SNAP-TECH-07-004

SNAP DESIGN LIMIT LOADS

- Structural Limit Loads
- Box *(or Unit)* Design Limit Loads

Launch loads depend on what is to be flown… so where does the poor engineer in the trenches start ?

LIMIT LOAD

The maximum anticipated load, or combination of loads, which a structure may experience during its ***service life*** under all expected conditions of operation or use.

NASA-STD-5001 paragraph 3.7

The Frequently Overlooked Consideration…

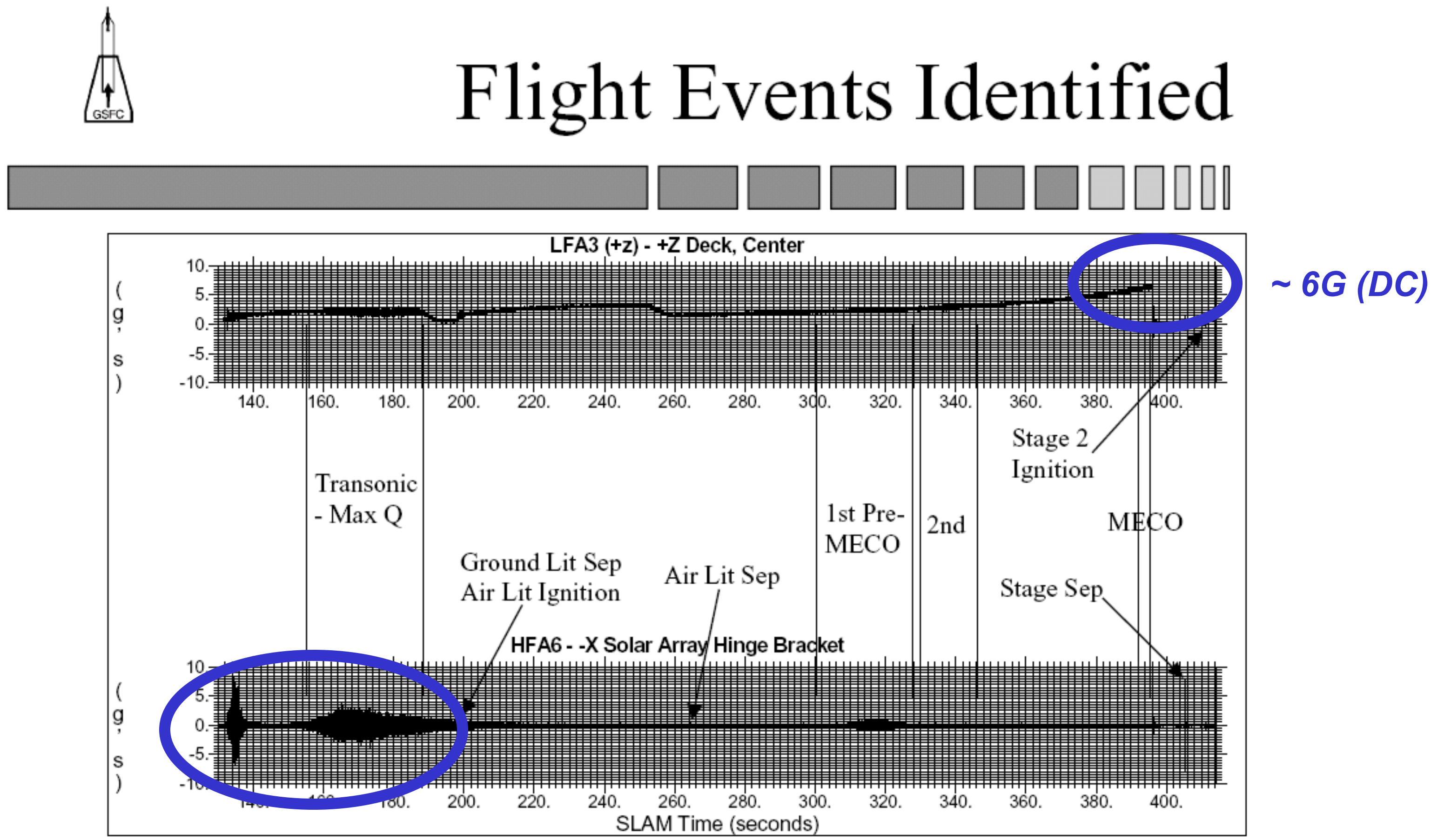
NASA SP-8077 on Limit Loads

TABLE 1. – TRANSPORTATION LIMIT LOAD FACTORS
[From ref. 15]

