Shock Severity Limits for Electronic Components
Revision D

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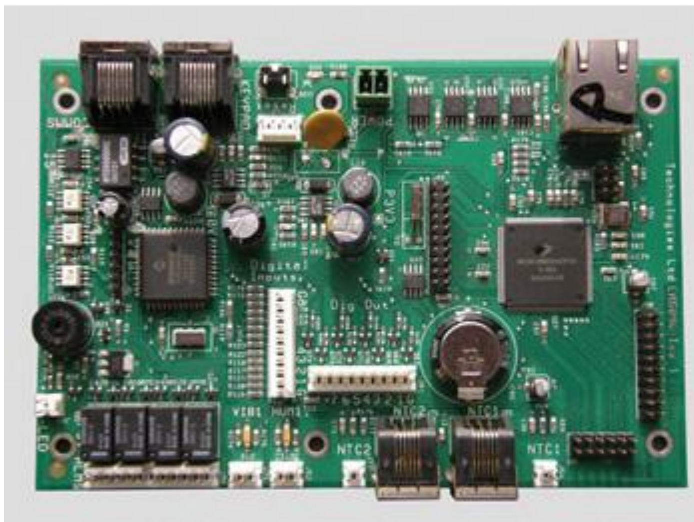

Figure 1. Sample Avionics Circuit Board

Introduction

Shock and vibration environments produce dynamic stresses which can cause material failure in structures. The potential failure modes include fatigue, yielding, and ultimate stress limit.

F.V. Hunt wrote a seminal paper on this subject, titled "Stress and Stress Limits on the Attainable Velocity in Mechanical Vibration," published in 1960 in Reference 1. This paper gave the relationship between stress and velocity for a number of sample structures.

H. Gaberson continued research on stress and modal velocity with a series of paper, presentations, and test results, as shown in References 2 through 6.

A shock severity limit has arisen for aerospace and military equipment from the work of Hunt, Gaberson, Morse, et al, based on pseudo velocity. This empirical limit is typically defined at 100 ips, or sometimes as 50 ips with a 6 dB safety margin. These limits have been used to determine whether component qualification shock testing is necessary for a given shock response spectrum (SRS) specification.[1]

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[1] SRS specifications are typically given in terms of acceleration. The specifications can be converted to equivalent pseudo velocity. If the peak pseudo velocity is less than, say, 50 ips, then a test may be deemed unnecessary.

The 100 ips limit appears to have been derived from two sources. The first was Gaberson's shock test of six squirrel cage fans or blowers. The second was a analytical calculation based on the yield stress limit of mild steel.

This paper accepts yield stress-derived pseudo velocity limits for mechanical structures, such as beams, plates, shells, or assemblies thereof.

But it asserts that a relative displacement shock severity limit should be used for the case of an avionics box with microelectronics-populated circuit boards, based on Steinberg, Reference 7. The equivalent pseudo velocity limit can be calculated from the relative displacement limit and the natural frequency.

A yield stress-derived pseudo velocity limit can still be used for the box housing material and any support bracket.

<u>Gaberson's Blower Shock Test</u>

Gaberson subjected six blowers to varying shock tests, as shown in Reference 6. Five failed, and one survived.

