Use of Composite Vibration Spectra in MIL-STD-331 Fuze Qualification Programs

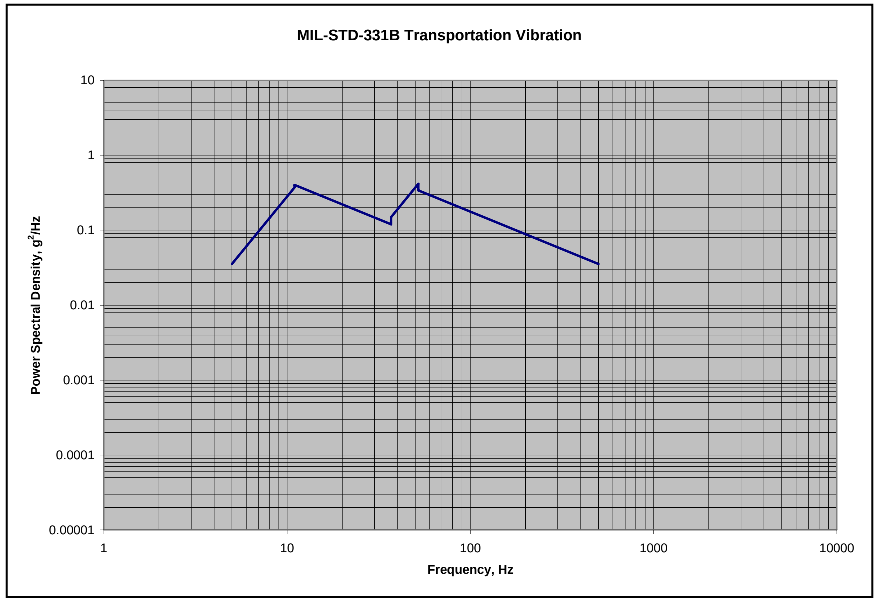
Julie S. Jennings
Lockheed Martin
Missiles and Fire Control - Dallas

Overview

- The release of Department of Defense Test Method Standard for Environmental and Performance Tests for Fuze and Fuze Components, MIL-STD-331C, in January 2005 introduced a more comprehensive approach to transportation vibration than earlier versions. The transportation vibration compliance criteria are now based on modes of transportation anticipated throughout the fuze life cycle. Although tailoring of the compliance criteria to the specific fuze requirements is essential, the effect of this change is dramatic as related to the required test times. For a typical qualification sample size of thirty fuzes, the typical transportation vibration test time increases from 10,800 minutes of required vibration as defined by MIL-STD-331B to 65,970 minutes as defined by MIL-STD-331C. An approach was developed by Lockheed Martin and approved by the Army Fuze Safety Review Board to allow combining many of the various spectra of MIL-STD-331C into a reduced number of exposures to reduce laboratory residence time without compromising the intent of the qualification program. The approach uses Miner's Rule and a custom MATLAB based compositing tool to produce a set of equivalent damage potential composite transportation vibration test spectra that are economic to perform while still ensuring compliance of the fuze with the requirements of MIL-STD-331C.

MIL-STD-331B (December 1989)

- Transportation Vibration Requirement
  - Commonly used transport vehicles from manufacturer to user
  - Induced vibration was a sinusoidal wave controlled by sweeping the frequency and varying the amplitude of the acceleration