Medium/mode	Longitudinal load factors, g	Lateral load factors, g	Vertical load factors, g
Water	±0.5	±2.5	+2.5
Air	±3.0	±1.5	±3.0
Ground			
Truck	±3.5	±2.0	+6.0
Rail (humping shocks)	±6.0 to ±30.0	±2.0 to ±5.0	+4.0 to +15.0
Rail (rolling)	±0.25 to ±3.0	±0.25 to ±0.75	+0.2 to +3.0
Slow-moving dolly	±1.0	±0.75	+2.0

The ELV Environments Reality

A Recent Case: Advanced Composition Explorer **(ACE) - DELTA II Launch**



Ignition & Reflected Motor Rumble

…followed by Buffeting Induced Random Vibration

ANOTHER RECENT EXAMPLE: DELTA II Launch

Hurricane Otto

GENERAL DYNAMICS
C4 Systems

Spectrum Astro Space Systems
1196 EB-XXXXXX-000
4

Would you really plan for something like this… (you will !)

QUASI-STEADY (DC) LOADING

BOEING / DELTA IV Payload Planners Guide, Oct 1999

Structural Loads (4.2.4.1)

- *6.5 G (acceleration) Loads occur just before Motor (MECO) Burnout*
  - *a quasi-steady acceleration (payload compression) with modest rebound (tension)*

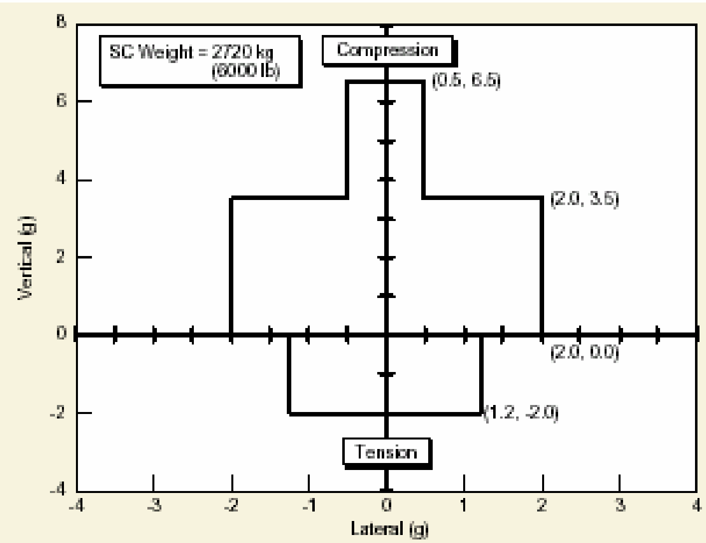


Figure 4-23. Delta IV Medium Design Load Factors for Dynamic Envelope Requirements

4-20

PAYLOAD SWEPT SINE VIBRATION

BOEING / DELTA IV Payload Planners Guide, Oct 1999 (4.2.3.4)