Figure 3. Sample Blower

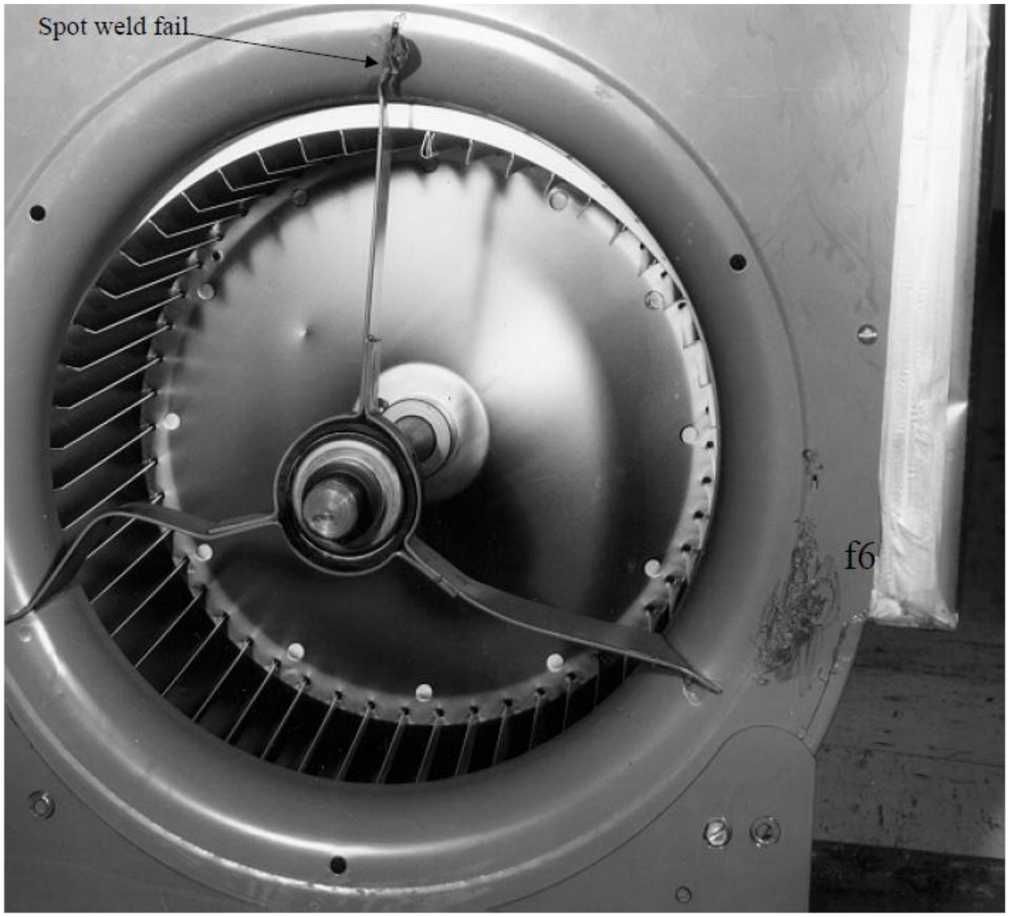


Figure 4. Blower Failure with Bent Spider Members

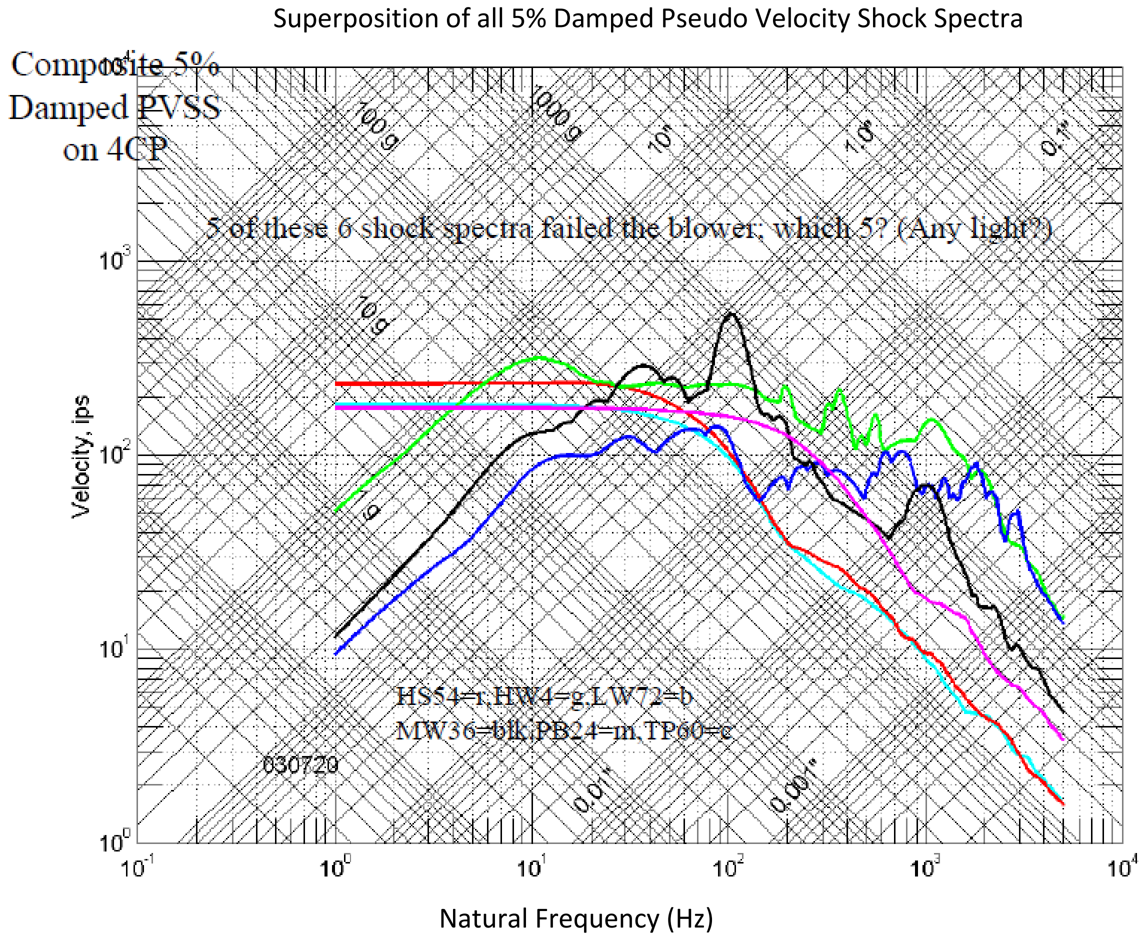


Figure 5.

Gaberson concluded that the damped pseudo-velocity spectrum was the best method for assessing shock severity. He favored this format because stress is theoretically directly proportional to velocity, among other reasons, as shown in References 1-6, & 11.

The blue curve represents unit LW72, the only blower to survive shock testing. Gaberson thus identified 150 ips as the failure threshold for this blower model.

