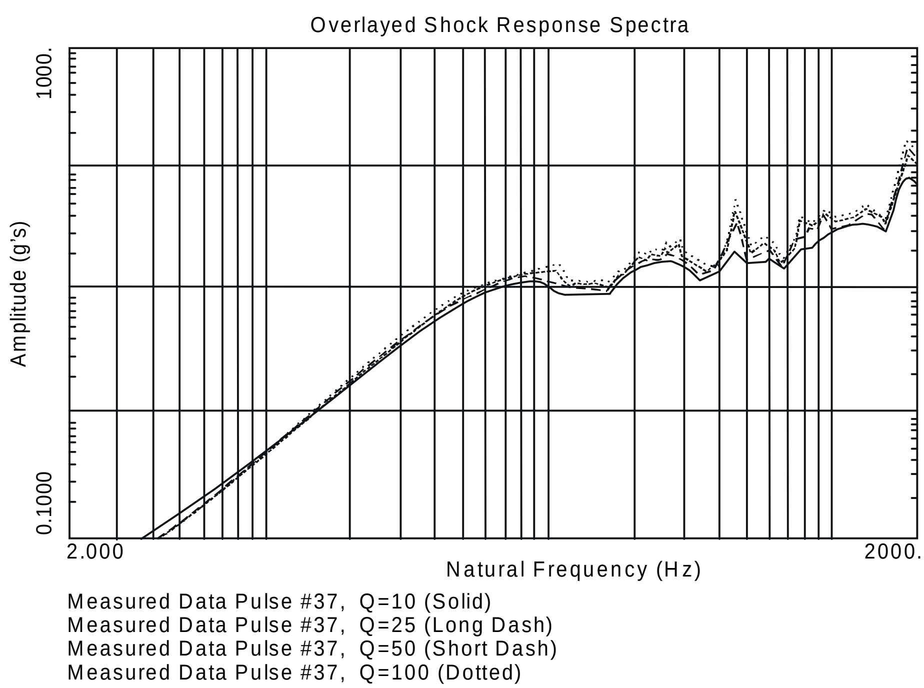



**FIGURE 519.5C-2. Comparison of representative gunfire pulse using a Q of 10, 25, 50 and 100**.

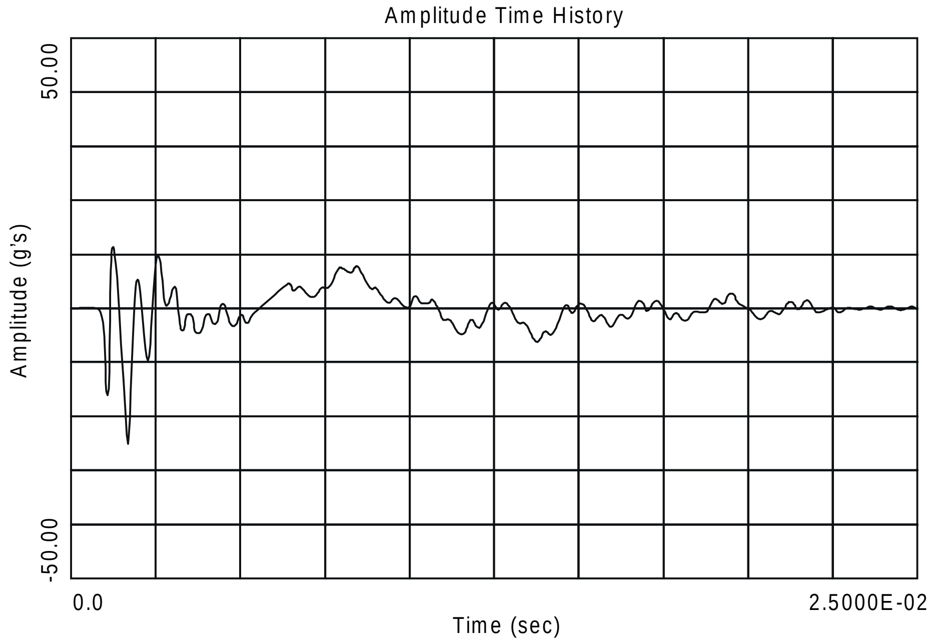



**FIGURE 519.5C-3. SRS gunfire pulse generated using a digital controller.**

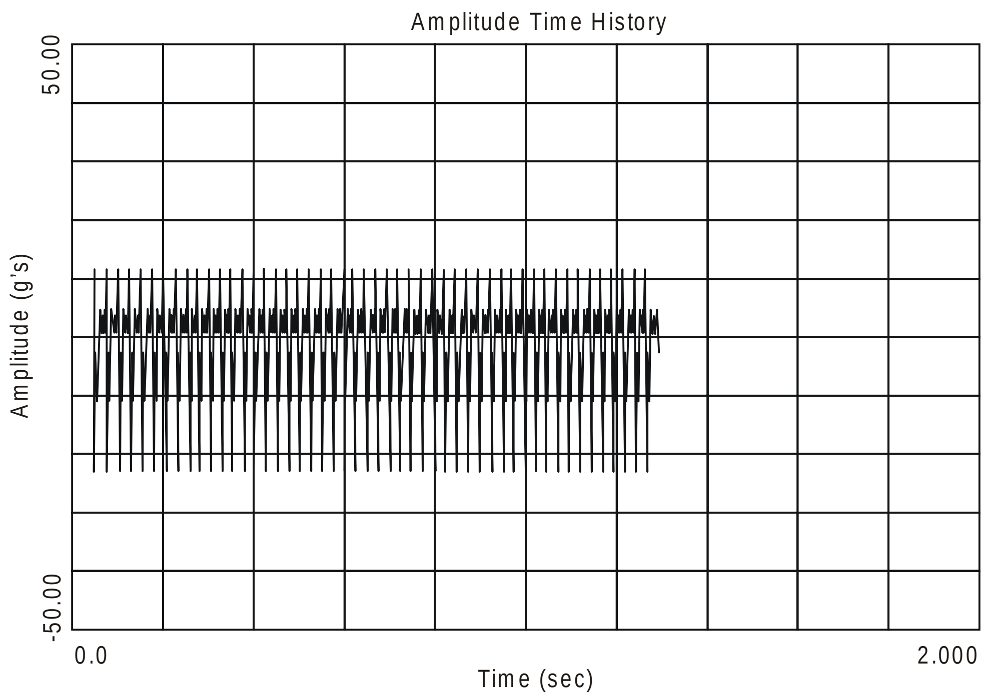



**FIGURE 519.5C-4. SRS pulse gunfire simulation-analytical pulse concatenation.**

# ANNEX D

# HIGH LEVEL RANDOM VIBRATION/SINE-ON-RANDOM VIBRATION/ NARROWBAND RANDOM-ON-RANDOM VIBRATION

## 1. SCOPE.

### 1.1 Purpose.

This Annex provides the option of utilizing predicted gunfire vibration data (when measured data is not available), to ensure that materiel mounted in an aircraft with onboard guns can withstand the vibration levels caused by (1) pulse overpressures emitting from the muzzle of the gun impinging upon materiel support structure, and (2) structure-borne vibration. (This Annex constitutes a reformatting of method 519.4, Gunfire Vibration, Aircraft, in MIL-STD-810E with a limited number of enhancements.) This Annex also provides the option for using high level random vibration (measured data are available) when the measured data spectrum displays no outstanding discrete harmonic components.

### 1.2 Application.

This Annex is applicable only for aircraft gunfire and materiel mounted in an aircraft with onboard guns. Guidance in this Annex is to be used only if in-service measured materiel response data is not available or will not be available in the early stages of a development program. This Annex is not intended to justify the use of sine-on-random or narrowband random-on-random for cases in which measured data displays a broadband spectra along with components at discrete frequencies. Use the information in this Annex only if it is vital to the design of the materiel. If there is a possibility of obtaining early measurements of the materiel response mounted on the in-service platform, supplant the