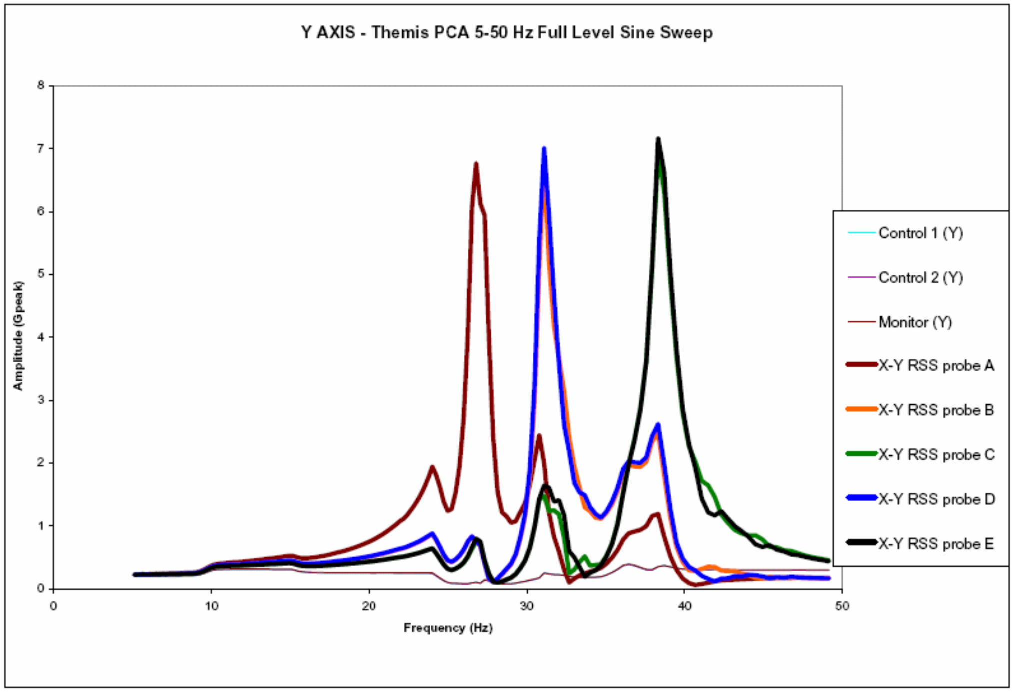
- The sinusoidal vibration levels are ***not intended for use in the design of primary structure***.
- The sinusoidal vibration levels should be used in conjunction with the results of the coupled dynamic loads analysis (Table 8-3, item 6) to aid in the design of spacecraft secondary structure (e.g., solar arrays, antennae, appendages, etc.) that may experience dynamic loading due to coupling with Delta IV launch vehicle low-frequency dynamic oscillations.
- **Notching of the sinusoidal vibration input** levels at spacecraft fundamental frequencies may be required during testing and should be ***based on the results of the launch vehicle coupled dynamic loads analysis***

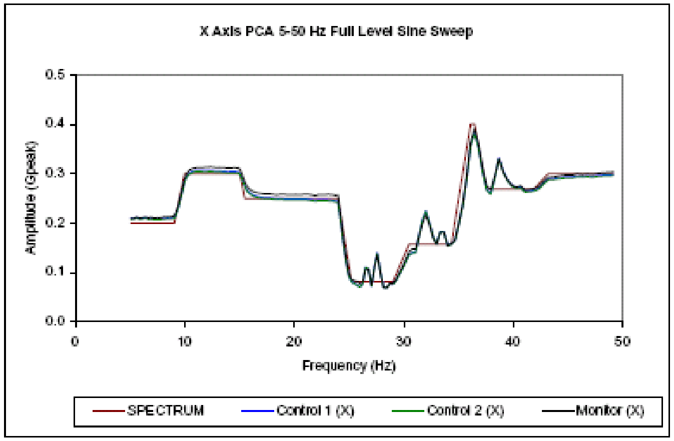
Table 4-8. Sinusoidal Vibration Levels

Axis	Frequency (Hz)	Maximum flight levels
Thrust	5 to 6.2 6.2 to 100	1.27 cm (0.5 in.) double amplitude 1.0 g (zero to peak)
Lateral	5 to 100	0.7 g (zero to peak)

0000589

A RECENT EXAMPLE: Themis on **DELTA II (7925) Launch Vehicle**





M+P Performance with Five Probe Accelerometers added to the Control Loop

M+P Controller Notch Tracking

It ***certainly appears*** there was a desire to capture the Max. Aerodynamic Bending in this test !