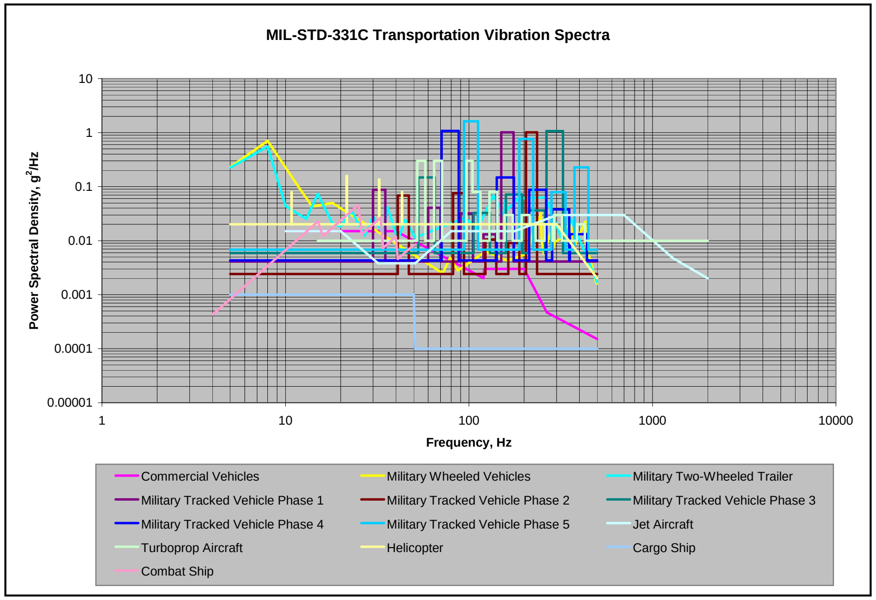


MIL-STD-331B Transportation Vibration, Test B1

Frequency (Hz)	Displacement and Acceleration Levels
5 – 11	10 mm (0.39 in) displacement, peak-to-peak
11 – 37	2.5 g acceleration, peak
37 – 52	0.9 mm (0.04 in) displacement, peak-to-peak
52 – 500	5.0 g acceleration, peak

MIL-STD-331C (January 2005)

- Transportation Vibration Requirements
  - Encompass the actual fuze modes of transportation from manufacturer to the user
  - Transportation scenario should be tailored and approved for each specific fuzing mechanism
  - Typical transportation scenario consists of seven transportation modes:
    - Commercial Vehicles
      - rail, truck, trailer and semi-trailer over improved roads
    - Military Vehicles
      - truck, semi-trailer, two-wheeled trailer and tracked vehicles over improved and unimproved roads
    - Jet Aircraft
    - Turboprop Aircraft
    - Helicopter
    - Cargo Ship
    - Combat Ship



Cumulative Test Hours

- MIL-STD-331B
  - 10 test articles at +71°C, +23°C and -54°C (30 total)
  - 2 hours vibration/axis
  - 6 hours/test article
  - Total for 30 test articles = 180 hours
- MIL-STD-331C
  - 10 test articles at +71°C, +23°C and -54°C (30 total)
  - 12 hours 13 minutes vibration/axis
  - 36 hours 39 minutes/test article
  - Total for 30 test articles = 1,099.5 hours

Miner’s Rule

- Calculate Equivalent Damage Potential
  - Fatigue relationship to determine vibratory fatigue equivalency between vibration exposures, to sum vibratory fatigue damage of separate vibration exposures, and to define accelerated test levels for vibration endurance tests
- Derive Smaller Set Of Transportation Vibration Test Spectra

$$\left(\frac{W_0}{W_1}\right) = \left(\frac{T_1}{T_0}\right)^{\left(\frac{1}{4}\right)}$$

Where...

W_o = Random vibration level of the original test spectrum $\left(g^2/Hz\right)$

W_1 = Random vibration level of the combined test spectrum $\left(g^2/Hz\right)$

T_o = Test time of the original test spectrum

T_1 = Test time of the combined test spectrum

Exponent = Material constant

Equivalency Techniques

- Express Each Test Spectra in Similar Terms (g^2/Hz):
  - Equivalent Acceleration of Sinusoidal Vibration Expressed as Displacement (g)
  - Equivalent Random Vibration of Sinusoidal Vibration Expressed as Acceleration (PSD_{eqv})
  - Conversion assumes a typical value of 5% critical damping (Q = 10)
  - Real values do not necessarily agree with that assumption, and certainly not at all frequencies

$$g = 0.0511 f^2 D$$

Where...

g = Sinusoidal acceleration (g)

f = Frequency (Hz)