severity's developed using the information in this Annex with the severity's estimated from the materiel response under in-service measurements and one of the other procedures used for testing. In particular, if the measured materiel response in-service environment has the character of high level broadband random vibration with no characteristics conducive to application of Procedure II or Procedure III, then

a. apply Procedure I in the form of transient vibration, or

b. submit the materiel to a specified level of high level broadband random vibration (based on ASD estimates of the measured in-service materiel response) over a period of time consistent with low cycle fatigue assumptions in accelerated testing or as specified in the test plan (see method 514.5).

## 2. DEVELOPMENT.

### 2.1 Introduction.

This Annex is essentially a reorganized reproduction of the information contained in reference a. of paragraph 2.5. with some additional guidance. Mention of the pulse method in paragraph I-4.4.1 of reference a. has not been included, but is covered in reference b. that provides insight into the use of the pulse method in conjunction with a predictive rationale. Procedure IV differs from the other three procedures in that it is a result of a prediction procedure developed on the basis of an analysis of a comparatively small set of measured gunfire materiel response data. The predicted spectrum therefore provides estimates of materiel vibration response that may be substantially different from in-service measured vibration response of a particular materiel. For a particular materiel and gun/materiel configuration, materiel response to gunfire is generally not amenable to accurate prediction. The prediction methodology provided below is generally subject to a large degree of uncertainty with respect to test level. This uncertainty is very apparent in gunfire configurations where the gun is less than a meter from the materiel.