MIL-STD-810E

An empirical rule-of-thumb in MIL-STD-810E states that a shock response spectrum is considered severe only if one of its components exceeds the level

$$\text{Threshold} = [\ 0.8\ (\text{G/Hz}) * \text{Natural Frequency (Hz)}\ ] \tag{1}$$

For example, the severity threshold at 100 Hz would be 80 G.

This rule is effectively a velocity criterion.

MIL-STD-810E states that it is based on unpublished observations that military-quality equipment does not tend to exhibit shock failures below a shock response spectrum velocity of 100 inches/sec (254 cm/sec).

Equation (1) actually corresponds to 50 inches/sec. It thus has a built-in 6 dB margin of conservatism.

Note that this rule was not included in MIL-STD-810F or G, however.

SMC-TR-06-11

This reference states:

> A response velocity to the shock less than 50 inches/second is judged to be non-damaging. This is the case if the shock response spectrum value in G is less than 0.8 times the frequency in Hz.

Morse Chart

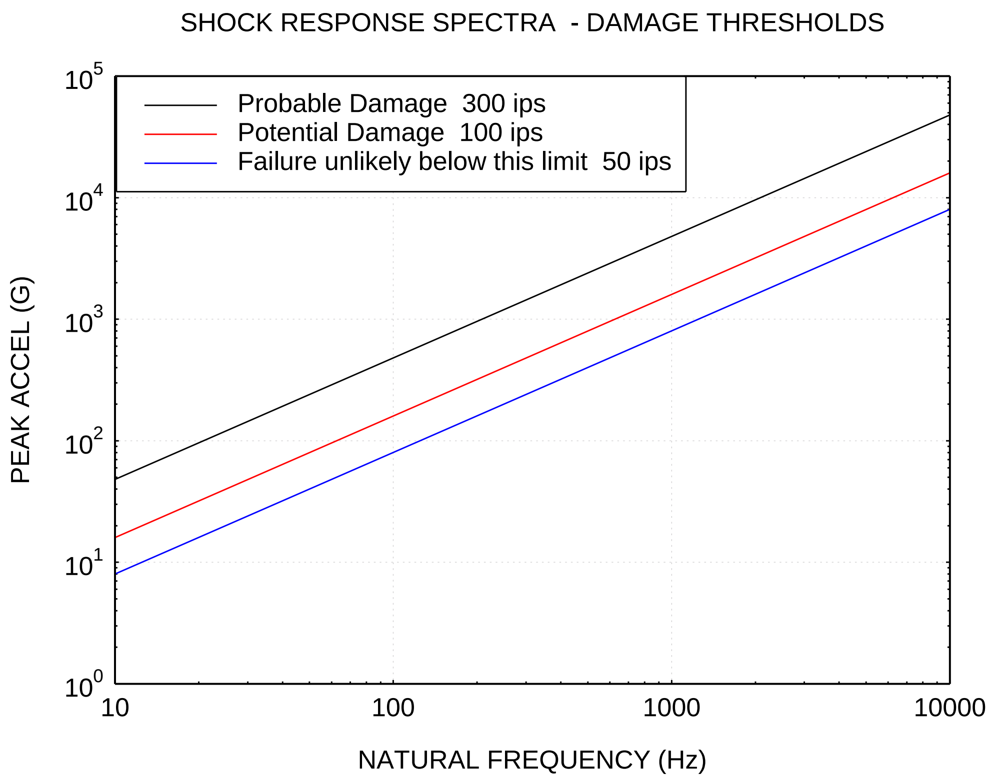


Figure 2.

The curves in Figure 2 are taken from Reference 9. The curves are defined by the following formulas.

Threshold	Formula
300 ips	[4.8 (G/Hz) * Natural Frequency (Hz)]
100 ips	[1.6 (G/Hz) * Natural Frequency (Hz)]
50 ips	[0.8 (G/Hz) * Natural Frequency (Hz)]

The 100 ips threshold is defined in part by the observation that the severe velocities which cause yield point stresses in mild steel beams turn out to be about 130 ips, per Reference 5. It is also less than Gaberson's 150 ips limit for blowers.

Calculation of the Velocity Limit for Mild Steel

The following equation is taken from Reference 11.

The maximum velocity v_{max} for a given beam undergoing bending vibration is calculated as

$$v_{max} = \frac{\sigma_{yield}}{k \rho c} \quad (2)$$

where

σ_{yield}	=	Material yield stress
ρ	=	Mass per volume
c	=	Wave speed in the material
k	=	Constant

Values for the k constant for typical beam cross-sections are:

Cross-section	k
Solid Circular	2
Rectangular	$\sqrt{3}$

Consider a mild steel beam with the following material properties:

σ_{yield}	=	33,000 lbf/in^2
ρ	=	0.283 lbm/in^3
	=	0.00073308 lbf sec^2/in^4
E	=	29e+06 lbf^/in^2
c	=	1.99e+05 ips

Note that E is the elastic modulus.

Note that stress is directly proportional velocity in equation (2). No frequency term is present in this equation, but a resonant response is effectively assumed.