D = Peak to peak displacement (inch)

$$PSD_{eqv} = \frac{0.707 \times g^2}{f}$$

Where...

g = Sinusoidal acceleration (g)

f = Frequency (Hz)

Logarithmic Interpolation

- Determine All-Inclusive Set of Breakpoints for Each Test Spectrum
  - Logarithmic interpolation of power spectral density values

$$P_n = \frac{P_0 f_n^{\left[\frac{\mathrm{Log}\left(\frac{P_1}{P_0}\right)}{\mathrm{Log}\left(\frac{f_1}{f_0}\right)}\right]}}{f_0^{\left[\frac{\mathrm{Log}\left(\frac{P_1}{P_0}\right)}{\mathrm{Log}\left(\frac{f_1}{f_0}\right)}\right]}}$$

Where...

f_0 = Frequency of First Known Breakpoint

P_0 = PSD Level of First Known Breakpoint

f_1 = Frequency of Second Known Breakpoint

P_1 = PSD Level of Second Known Breakpoint

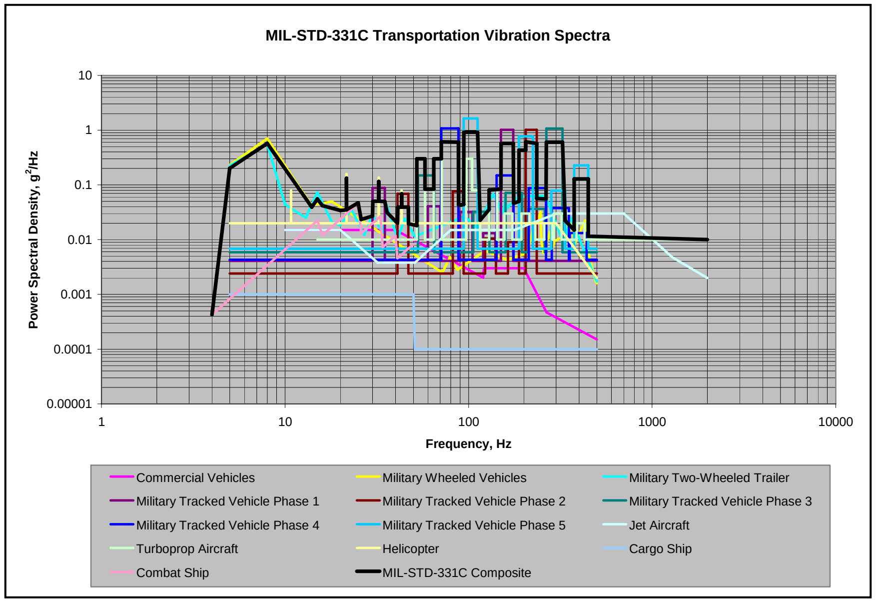
f_n = Frequency of New Breakpoint

P_n = PSD Level of New Breakpoint

New Power Spectral Density

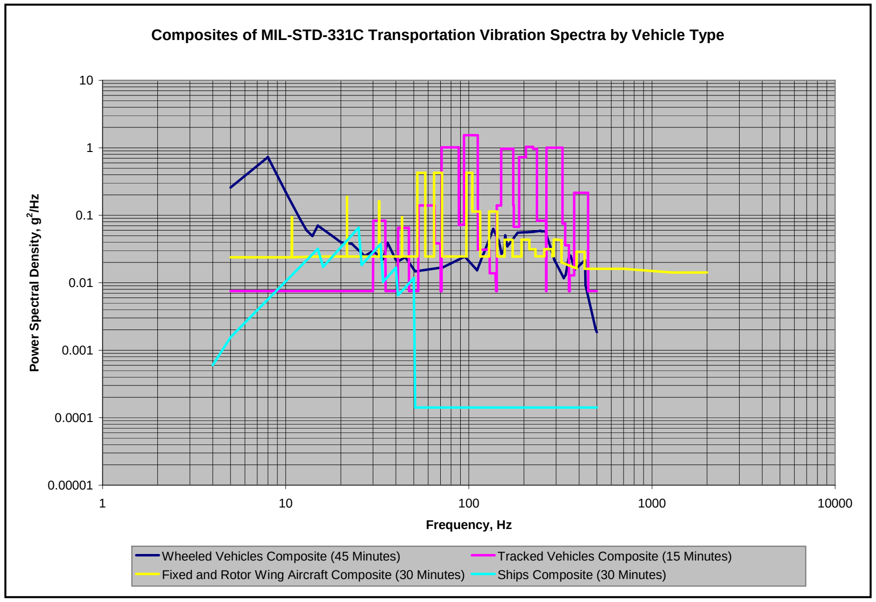
- Determine New PSD Level at Each Frequency of the New Test Spectrum
  - Miners' rule solved to determine the new power spectral density at each frequency
  - Each modified MIL-STD-331C test spectra normalized to a common time at each common frequency
  - Equivalent times for each test spectrum being combined are added and the PSD levels reconverted to a single PSD amplitude at each common frequency for the chosen time
  - Resulting test spectrum has the same damage potential as the sum of the combined vibration spectra
- Single test spectrum derived using the maximum PSD for each spectral line
- Good engineering judgment must be used in determining which spectra to combine

$$W_1 = W_0 \left(\frac{T_0}{T_1} \right)^{\left(\frac{1}{4}\right)}$$