**2.2 Predicting Gunfire Vibration Spectra.**

Gunfire vibration prediction spectra consist of a broadband spectrum representative of an ASD estimate from stationary random vibration along with four harmonically related sine waves. Figure 519.5D-1 provides a generalized vibration spectrum for gunfire-induced vibration that defines the predicted response of materiel to a gunfire environment. It is characterized by four single frequency harmonically related (sine) vibration peaks superimposed on a broadband random vibration spectrum. The vibration peaks are at frequencies that correspond to the nominal gunfire rate and the first three harmonics of the gunfiring rate. The specific values for each of the parameters shown on figure 519.5D-1 can be determined from table 519.5D-I, table 519.5D-II, table 519.5D-III, and figures 519.5-2 through 8. The suggested generalized parametric equation for the three levels of broadband random vibration, $T_j$, defining the spectrum on figure 519.5D-1 is given in dB for $g^2$/Hz (reference to 1 $g^2$/Hz) as

$$10\log_{10}(T_j) = 10\log_{10}(N F_1 E) + H + M + W + J + B_j - 53\text{ dB} \qquad j=1,2,3 \qquad \text{(D-1)}$$

where the parameters are defined in table 519.5D-I. The suggested generalized parametric equation for the four levels of single frequency (sine) vibration defining the spectrum on figure 519.5D-1 is given in dB for $g^2$/Hz (reference to 1 $g^2$/Hz) as

$$10\log_{10}(P_i) = 10\log_{10}(T_3) + K_i + 17\text{ dB} \qquad i=1,2,3,4 \qquad \text{(D-2)}$$

where the parameters are defined in table 519.5D-I.

The key geometrical relations used to determine the predicted vibration spectra are the following four geometrical factors :

a. Vector distance (D). The vector distance from the muzzle of the gun to the mean distance between materiel support points as shown on figure 519.5D-2. For configurations involving multiple guns, the origin of vector D is determined from the centroidal point of the gun muzzle, as shown on figure 519.5D-3. Figure 519.5D-7 and figure 519.5D-8 provide for spectra reduction factors related to D for the random spectra and the discrete frequency spectra, respectively.

b. Gun standoff distance (h). The distance normal to the aircraft's surface as shown on figure 519.5D-4.

c. Depth parameter ($R_s$). The distance normal to the aircraft's skin to the materiel location inside the aircraft. If $R_s$ is unknown, use $R_s$ = 7.6 cm (see figure 519.5D-2). Figure 519.5D-6 provides spectra reduction factors related to $R_s$.

d. Gun caliber (c). Table 519.5D-III defines the gun caliber parameter, c, in millimeters and inches.

For this procedure, base the vibration peak bandwidths consistent with windowed Fourier processing on in-service measured materiel response data if available. When such in-service data are not available, the vibration peak bandwidths can be calculated as:

$$BW_{3dB} = (\pi F^{1/2})/4 \qquad \text{(D-3)}$$

for

$BW_{3dB}$ = the bandwidth at a level 3dB (factor of 2) below the peak ASD level

F = the fundamental frequency or one of the harmonics $F_1$, $F_2$, $F_3$, or $F_4$

For cases where the gunfiring rate changes during a development program or the gun may be fired at a sweep rate, it is desirable to either (1) perform sinusoidal sweeps within the proposed bandwidth for the fundamental and each harmonic or (2) apply narrowband random vibration levels provided the sweep frequency bandwidth is not too large. This technique may over-predict those frequencies where the attachment structure or materiel responses become significantly nonlinear. Likewise, for those cases in which the attachment structure or materiel resonances coincide with the frequencies in the gunfire environment, the materiel vibration response could be under-predicted. The practitioner should clearly understand the options available and inherent limitations in the vibration control system software.

**2.3 Duration of Test.**

Use a duration for the gunfire vibration test in each of the three axes, equivalent to the expected total time the materiel will experience the environment in in-service use. This duration may be conservatively estimated by multiplying the expected number of aircraft sorties in which gunfiring will occur by the maximum amount of time that gunfiring can occur in each sortie. The number of sorties in which gunfire will occur will be associated with planned aircraft training and combat utilization rates, but will generally be in the vicinity of 200 to 300 sorties. The maximum time of gunfire per sortie can be determined from table 519.5D-II by dividing total rounds per aircraft by the firing rate. When a gun has more than one firing rate, perform the test using both firing rates, with test time at each firing rate based on the expected proportion of time at each firing rate for in-service use. The guns carried by an aircraft are generally fired in short bursts that last a few seconds. Testing to a gunfire environment should reflect a form of in-service use in compliance with the test plan. For example, vibration could be applied for two seconds followed by an eight-second rest period during which no vibration is applied. This two-second-on/eight-second-off cycle is repeated until the total vibration time equals that determined for the aircraft type and its in-service use. This cycling will prevent the occurrence of unrealistic failure modes due to vibration isolator overheating or buildup of materiel response in continuous vibration. Intermittent vibration can be achieved by several means including (1) the interruption of the exciter input signal, and (2) a waveform replication strategy for transient vibration discussed in Annex A.