The wave speed is calculated as

$$c = \sqrt{E/\rho} \tag{3}$$

The velocity limit for the mild steel beam with rectangular cross-section is thus

$$v_{max} = \frac{33{,}000\ \text{lbf/in\^{}2}}{\sqrt{3}\ (0.00073308\ \text{lbf sec\^{}2/in\^{}4})(1.99e+05\ \text{in/sec})} = 130\ \text{in/sec} \tag{4}$$

The velocity limit for mild steel plate requires a complicated equation but is given as 113 ips in Appendix A. Note that the velocity limits for aluminum, copper, magnesium and titanium are higher than that of mild steel, as shown in Appendix A.

Now round the velocity limit for mild steel in either beam or plate form down to 100 ips. This calculation appears to validate the severity threshold of 100 ips for at least simple structures composed of typical metals. Again, a safety margin of 6 dB can be applied to reduce the threshold to 50 ips.

Steinberg's Relative Displacement Limit

The following is taken from Reference 7.

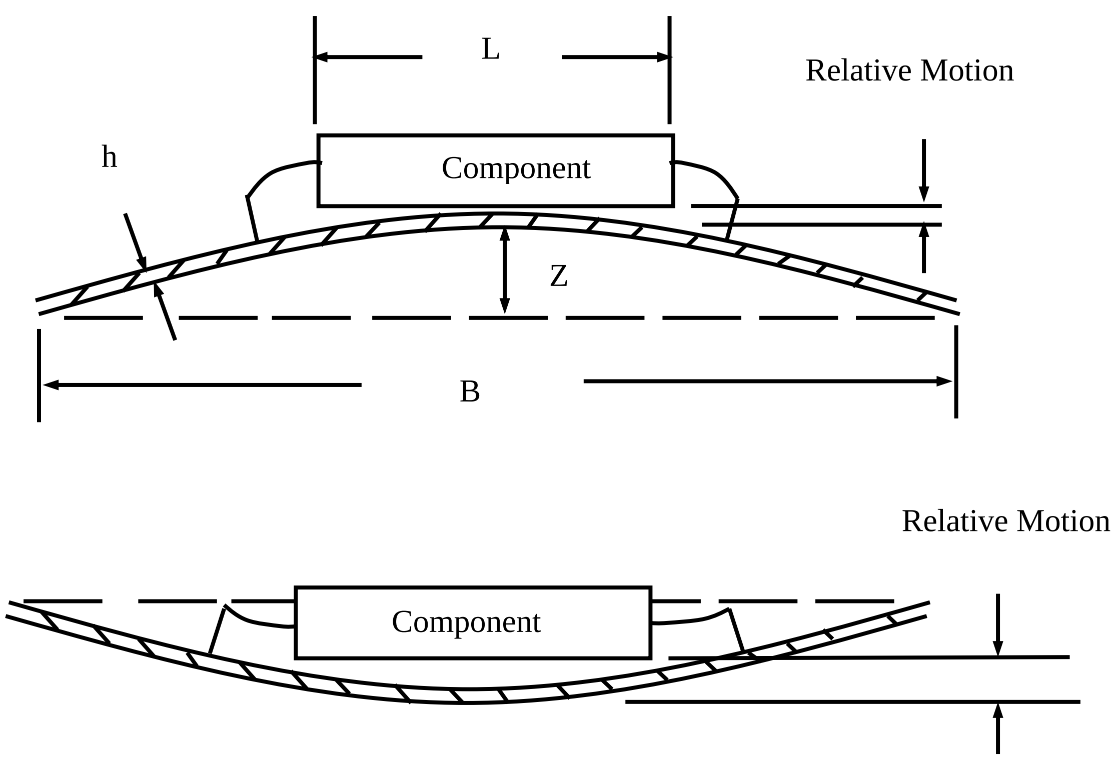


Figure 3. Circuit Board Bending Deflection

Let Z be the single-amplitude displacement at the center of the board that will give a fatigue life of about 20 million stress reversals in a random vibration environment, based upon the 3σ circuit board relative displacement.

Steinberg's empirical formula for $Z_{3\sigma \text{ limit}}$ is

$$Z_{3\sigma \text{ limit}} = \frac{0.00022\, B}{C\, h\, r\, \sqrt{L}} \quad \text{inches, for 20 million cycles} \tag{5}$$

where

B = length of the circuit board edge parallel to the component, inches

L = length of the electronic component, inches

H = circuit board thickness, inches

R = relative position factor for the component mounted on the board (Table 1)

C = Constant for different types of electronic components (Table 2) $0.75 \le C \le 2.25$

Table 1. Relative Position Factors for Component on Circuit Board	
r	Component Location (Board supported on all sides)
1	When component is at center of PCB (half point X and Y).
0.707	When component is at half point X and quarter point Y.
0.50	When component is at quarter point X and quarter point Y.