Miner's Rule Limitations

- Generally combine like vehicle types and similar spectral shapes of similar amplitude
  - Wheeled vehicle vibration is typically broadband random excitation with relatively high vibration levels in relatively low frequency ranges due to the natural resonance of the vehicle suspension
  - Tracked vehicle vibration is typically low level broadband random vibration with high level narrowband random vibrations at the resonant frequencies of the tracks at various vehicle speed increments
  - Most fixed wing aircraft vibration tends to exhibit similar broadband random characteristics
  - Rotor wing aircraft vibration tends to have sinusoidal resonances associated with the rotational speed and harmonics of the main rotor and tail rotor
  - Ship vibration consists of random vibration coupled with a periodic component imposed by propeller shaft rotation and hull resonance
- Extreme exaggeration factors can exceed the bounds of Miner's Rule applicability
- General guideline is to limit the exaggeration factor to two on overall RMS and four on PSD



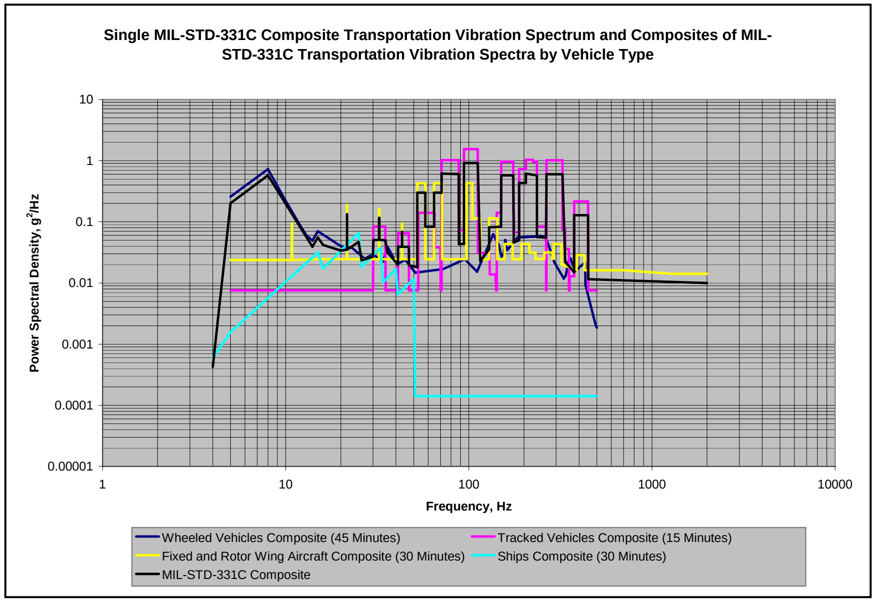
Miner’s Rule Limitations

- Slope of a log/log fatigue or S/N curve
  - Per MIL-STD-810F:
    - Many materials exhibit exponents between 1/6 and 1/6.5
    - 1/4 is widely used for Air Force avionics
    - Missile programs range from 1/3.25 to 1/6.6
    - Space programs sometimes use 1/2
    - Wide variation based on degree of conservatism desired as well as material properties
    - Sophisticated analyses based on fatigue data (S/N curves) for specific materials should be used when practical

