UNCERTAINTY MARGINS IN AEROSPACE VIBROACOUSTIC LEVELS
Revision H

By Tom Irvine
Email: tom@irvinemail.org

November 27, 2018

Introduction

Launch vehicles and spacecraft must be designed and tested to withstand the vibroacoustic levels which they will be subjected to during flight.

Maximum expected environment (MEE) levels[1] must be derived. This derivation is an imprecise empirical, or semi-empirical, process which requires engineering judgment. Derivations are made using a variety of reference data and analytical methods.

The reference data may include:

1. Wind tunnel test data
2. Static fire test data
3. Modal test data
4. Shaker table transmissibility tests
5. Acoustic reverberant chamber tests
6. Flight accelerometer data

The analytical methods include:

1. Finite element method
2. Boundary element method
3. Statistical energy analysis

The measured data can be used to calibrate analytical models. The data can also be scaled or extrapolated to new vehicles.

Uncertainty Sources

The derivation of the MEE level must account for the following uncertainty factors. Margin must be added accordingly.

1. Flight-to-Flight
2. Spatial
3. Model Uncertainty

---

[1] These levels are sometimes referred to as maximum predicted environment (MPE) levels.

The flight-to-flight uncertainty factor may account for many possible variables. Here is one example. Consider a rocket vehicle which is launch on a relatively calm day. Flight accelerometer data is recorded on this vehicle.

Sometime later, the same type of vehicle is launched but encounters three-sigma wind gusts during its ascent. The second vehicle has higher vibration levels over certain frequency bands as a result.

Note that only a small number of locations can be monitored with sensors during a ground test or flight. A location between a given pair of accelerometers may have a higher level than either of them at certain frequencies depending on the location of nodal lines, anti-nodal points, and mode shapes. The spatial uncertainty factor is intended to account for this difference.

Modeling requires assumptions about mass, damping, stiffness, boundary conditions, number of degrees-of-freedom, linearity, etc. The model uncertainty factor is intended to account for these factors.

There is another potential uncertainty factor when one-third octave band data in converted to narrowband. This factor is sometimes embedded in other factors, as shown briefly in the next section.

Uncertainty Margins

Uncertainty margins are essentially estimates based on engineering judgment and experience. There is ongoing debate in the aerospace community regarding margin values.

This section gives some sample guidelines.

Table 1. Flight-to-Flight Variation

Reference	Margin	Notes
NASA-HDBK-7005, Equation 6.16	3 dB	Lognormal distribution
MIL-STD-1540C, 3.3.2 & MIL-HDBK-340A, 3.3.2	3 dB	Lognormal distribution
Isam Yunis	3 dB	Lognormal distribution

The 3 dB factor is reasonably conservative for the case of the Space Shuttle ignition acoustic data as shown in Appendix E.

Table 2. Spatial Variation		
Reference	Margin	Notes
NASA-HDBK-7005, Equation 6.14	6 dB	Upper bound on the standard deviation. Includes the correction from one-third octave to narrowband.

Model uncertainty factor guidelines are not readily apparent in the references used in this tutorial.

Overall Uncertainty

The following approach assumes a sound pressure level or a power spectral density.

The uncertainty factors are assumed to be independent. Thus, they should not be added together.

Rather the corresponding standard deviations should be combined in an RSS manner.

$$\sigma_{\text{total}} = \sqrt{\sigma^2_{\text{spatial}} + \sigma^2_{\text{flight}} + \sigma^2_{\text{model}}} \tag{1}$$

Equation (1) is calculated for dB factors using the follow Matlab code snippet:

```
%  R(i) represents the dB factors

C=20;

sum=0;

for i=1:m
  scale=10^(R(i)/C);
  sum=sum+(scale-1)^2;
end


oadb=C*log10(1+sqrt(sum));
%
out1=sprintf('\n overall margin = %8.4g dB \n',oadb);
disp(out1);
```

Here are examples of equation (1).

$$3\ \text{dB} + 3\ \text{dB} = 4.0\ \text{dB} \tag{2}$$

$$3\ \text{dB} + 6\ \text{dB} = 6.4\ \text{dB} \tag{3}$$

$$3\ \text{dB} + 3\ \text{dB} + 3\ \text{dB} = 4.7\ \text{dB} \tag{4}$$

$$3\ \text{dB} + 3\ \text{dB} + 6\ \text{dB} = 6.7\ \text{dB} \tag{5}$$

<u>MIL-STD-1540C</u>

MIL-STD-1540C addresses flight-to-flight variation only.