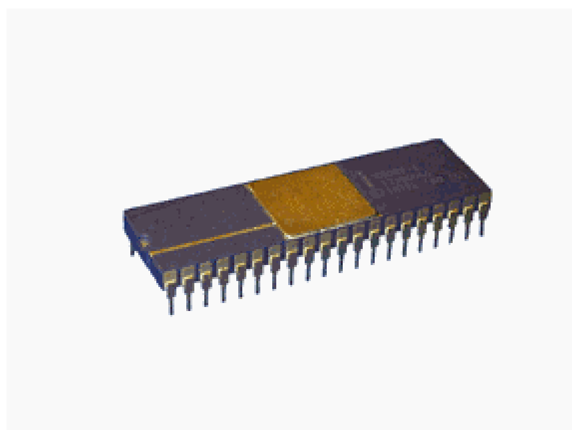
Table 2. Constant for Different Types of Electronic Components		
C	Component	Image
0.75	Axial leaded through hole or surface mounted components, resistors, capacitors, diodes	
1.0	Standard dual inline package (DIP)	
1.26	DIP with side-brazed lead wires	

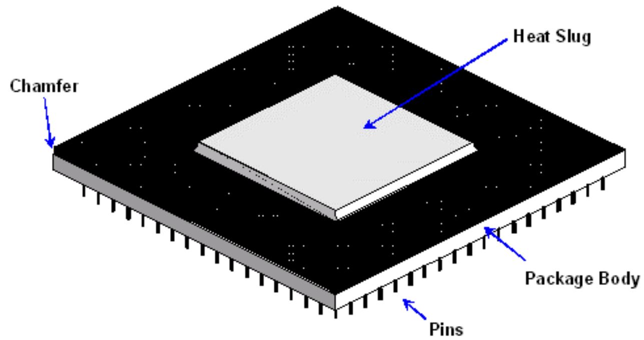
Table 2. Constant for Different Types of Electronic Components (continued)		
C	Component	Image
1.0	Through-hole Pin grid array (PGA) with many wires extending from the bottom surface of the PGA	
2.25	Surface-mounted leadless ceramic chip carrier (LCCC). A hermetically sealed ceramic package. Instead of metal prongs, LCCCs have metallic semicircles (called castellations) on their edges that solder to the pads.	
1.26	Surface-mounted leaded ceramic chip carriers with thermal compression bonded J wires or gull wing wires.	

Table 2. Constant for Different Types of Electronic Components (continued)		
C	Component	Image
1.75	Surface-mounted ball grid array (BGA). BGA is a surface mount chip carrier that connects to a printed circuit board through a bottom side array of solder balls.	
0.75	Fine-pitch surface mounted axial leads around perimeter of component with four corners bonded to the circuit board to prevent bouncing	—
1.26	Any component with two parallel rows of wires extending from the bottom surface, hybrid, PGA, very large scale integrated (VLSI), application specific integrated circuit (ASIC), very high scale integrated circuit (VHSIC), and multichip module (MCM).	—

Furthermore, Steinberg stated the maximum allowable relative displacement for shock as six times the 3-sigma limit value at 20 million cycles for random vibration. This shock limit is valid up to approximately 200 cycles due to the strain hardening effect discussed in Reference 12.

Steinberg's empirical formula for the shock peak relative displacement Z_{peak} is thus

$$Z_{peak} = 6\, Z_{3\sigma\ limit} \quad \text{inches, for < 200 cycles} \qquad (6)$$

The corresponding pseudo velocity limit PV_{peak} for shock response is

$$PV_{peak} = 2\pi\, f_n\; Z_{peak} \qquad \text{for} < 200 \text{ cycles} \tag{7}$$

where fn is the natural frequency in Hz.

Equation (7) is plotted in Figure 4 for a family of natural frequencies.