$$W_1 = W_0 \left(\frac{T_0}{T_1} \right)^{\left(\frac{1}{4}\right)}$$

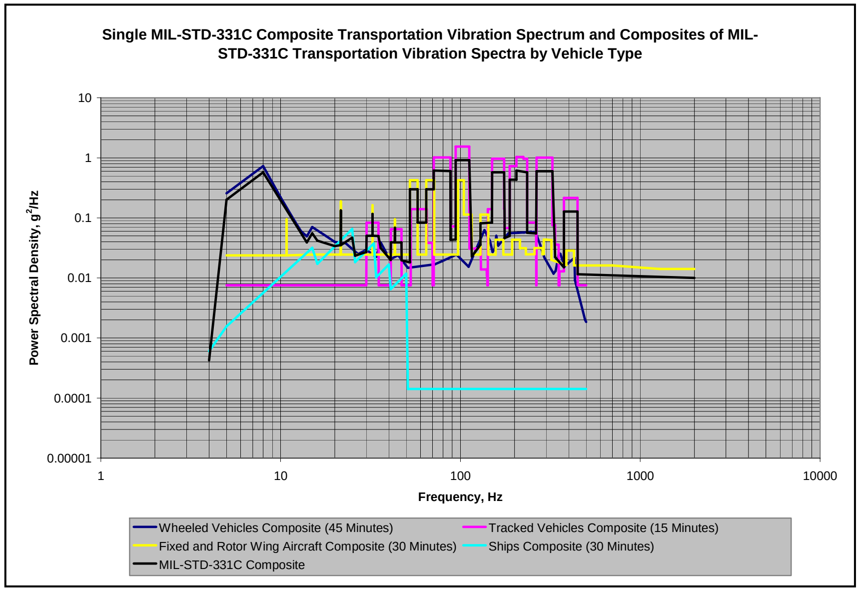
Hardware Limitations

- Special consideration should be given to combining different vibration types of input vibration (i.e. broadband random, sine-on-random or narrowband random-on-random).
  - Sinusoidal resonances may be amplified when superimposed on a high-level broadband random vibration
  - Unrealistic long duration acceleration at a resonant frequency of the fuze may be induced and potentially damage good hardware
  - Be aware of the resonant frequencies of the hardware and try to avoid unrealistic resonances in these areas