**2.4 Spectrum Generation Techniques.**

Gunfire materiel response vibration is characterized by broadband random vibration with four vibration peaks that occur at the first three harmonics and the fundamental frequency of the firing rate of the onboard guns. Virtually all modern vibration control system software packages contain a provision for performing a gunfire vibration test based on this form of predicted sine-on-random spectra. The details of these software packages are in general proprietary, but the practitioner is expected to have a clear understanding of the capabilities and limitations of the software. On occasion it has been noted that the dynamic range required to produce and control a specified gunfire spectrum is beyond the ability of some available vibration controllers. A way of solving this problem is to enter into the vibration controller the desired broadband random spectrum with its strong vibration peaks. At those frequencies that have the intense vibration peaks, sine waves may be electronically added to the input of the vibration exciter amplifier. Ensure the amplitude of these sine waves is such that the vibration levels produced at those frequencies is slightly less than the desired spectrum level. The vibration controller can make the final adjustment to achieve the needed test level. It is important to note that $P_i$ is in terms of $g^2$/Hz and not g's, (care must be exercised in specifying the amplitude of the sine waves in g's or equivalently input voltage corresponding to a g level). This means of environment replication allows the gunfire vibration test to be done closed loop with commonly available laboratory test equipment and control system software.

**2.5 Reference/Related Documents.**

a. MIL-STD-810E Method 519.4, 14 July 1989.

b. Merritt, R. G., "A Note on Prediction of Gunfire Environment Using the Pulse Method", IEST, 40th ATM, Ontario, CA, May 1999.

**3. RECOMMENDED PROCEDURES.**

**3.1 Recommended Procedure.**

For aircraft vibration for materiel mounted in the aircraft with no available measured data, use this procedure with the prediction methodology. For cases in which available measured data demonstrate only broadband high level vibration with no "discrete" components, use this procedure.

**3.2 Uncertainty Factors.**

This procedure includes substantial uncertainty in general levels because of the sensitivity of the gunfire environment to gun parameters and geometrical configuration. It may be appropriate to increase levels or durations in order to add a degree of conservativeness to the testing. Change in levels, durations, or both for the sake of increasing test conservativeness must be backed up with rationale and supporting assessment documentation. Since extreme spectra prediction levels do not necessarily provide test inputs that correlate with measured data (for the same geometrical configuration), the uncertainty in damage potential is increased substantially as the predicted spectra increase in level, i.e., testing with this procedure may be quite unconservative.

**TABLE 519.5D-I. Suggested generalized parametric equations for gunfire-induced vibration.**

$$10 \log_{10} ( T_j ) = 10 \log_{10} (NF_1E) + H + M + W + J + B_j - 53 \text{ dB}$$

$$10 \log_{10} (P_i ) = 10 \log_{10} ( T_3 )+ K_i + 17 \text{ dB}$$

for

| | |
|---|---|
| N | Maximum number of closely spaced guns firing together. For guns that are dispersed on the host aircraft, such as in wing roots and in gun pods, separate vibration gunfire test spectra are determined for each gun location. The vibration levels, for test purposes, are selected for the gun that produces the maximum vibration levels. |
| E | Blast energy of gun (see table 519.5D-III). |
| H | Effect of gun standoff distance, h (see figure 519.5D-4). |
| M | Effect of gun location M = 0 unless a plane normal to the axis of the gun barrel and located at the muzzle of the gun does not intersect the aircraft structure, then M = -6 dB. |
| W | Effect of weight of the equipment to be tested (use figure 519.5D-5). If the weight of the materiel is unknown, use W = 4.5 kilograms (10 lbs). |
| J | Effect of the materiel's location relative to air vehicle's skin (use figures 519.5D-2 and 519.5D-6). |
| $B_j$ | Effect of vector distance from the gun muzzle to the materiel location (see figure 519.5D-7). |
| $F_1$ | Gunfiring rate where $F_1$ = fundamental frequency from table 519.5D-II ($F_2 = 2F_1$, $F_3 = 3F_1$, $F_4 = 4F_1$) |
| $T_j$ | Test level in $g^2$/Hz |
| $P_i$ | Test level for frequency $F_i$ in $g^2$/hz (where i = 1 to 4) |
| $K_i$ | Effect of vector distance on each vibration peak, $P_i$ (see figure 519.5D-8). |

Note: These equations are in metric units. The resultant dB values are relative to 1 $g^2$/Hz.

**TABLE 519.5D-II. Typical gun configurations associated with aircraft classes.**

| Aircraft/Pod | Gun (Quantity) | Location | Firing Rate | | Capacity |
|---|---|---|---|---|---|
| | | | Rnds/Min | Rnds/Sec | |
| A-4 | MK12 (2) | Wing roots | 1000 | 16.6 | 100/Gun |
| A-7D | M61A1 (1) | Nose, left side | 4000 & 6000 | 66.6 & 100 | 1020 |
| A-10 | GAU-8/A (1) | Nose | 2100 & 4200 | 35 & 70 | 1175 |
| A-37 | GAU-2B/A (1) | Nose | 6000 | 100 | 1500 |
| F-4 | M61A1 (1) | Nose | 4000 & 6000 | 66.6 & 100 | 638 |
| F-5E | M39 (2) | Nose | 3000 | 50 | 300/Gun |
| F-5F | M39 (1) | Nose | 3000 | 50 | 140 |
| F-14 | M61A1 (1) | Left side of nose | 4000 & 6000 | 66.6 & 100 | 676 |
| F-15 | M61A1 (1) | Right wing root | 4000 & 6000 | 66.6 & 100 | 940 |
| F-16 | M61A1 (1) | Left wing root | 6000 | 100 | 510 |
| F-18 | M61A1 (1) | Top center of nose | 4000 & 6000 | 66.6 & 100 | 570 |
| F-111 | M61A1 (1) | Underside of fuselage | 5000 | 83.3 | 2084 |
| GEPOD 30 | GE430 (1) (GAU-8/A) | POD | 2400 | 40 | 350 |
| SUU-11/A | GAU-2B/A (1) | POD | 3000 & 6000 | 50 & 100 | 1500 |
| SUU-12/A | AN-M3 (1) | POD | 1200 | 19 | 750 |
| SUU-16/A | M61A1 (1) | POD | 6000 | 100 | 1200 |
| SUU-23/A | GAU-4/A (1) | POD | 6000 | 100 | 1200 |