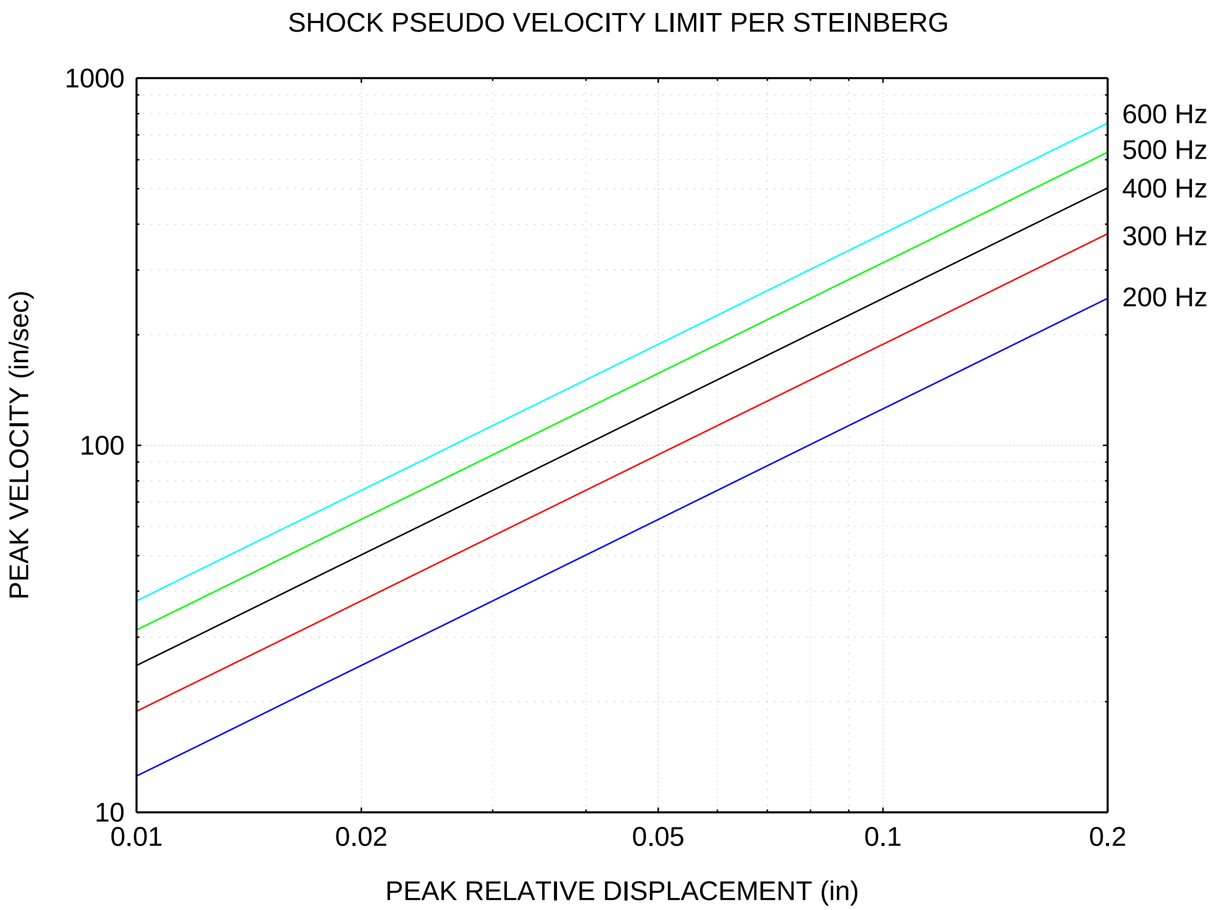


Figure 4.

Conclusion

Shock limit calculations for a given circuit board can be made using equations (5) through (7). Calculating the limit for every microelectronic part is probably unnecessary. Rather the calculation could be made for a few critical parts, such as those with higher C and L values or those located near the center of the board.

Limits can also be determine for housings and brackets simply based on their material properties using the tables in Appendix A.

The limits can then be compared with the shock test specification to determine whether testing is necessary.

Simple examples are shown in Appendix B. A list of questions are also given in this appendix to determine whether shock testing can be omitted for a given component.

Caveat

Daniel Kaufman of NASA/Goddard notes that certain spacecraft instruments are sensitive to shock environments and must be tested regardless of the specifications and the pseudo velocity limits.

Further insight from Erwin Perl is given in Appendix D.

References

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2. Gaberson and Chalmers, Modal Velocity as a Criterion of Shock Severity, Shock and Vibration Bulletin, Naval Research Lab, December 1969.

3. H. Gaberson, Using the Velocity Shock Spectrum for Damage Potential, SAVIAC, 74th Symposium, San Diego, CA, 2003.

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5. H. Gaberson, Shock Severity Estimation, Sound & Vibration, January 2012.

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7. Dave S. Steinberg, Vibration Analysis for Electronic Equipment, Second Edition, Wiley-Interscience, New York, 1988.

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10. R. Morse, presentation at Spacecraft & Launch Vehicle Dynamics Environments Workshop Program, Aerospace Corp., El Segundo, CA, June 20, 2000.

11. T. Irvine, Shock and Vibration Stress as a Function of Velocity, Revision G, Vibrationdata, 2013.

12. T. Irvine, Extending Steinberg's Fatigue Analysis of Electronics Equipment Methodology to a Full Relative Displacement vs. Cycles Curve, Revision C, Vibrationdata, 2013

APPENDIX A

Velocity Limits of Materials

Gaberson gave the limits in the following tables in Reference 5.

Table A-1. Severe Velocities, Fundamental Limits to Modal Velocities in Structures						
Material	E (psi)	σ (psi)	ρ (lbm/in^3)	Rod V_{max} (ips)	Beam V_{max} (ips)	Plate V_{max} (ips)
Douglas Fir	1.92e+06	6450	0.021	633	366	316
Aluminum 6061-T6	10.0e+06	35,000	0.098	695	402	347
Magnesium AZ80A-T5	6.5e+06	38,000	0.065	1015	586	507
Structural Steel, High Strength	29e+06	33,000 100,000	0.283	226 685	130 394	113 342

The original sources are noted. The velocity terms are "modal velocities at the elastic limit."

(*Values from Sloan, 1985, Packaging Electronics*)

Material	E (1e+06 psi)	μ	ρ (lbm/in^3)	σ_{ult} (ksi)	σ_{yield} (ksi)	v_{rod} (ips)	v_{beam} (ips)
Aluminum 5052	9.954	0.334	0.098	34	24	477.4	275.9
Aluminum 6061-T6	9.954	0.34	0.098	42	36	716.2	413.9
Aluminum 7075-T6	9.954	0.334	0.1	77	66	1299.8	751.3
Be	42	0.1	0.066	86	58	684.5	395.7
Be-Cu	18.5	0.27	0.297	160	120	1005.9	581.5
Cadmium	9.9	0.3	0.312	11.9	11.9	133.0	76.9
Copper	17.2	0.326	0.322	40	30	250.5	144.8
Gold	11.1	0.41	0.698	29.8	29.8	210.4	121.6
Kovar	19.5	-	0.32	34.4	59.5	468.0	270.5
Magnesium	6.5	0.35	0.065	39.8	28	846.4	489.3