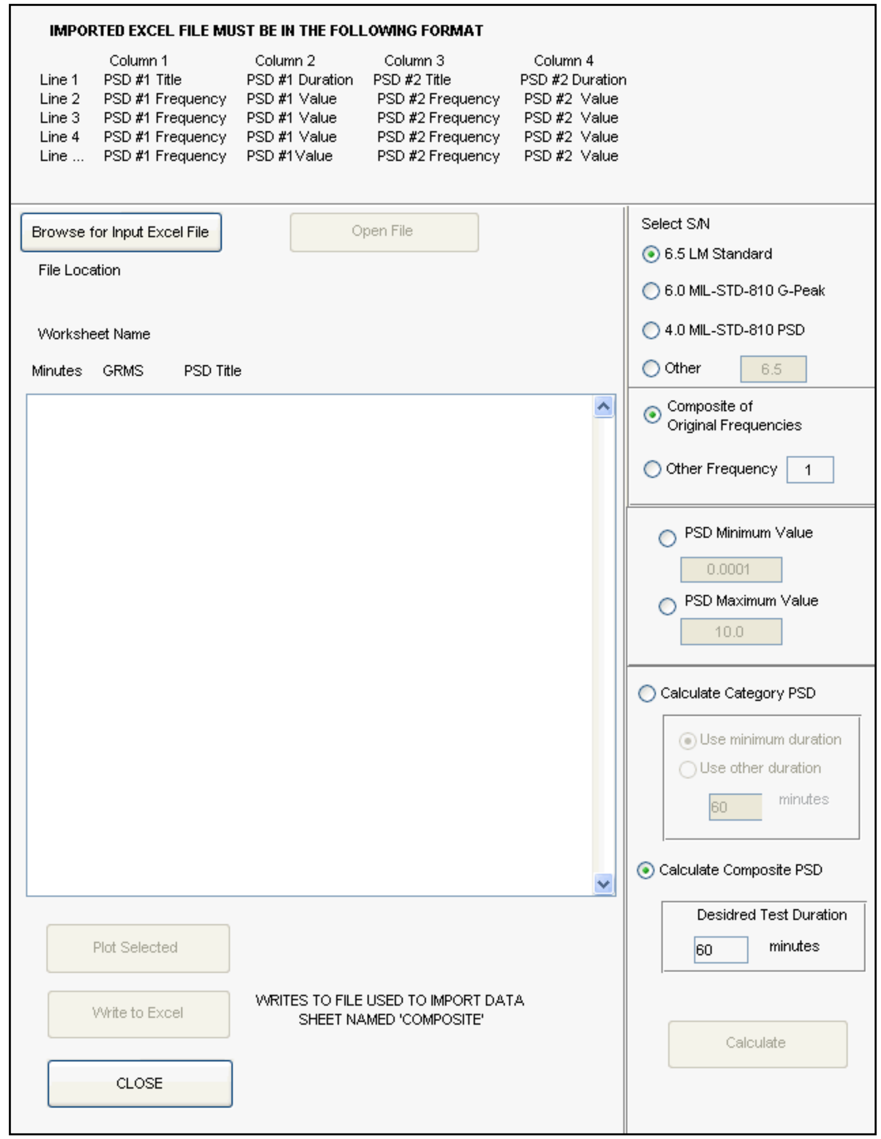
Test Facility Limitations

- Special consideration should be given to the limitations of vibration test equipment
  - Shaker maximum force and stroke capabilities vary widely depending on the size and control scheme of the shaker
  - The composite vibration spectrum for all of the transportation vibration requirements of MIL-STD-331C require an electrodynamic shaker with at least a 40-inch per second velocity capability and a 1.7-inch stroke capability
  - This capability is readily available on an LDS V-9 or LDS V-994 shaker



MATLAB Routine Overview

- As the number of unique test spectra increases, the task of determining a single, all-inclusive set of breakpoints can become quite cumbersome
  - Microsoft Excel logarithmic interpolation capabilities limited
  - MATLAB computational and graphic capabilities automate process
  - MATLAB routine uses Miner's Rule to generate a smaller set of vibration test spectra
  - GUIs make the routine user friendly



Smaller Set of Transportation Vibration Test Spectra

- Smaller set of transportation vibration spectra recommended to test all fuzes to be qualified to the requirements of MIL-STD-331C
  - Special consideration should still be given to tailoring the compliance criteria to the specific fuze life cycle requirements
  - As always, it will be necessary to gain final approval from the procuring agency