MIL-STD-1540C, paragraph 3.3.2 states the maximum expected environment should meet the P95/50 rule. This is the level not exceeded on 95% of flights with 50% confidence. If only one flight data point is available, that data is assumed to represent the mean and the P95/50 margin is 5 dB.

Note that this requirement is also given in MIL-HDBK-340A, 3.3.2.

The P95/50 rule can be applied using the following formula. The limit is

$$\text{Limit} = \bar{x} + k\,s \tag{6}$$

where

$\bar{x}$ is the sample mean

k is the tolerance factor

s is the sample standard deviation

Note that both the limit and the tolerance factor are taken as one-sided for the purpose of deriving maximum expected levels.

The standard deviation can be taken as 3 dB above the mean if the database is small.

The tolerance factor depends on the number of samples as shown in Appendix A.

NASA-STD-7001A, Payload Vibroacoustic Test Criteria

NASA-STD-7001A, section 1.4, specifies the P95/50 criteria for the payload vibroacoustic maximum expected flight level (MEFL).

The test levels are given in the following table taken from NASA-STD-7001A.

1.4 Summary of Verification Test Requirements

Maximum Expected Flight Level (MEFL)	95%/50% Probability Level
Test levels	
Qualification/protoflight	MEFL +3 dB
Flight acceptance	MEFL
Minimum component vibration workmanship test	6.8 grms
Minimum acoustic workmanship test	138 dB
Test durations	
Qualification, single mission	2 minutes
Qualification, multiple (N) reflights	2 + 0.5N minutes
Protoflight	1 minute
Flight acceptance	1 minute
Payload classification applicability	Classes A, B, and C

NASA, MSFC-STD-3676

The major requirements in this standard are:

- Random vibration, acoustic and shock qualification test criteria shall be based on the P97.5/50 statistical basis. No margin is required above the maximum predicted environment.
- Acceptance testing shall be conducted 6 dB below the qualification test levels.
- Qualification test duration shall encompass flight environments as well as the fatigue induced by multiple acceptance tests.

Lognormal Distribution

Vibroacoustic levels are often assumed to follow a lognormal distribution per Reference 7.

In this case, the levels should be transformed by the following equation prior to taking the sample mean and standard deviation.

$$y = \log_{10} x \tag{7}$$

where x is the spectral value of a specific frequency of the response within a zone.

The transformed variable y is assumed to have a normal distribution.

The tolerance equation is then

$$\text{Limit} = \bar{y} + k\, s_y \tag{8}$$

Further Information

The mathematical formulas used to derive the tolerance factors are given in Reference 8.

References

1. NASA-HDBK-7005, Handbook for Dynamic Environmental Criteria, 2001.
2. MIL-STD-1540C, Military Standards: Test Requirements for Launch, Upper-Stage, and Space Vehicles, 1994.
3. MIL-HDBK-340A, Military Handbook: Test Requirements for Launch, Upper-Stage, and Space Vehicles, 1999.
4. Isam Yunis, The Standard Deviation of Launch Vehicle Environments, Spacecraft and Launch Vehicle Workshop, 2005.
5. T. Irvine, P95/50 Rule – Theory and Application, Vibrationdata, 1996.
6. H. Himelblau, et al, “Development of Cassini Acoustic Criteria using Titan IV Flight Data,” IES ATM, May 1992.

7. Cyril Harris, editor; Shock and Vibration Handbook, 4th edition, McGraw-Hill, New York, 1995. See Chapter 20, Test Criteria and Specifications, Allan G. Piersol.

8. T. Irvine, Normal Tolerance Factors for Upper Tolerance Limits, Vibrationdata, 2010.

9. Isam Yunis and Damian Ludwiczak, On the Use of 3 dB Qualification Margin for Structural Parts on ELV, Spacecraft and Launch Vehicle Workshop, 2005.

10. NASA-STD-7001A, Payload Vibroacoustic Test Criteria, 2011.

11. MSFC-STD-3676A, Development of Vibroacoustic and Shock Design and Test Criteria, Marshall Space Flight Center, Alabama 2013.

APPENDIX A

Tolerance Factors

The one-sided tolerance factors are taken from Reference 6.