**TABLE 519.5D-III. Gun specifications.**

| Gun | Gun Caliber, c | | Blast Energy, E |
|---|---|---|---|
| | mm | in | (J)* |
| GAU-2B/A | 7.62 | .30 | 6,700 |
| GAU-4/A | 20 | .79 | 74,600 |
| GAU-8/A | 30 | 1.18 | 307,500 |
| AN-M3 | 12.7 | .50 | 26,000 |
| M3 | 20 | .79 | 83,000 |
| M24 | 20 | .79 | 80,500 |
| M39 | 20 | .79 | 74,600 |
| M61A1 | 20 | .79 | 74,600 |
| MK11 | 20 | .79 | 86,500 |
| MK12 | 20 | .79 | 86,500 |

* joules (J) x 0.7376 = foot-pounds

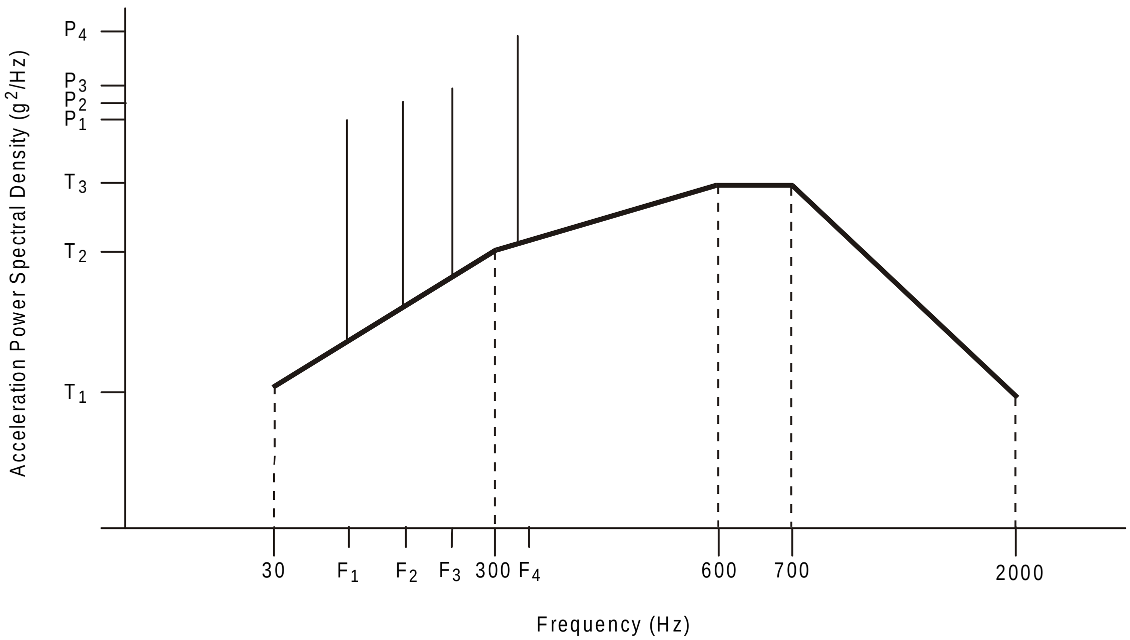



**FIGURE 519.5D-1. Generalized gunfire induced vibration spectrum shape.**

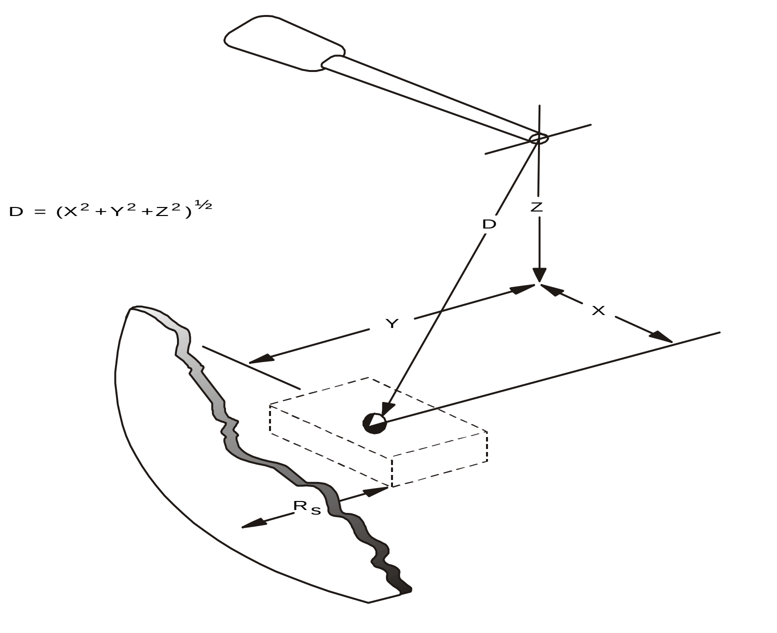



**FIGURE 519.5D-2. The distance parameter (D) and the depth parameter ($R_s$)**

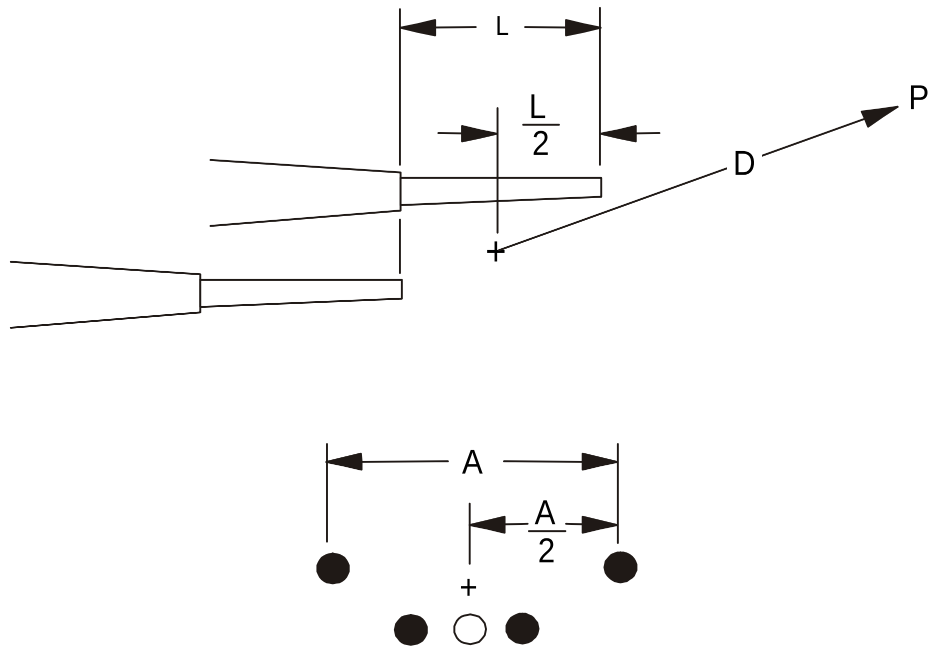



**FIGURE 519.5D-3. Multiple guns, closely grouped.**

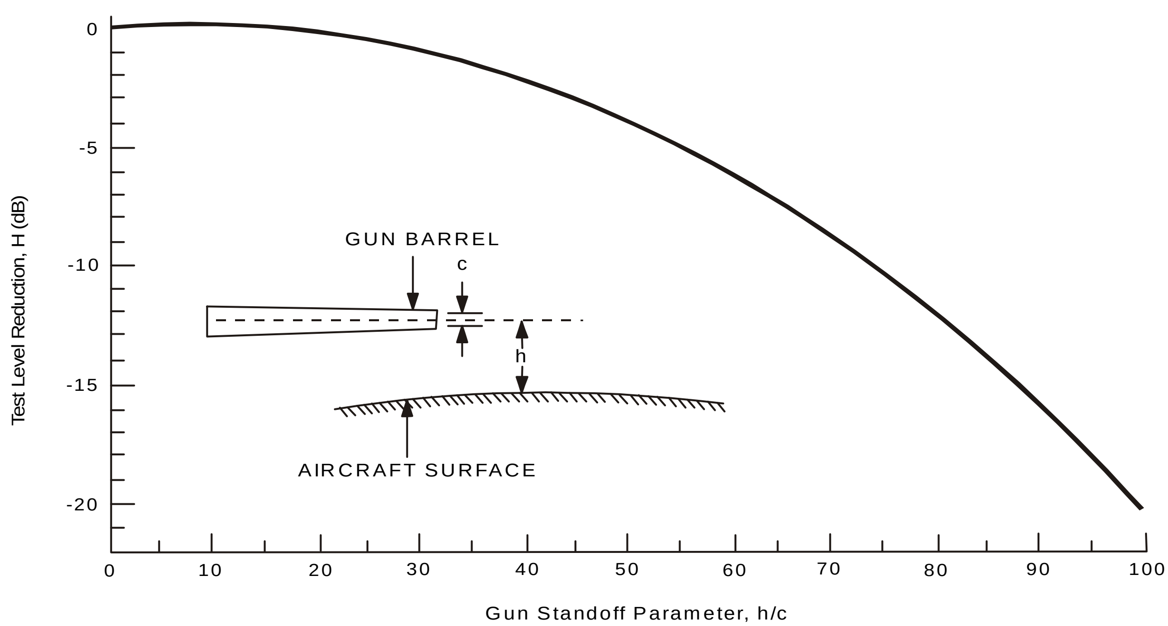



**FIGURE 519.5D-4. Test level reduction due to gun standoff parameter.**

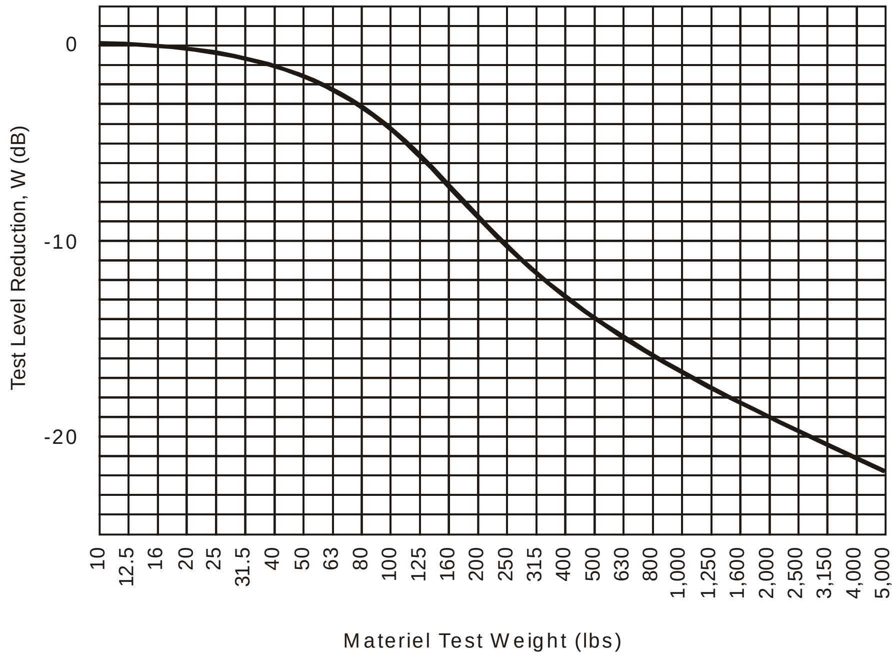



**FIGURE 519.5D-5. Test level reduction due to materiel mass loading.**

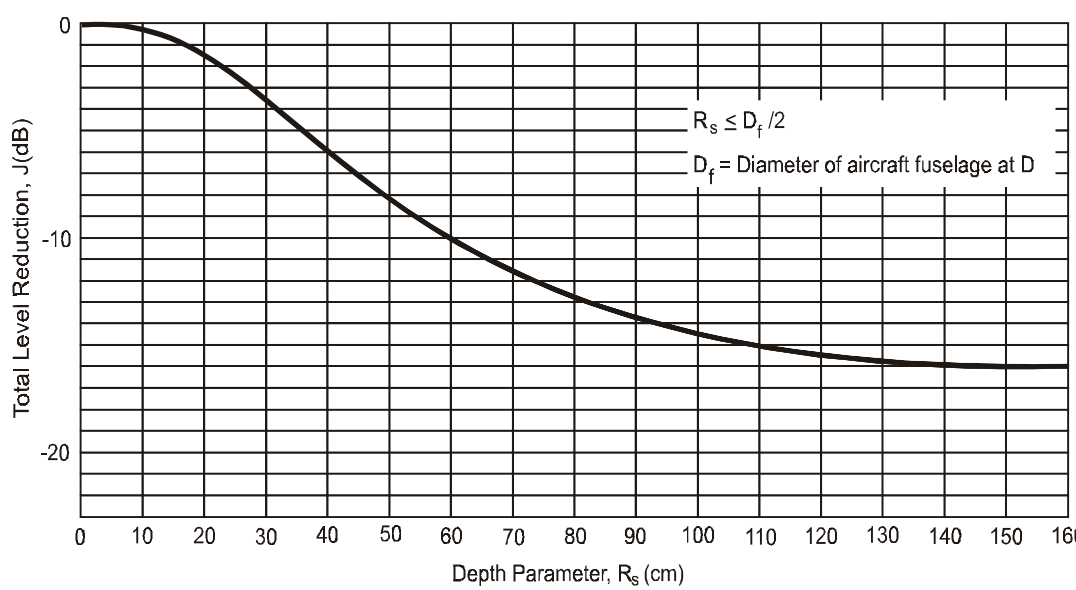