Wheeled Vehicles Composite (45 Minutes)		Tracked Vehicles Composite (15 Minutes)		Fixed and Rotor Wing Aircraft Composite (30 Minutes)		Ships Composite (30 Minutes)	
Hz	g^2/Hz	Hz	g^2/Hz	Hz	g^2/Hz	Hz	g^2/Hz
5	0.2568	5	0.0075	5	0.0238	4	0.0006
8	0.7300	30	0.0075	10.8	0.0238	15	0.0317
10	0.2207	30.1	0.0828	10.81	0.0942	16	0.0172
12	0.0879	35	0.0828	10.82	0.0238	25	0.0653
14	0.0491	35.1	0.0075	21.6	0.0245	26	0.0184
15	0.0703	41	0.0075	21.61	0.1884	33	0.0376
20	0.0397	41.1	0.0649	21.62	0.0245	34	0.0103
27	0.0249	47	0.0649	32.4	0.0245	40	0.0167
30	0.0294	47.1	0.0075	32.41	0.1622	41	0.0065
34	0.0223	53	0.0075	32.42	0.0245	50	0.0118
36	0.0391	53.1	0.1400	43.2	0.0245	51	0.0001
41	0.0206	65	0.1402	43.21	0.0942	500	0.0001
45	0.0239	65.1	0.0383	43.22	0.0245	RMS	0.99
51	0.0147	70	0.0383	52.3	0.0245		
95	0.0244	71.1	1.0140	52.31	0.4243		
111	0.0153	88	1.0140	57.8	0.4243		
136	0.0627	88.1	0.0718	57.81	0.0245		
151	0.0269	94	0.0723	64.6	0.0245		
185	0.0554	94.1	1.5404	64.61	0.4243		
266	0.0509	112	1.5404	71.4	0.4243		
338	0.0132	112.1	0.0308	71.41	0.0245		
360	0.0250	130	0.0310	96.9	0.0245		
431	0.0218	130.1	0.0138	96.91	0.4243		
500	0.0019	140	0.0138	104.5	0.4243		
RMS	4.03	150.1	0.9622	104.51	0.1132		
		175	0.9622	115.5	0.1132		
		175.1	0.1419	115.51	0.0245		
		176	0.1419	129.2	0.0245		
		176.1	0.0678	129.21	0.1132		
		188	0.0678	142.8	0.1132		
		188.1	0.7265	142.81	0.0245		
		205	0.7265	156.8	0.0245		
		205.1	1.0323	156.81	0.0434		
		224	1.0323	173.3	0.0434		
		224.1	0.9621	173.31	0.0245		
		235	0.9621	178	0.0245		
		235.1	0.0832	193.8	0.0245		
		264	0.0826	193.81	0.0434		
		264.1	0.0075	214.2	0.0435		
		265	0.0075	214.21	0.0313		
		265.1	1.0077	231	0.0314		
		325	1.0077	231.1	0.0246		
		325.1	0.0754	258.4	0.0247		
		336	0.0754	258.41	0.0314		
		336.1	0.0358	285.6	0.0315		
		352	0.0358	285.61	0.0248		
		352.1	0.0075	290.7	0.0249		
		355	0.0075	290.71	0.0435		
		355.1	0.0128	321.3	0.0428		
		376	0.0128	321.31	0.0200		
		376.1	0.2156	387.6	0.0163		
		448	0.2156	387.61	0.0286		
		448.1	0.0075	428.4	0.0286		
		500	0.0075	428.41	0.0161		
		RMS	14.05	2000	0.0141		
				RMS	6.71		

Single Transportation Vibration Test Spectrum

- A single transportation vibration spectrum could be used to test all fuzes to be qualified to the requirements of MIL-STD-331C
  - Special consideration should still be given to tailoring the compliance criteria to the specific fuze requirements
  - It is not recommended that the single test spectrum be used without appropriate engineering discretion
- Single test spectrum exceeds most of the limitations of Miner's Rule and possibly falls on the edge of the hardware and test facility capabilities
- This option should only be pursued for fuzes that are exceptionally impervious to vibratory fatigue