Nickel	29.8	0.3	0.32	71.1	50	318.1	183.9
Silver	10.6	0.37	0.38	41.2	41.2	403.4	233.2
Solder 63/37	2.5	0.4	0.30008	7	7	158.8	91.8
Steel 1010	30	0.292	0.29	70	36	239.8	138.6
Stainless	28.4	0.305	0.29	80	40	273.9	158.3
Alumina al203	54	-	0.13	25	20	148.3	85.7
Beryllia Beo	46	-	0.105	20	20	178.8	103.4
Mira	10	-	0.105	-	5.5	105.5	60.0
Quartz	10.4	0.17	0.094	27.9	27.9	554.5	320.5
Magnesia Mgo	10	-	0.101	12	12	234.6	135.6
EPO GLS G10 X/Y	2.36	0.12	0.071	25	35	1680.1	971.1
EPO GLS G10 Z	2.36	0.12	0.071	25	35	1680.1	971.1
Lexan	0.379	-	0.047	9.7	9.7	1428.1	825.5
Nylon	0.217	-	0.041	11.8	11.5	2395.6	1384.8
Teflon	0.15	-	0.077	-	4	731.3	422.7
Mylar	0.55	-	0.05	25	25	2962.2	1712.3

(*Values from Roark, 1965, p 416*)

Material	E (1e+06 psi)	μ	ρ (lbm/in^3)	σ_{ult} (ksi)	σ_{yield} (ksi)	v_{rod} (ips)	v_{beam} (ips)
Aluminum Cast Pure	9	0.36	0.0976	11	11	230.6	133.3
Al Cast 220-T4	9.5	0.33	0.093	42	22	459.9	265.8
Al 2014-T6	10.6	0.33	0.101	68	60	1139.4	658.6
Beryllium Cu	19	0.3	0.297	150	140	1158.0	669.4
Cast Iron, Gray	14	0.25	0.251	20	37	357.8	224.2
Mg AZ80A-T5	6.5	0.305	0.065	55	38	1148.7	663.0
Titanium Alloy	17	0.33	0.161	115	110	1306.5	755.2
Steel Shapes	29	0.27	0.283	70	33	226.3	130.8
Concrete	3.5	0.15	0.0868	0.35	0.515	18.4	10.6
Granite	7	0.28	0.0972	-	2.5	59.6	34.4

APPENDIX B

Example

An avionics box has a circuit board with a surface mount BGA. For brevity, assume that this is the only vulnerable part on the board.

The avionics box is to be hardmounted on a bulkhead in a launch vehicle.

The BGA has a length of 0.6 inches. The coefficient for this component is C=1.75. It is mounted at the center of square circuit board with dimensions: (4 in x 4 in x 0.063 in). The boundary conditions are fixed-free-fixed-free.

The center of the board corresponds to r = 1.

The vibration relative displacement limit is

$$Z_{3\sigma\ \mathrm{limit}} = \frac{0.00022\,(4.0)}{(1.75)(0.063)(1.)\,\sqrt{0.6}} = 0.010 \ \text{ inches, for 20 million cycles} \qquad \text{(B-1)}$$

The shock limit is

$$Z_{\mathrm{peak}} = 6\,Z_{3\sigma\ \mathrm{limit}} = 0.060 \ \text{ inches, for < 200 cycles} \qquad \text{(B-2)}$$

Now assume that the circuit board is made from G10 material with uniformly-distributed nonstructural mass = 0.12 lbm. G10 fiberglass epoxy laminate has a velocity limit of 971 ips.

The resulting circuit board natural frequency is 306 Hz using a plate bending formula from Reference 7, included in Appendix C.

The corresponding pseudo velocity limit PV_{peak} for shock response at the circuit board natural frequency is

$$PV_{\mathrm{peak}} = 2\pi\, f_n\, Z_{\mathrm{peak}} \qquad \text{for < 200 cycles} \qquad \text{(B-3a)}$$

$$PV_{\mathrm{peak}} = 2\pi\,(306\,\mathrm{Hz})\,(0.060\ \mathrm{in}) = 115\ \mathrm{ips} \qquad \text{(B-3b)}$$

Also assume that the circuit board is mounted in a housing consisting of aluminum 6061-T6 with a plate velocity limit of 347 ips. The housing limit is about three times higher than the board limit. So the housing is of no further concern because the BGA would fail at a lower threshold.

The avionics box assembly is to be subjected to the specification in Table B-1.

Table B-1. SRS Q=10		
fn(Hz)	Peak Accel (G)	PV (ips)
100	100	61.4
2000	2000	61.4
10000	2000	12.3

PV = pseudo velocity

The pseudo velocity is more properly calculated from relative displacement, but can also be approximated as

$$PV \cong (\text{Peak Accel})/(2\,\pi\,fn) \tag{B-4}$$

The circuit board pseudo velocity threshold is 115 ips for the BGA. Thus, the avionics box should pass the test with nearly a 6 dB margin.