Number	Tolerance P95/50	Tolerance P97.5/50
2	2.339	2.820
3	1.939	2.321
4	1.830	2.186
5	1.779	2.124
6	1.750	2.089
7	1.732	2.066
8	1.719	2.050
9	1.709	2.038
10	1.702	2.029
11	1.696	2.022
12	1.691	2.016
13	1.687	2.011
14	1.684	2.007
15	1.681	2.004

Number	Tolerance P95/50	Tolerance P97.5/50
16	1.678	2.001
17	1.676	1.998
18	1.674	1.996
19	1.673	1.994
20	1.671	1.992
21	1.670	1.990
22	1.669	1.989
23	1.668	1.988
24	1.667	1.986
25	1.666	1.985
30	1.662	1.981
35	1.659	1.978
40	1.658	1.975
45	1.656	1.974
∞	1.64485	1.961

APPENDIX B

Excerpt from MIL-HDBK-340A, Vol. I.

3.3.2 Statistical Estimates of Vibration, Acoustic, and Shock Environments.

Qualification and acceptance tests for vibration, acoustic, and shock environments are based upon statistically expected spectral levels. The level of the extreme expected environment, used for qualification testing, is that not exceeded on at least 99% of flights, estimated with 90% confidence (P99/90 level). The level of the maximum expected environment, used for acceptance testing, is that not exceeded on at least 95% of flights, estimated with 50% confidence (P95/50 level).

These statistical estimates are made assuming a lognormal flight-to-flight variability having a standard deviation of 3 dB, unless a different assumption can be justified. As a result, the P95/50 level estimate is 5 dB above the estimated mean (namely, the average of the logarithmic values of the spectral levels of data from all available flights).

When data from N flights are used for the estimate, the P99/90 estimate in dB is

$$2.0 + 3.9 / \sqrt{N}$$

above the P95/50 estimate.

When data from only one flight are available, those data are assumed to represent the mean and so the P95/50 is 5 dB higher and the P99/90 level is 11 dB higher.

When ground testing produces the realistic flight environment (for example, engine operation or activation of explosive ordnance), the statistical distribution can be determined using the test data, providing data from a sufficient number of tests are available. The P99/90 and P95/50 levels are then determined from the derived distribution.

Note that:

P95/50 means that there is a 50% chance of 1 exceedance in 20 flights.

P99/90 means that there is a 10% chance of 1 exceedance in 100 flights.

See also NASA-HDBK-7005.

APPENDIX C

Qualification Level, Excerpts from Reference 9

- The standard qualification approach for ELV random vibration qualification is MPE+6 dB for 4x life duration
    - Consistent with MIL-STD-1540 (no applicable NASA standard)
    - "Life" is flight + acceptance testing
- This can be a severe environment for fatigue sensitive structures
- Structure and black boxes are different
    - Black boxes have unknown failure modes and have margin by virtue of test
    - Structure has known failure modes and can have margin by analysis against these modes
- Using standard development of MPE, structure may be qualified by MPE+3 dB for 1x life
    - Black boxes have unknown failure modes and have margin by virtue of test
    - Standard development = max (1 second average) for duration of event
- "Structure" in this study includes: ducts, bellows, tubing, nonfunctional structure, etc.
- "Structure" does not include primary or secondary structure designed by transient peak loads or quasi-static loads