MIL-STD-331C Composite Transportation Vibration Spectrum			
Hz	g^2/Hz	Hz	g^2/Hz
4	0.0004	64.61	0.3005
5	0.2010	71	0.3000
8	0.5712	71.1	0.6120
14	0.0392	88	0.6030
15	0.0555	88.1	0.0432
16	0.0417	94	0.0437
20	0.0340	94.1	0.9159
21.6	0.0351	112	0.9160
21.61	0.1334	115.51	0.0227
21.62	0.0351	129.2	0.0356
25	0.0470	129.21	0.0808
26	0.0233	150	0.0834
30	0.0270	150.1	0.5721
30.1	0.0503	175	0.5721
32.4	0.0505	176	0.0851
32.41	0.1157	176.1	0.0460
32.42	0.0505	188	0.0501
35	0.0498	188.1	0.4320
36	0.0314	205	0.4320
41	0.0200	205.1	0.6138
41.1	0.0392	235	0.5721
43.2	0.0392	235.1	0.0564
43.21	0.0685	264	0.0553
43.22	0.0392	265.1	0.5992
47	0.0392	325	0.5992
47.1	0.0196	336.1	0.0222
52.3	0.0181	376	0.0150
52.31	0.3000	376.1	0.1282
57.8	0.3004	448	0.1282
57.81	0.0833	448.1	0.0115
64.6	0.0834	2000	0.0100
		RMS	11.88

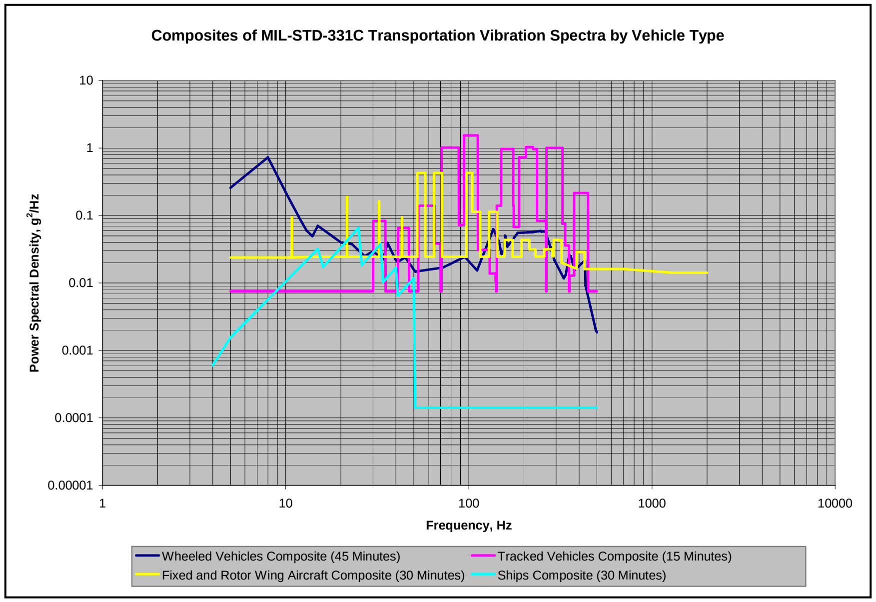
Overall Laboratory Residence Time

- MIL-STD-331C Transportation Vibration Test B1.1 Requirements
  - 10 test articles at +71°C, +23°C and -54°C (30 total)
  - 12 hours 13 minutes vibration/axis
  - 36 hours 39 minutes/test article
  - Total for 30 test articles = 1,099.5 hours
  - More than 6 months of laboratory residence time (assuming a 40-hour work week)
- Using the Miner's Rule to generate a small set of transportation vibration test spectra
  - 10 test articles at +71°C, +23°C and -54°C (30 total)
  - 2 hours vibration/axis (total)
  - 6 hours/test article
  - Total for 30 test articles = 180 hours
  - Five weeks of laboratory residence time (assuming a 40-hour work week)
- Overall test time can be reduced even further by designing a test fixture capable of testing multiple fuzes simultaneously

Conclusion

- MIL-STD-331C Fuze Compliance
  - MIL-STD-331C introduced a more comprehensive approach to transportation vibration based on modes of transportation anticipated throughout the fuze life cycle with a dramatic effect related to the required test times
  - By combining the transportation vibration spectra of MIL-STD-331C into a small set of test spectra having an equivalent damage potential, the laboratory residence time can be reduced while still ensuring compliance of the fuze with the requirements of MIL-STD-331C

Questions and Discussion



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