Does this result justify skipping the actual shock test? The answer depends on a number of factors.

How certain are the circuit board natural frequency and damping estimates?

Does the component have a linear response?

How much margin does the specification contain over the maximum predicted environment?

How critical is the avionics box to mission success?

Are the piece parts staked down to the circuit board with an epoxy compound? Or is conformal coating used?

Are the parts Mil-Spec quality or commercial grade?

Are there any other sensitive parts such as crystal oscillators which are not covered by Steinberg's method?

Has the component already been subjected to a rigorous random vibration test? If so, does the "damage potential" from the random test cover that from the shock test?

The final decision ultimately depends on engineering judgment. *When in doubt, test!*

APPENDIX C

Fixed-Free-Fixed-Free Plate

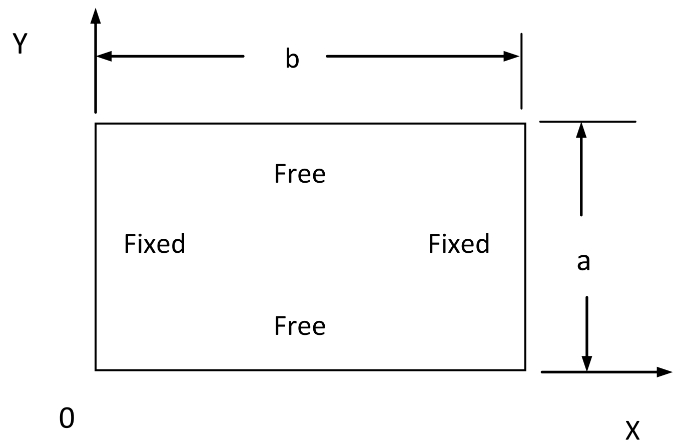

Figure C-1.

The plate stiffness factor D is given by

$$D = \frac{Eh^3}{12\ (1-\mu^2\ )} \tag{C-1}$$

where

E	=	elastic modulus
H	=	plate thickness
μ	=	Poisson's ratio

The natural frequency f_n is

$$f_n \approx \frac{3.55}{b^2}\sqrt{\frac{D}{\rho}} \quad , \quad \text{where b is the free edge length} \tag{C-2}$$

where

ρ	=	mass per volume

APPENDIX D

Email from Erwin Perl

Tom,

Thanks for sending me this information. The source of the 50 ips velocity and its applicability comes up very often, especially when we specify shock test requirements for various pieces of hardware.

Here at Aerospace have, in the past, attributed the 6 dB "factor of safety" applied to the 100 ips shock velocity to specify 50 ips as the threshold for a benign shock, to Sheldon Rubin.

This was restated verbally about a year ago, in public, at a Shock Working Group Meeting at Aerospace with both Howard Gaberson and Sheldon Rubin in attendance. I believe the basis was an extensive shock test program conducted by the Navy. My best interpretation is that various people have reached roughly the same conclusion in a relatively short period of time.

We also specify that testing is required for shock velocity less that 50 ips for shock sensitive components, unless technical rationale indicates that it isn't necessary

Thanks
Erwin

Erwin Perl
Director, Environments, Test, and Assessment Dept.
The Aerospace Corp.

APPENDIX E

Email from Larry Trilling

At Ball, we look at 4 failure modes for EEE parts:

1. Solder joint or lead failure due to combined fatigue from random vibration and thermal cycling. We use an extension of Steinberg's methodology for vibe, and Steinberg and Engelmaier methodology for thermal fatigue.

2. Lead failure on leaded surface mount parts due to random vibration. This occurs when the as-mounted part has a resonance that couples with a board or chassis resonance. While rare, and easily averted by staking the part to the board, this happens to us once in a while.

3. Failure of the part itself due to random vibration. Relay chatter or state change is the most common failure, though hybrids also fail from time to time.

4. Failure of the part itself due to **shock**. While a number of part classes are considered "shock sensitive", my only experience with failures is relay chatter or state change. Crystal oscillator resonances are typically in the MHz range, so should not be affected by 10 kHz shock. Failures in ceramic parts, in my experience, are due to cracks induced by thermal gradients during soldering, which were likely themselves initiated by micro cracks due to manufacturing.

I did an interesting study awhile back on the PVSS of the various shock tests defined in MIL-STD-202, Method 213 and MIL-STD-883, Method 2002. I found peak PV values ranging from 81 ips for switches to 172 ips for ICs. We use these specification part qual PV peak values for internal assessment of susceptibility to failure mode 4. I have more faith in these part qual levels for EEE parts than the 100 ips level. I presented the attached paper at SAVIAC a few years ago on this topic. While I find Gaberson's squirrel cage blower testing to be a great example of why PVSS is a highly perceptive means to assess shock damage potential, I'm not comfortable extrapolating his absolute level of 130 ips to EEE parts. I don't think that the old adage from Wendy's commercials that "parts is parts" holds true with EEE components.

We do not use Steinberg's method for determining shock allowables based on board deflection (curvature, actually). Steinberg focused on solder joint and lead failures due to fatigue, and I believe that these failures comprised his secret database. I just don't believe that shock is going to contribute significantly to the failure of ductile materials such as solder and Kovar leads.