APPENDIX D

Space Shuttle, Main Engine Ignition Acoustics, Flight-to-Flight Variation

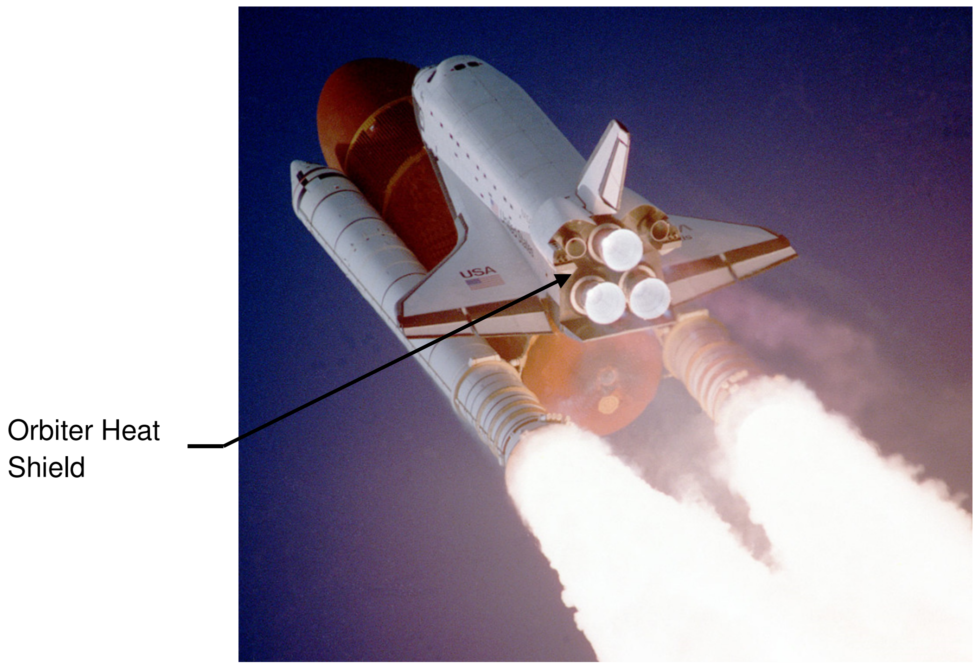

Figure D-1.

Main engine ignition acoustic results from the Orbiter Heat Shield for 16 flights are given in Figure D-1.

The standard deviation values range from 1.26 to 2.48 dB. Thus, an assumption of 3 dB flight-to-flight variation is conservative for this case.

The mean and the standard deviation of the dB levels can be taken due to the assumption of a lognormal distribution.

Table D-1. Space Shuttle Orbiter Heat Shield Main Engine Ignition Acoustics Levels

N	STS#	Sound Pressure Levels (dB) per One-Third Octave Bands, Ref 20 micro Pa										
		20 Hz	25 Hz	31.5 Hz	40 Hz	50 Hz	63 Hz	80 Hz	100 Hz	125 Hz	160 Hz	200 Hz
1	75	149.7	148.1	149.7	151.9	153.3	151.5	160.0	160.8	167.0	165.3	157.4
2	78	146.8	147.1	151.9	152.6	153.5	153.2	157.7	158.0	167.1	165.7	155.8
3	80	147.8	147.7	149.7	152.0	155.1	152.4	158.7	160.6	167.4	168.6	157.9
4	83	148.6	147.4	153.5	152.1	150.0	149.3	157.4	160.2	169.6	165.0	156.9
5	90	146.7	148.4	149.1	152.5	151.8	151.7	161.0	162.5	167.7	165.9	155.9
6	93	145.0	148.0	152.1	153.6	151.2	150.0	158.2	159.2	162.6	163.0	155.8
7	107	149.8	149.7	148.3	154.0	152.7	154.0	159.7	161.8	165.2	163.2	157.2
8	116	152.1	150.3	149.2	148.9	152.9	150.1	154.0	160.7	166.7	164.6	156.1
9	119	151.0	151.1	156.0	155.2	152.8	152.5	160.8	164.3	168.4	165.0	157.0
10	121	153.7	153.5	152.9	151.5	149.1	153.1	157.2	160.8	164.7	164.8	163.3
11	124	148.4	149.2	153.8	150.3	152.2	152.5	156.5	159.4	165.5	165.6	159.8
12	109	145.1	148.2	150.5	152.2	152.2	156.0	163.6	164.0	167.6	165.0	158.4
13	94	147.2	146.0	149.6	152.1	149.2	148.7	156.2	157.7	166.2	164.3	156.5
14	128	149.0	147.7	150.2	152.2	151.4	152.4	158.3	157.2	161.9	163.9	158.8
15	130	151.6	149.6	155.2	153.5	153.1	154.5	157.6	160.3	167.3	165.1	158.8
16	131	147.2	147.4	152.3	153.2	153.9	153.5	161.1	162.1	168.6	164.8	157.9
	Mean	***148.7***	***148.7***	***151.5***	***152.4***	***152.2***	***152.2***	***158.6***	***160.6***	***166.5***	***165.0***	***157.7***
	STDEV	***2.48***	***1.82***	***2.32***	***1.46***	***1.66***	***1.96***	***2.34***	***2.05***	***2.08***	***1.26***	***1.91***