**FIGURE 519.5D-6. Test level reduction due to depth parameter.**

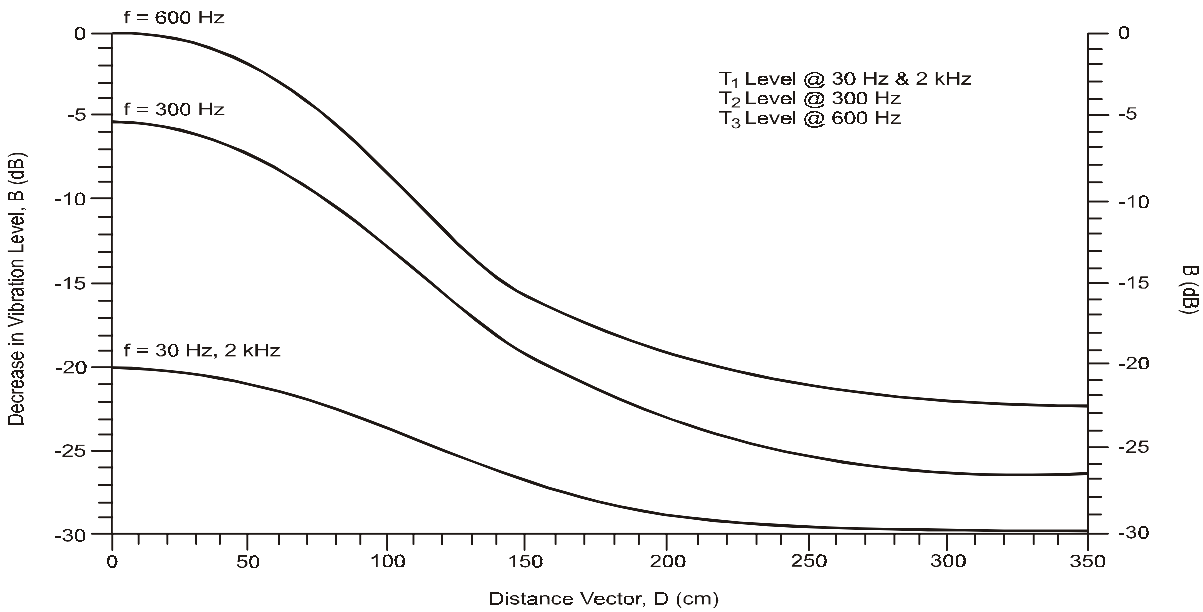



**FIGURE 519.5D-7. Decrease in vibration level with vector distance from gun muzzle.**

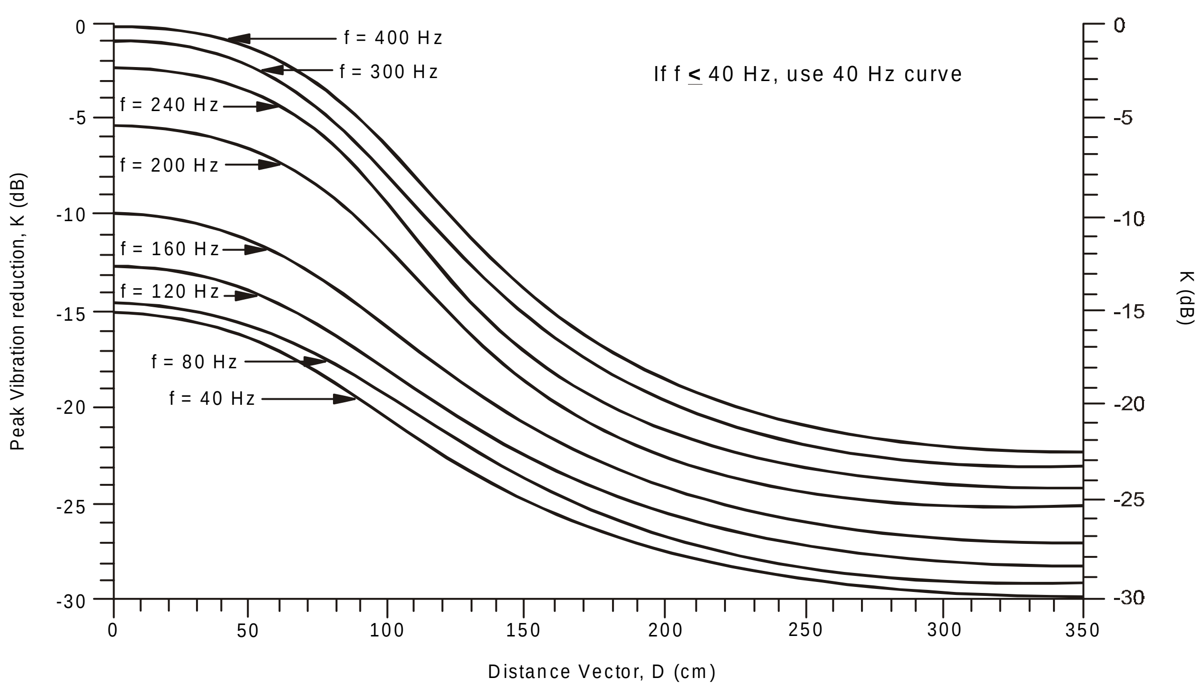



**FIGURE 519.5D-8. Gunfire peak vibration reduction with distance.**