(sweep rate is a slow 1.5 octave / minute in mid-band)

Collected COMMENTS

Scott Gordon: *Many Reviewers consider this to be a **"Dress Rehearsal for Flight"***

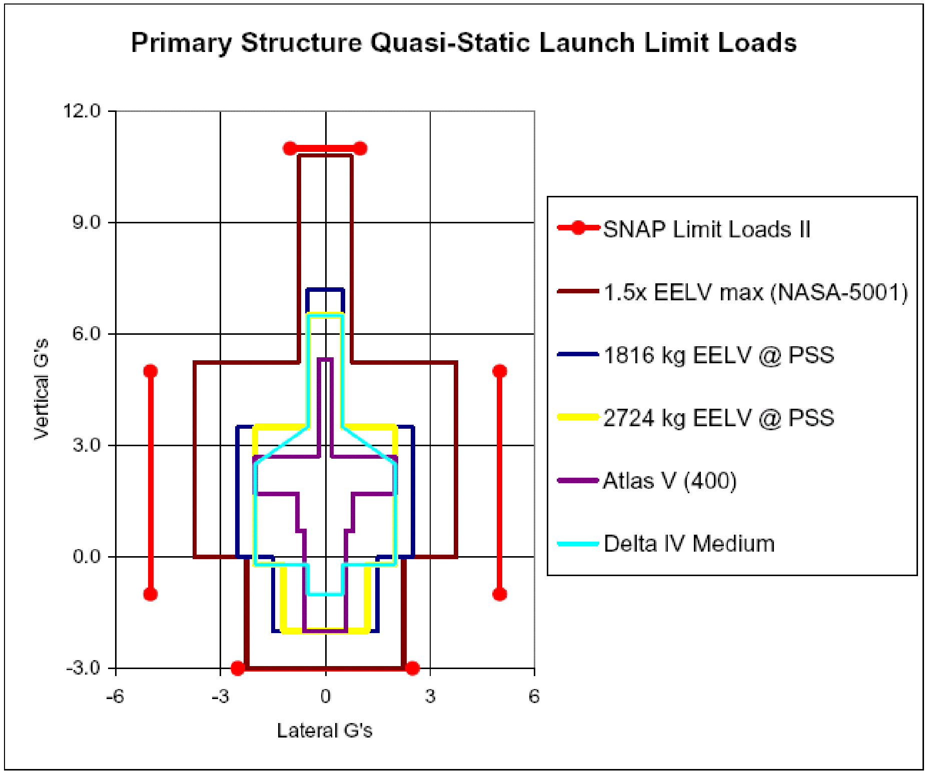
Terry Scharton: *(1) Boeing has been known to waive the test because Government Projects are not insured*

(2) David… you're simply under-estimating the difficulties in conducting this test on an entire spacecraft.

EELV Environments Design Practice

Candidate Launch Vehicles Overlay

OUR STARTING POINT: **Axial: +11/-3G, Lateral: ± 5G**



Lateral design margin increased for:

(1) Zcg elevation

(2) 5-50 Hz Sine Test

very little vibration remains at MECO

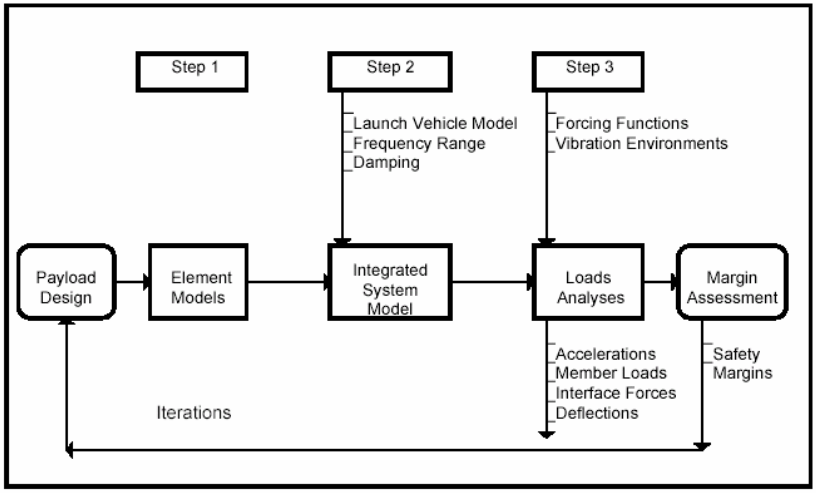
"General practice calls for a ***minimum factor of 1.5*** *for the preliminary load cycle."*

(NASA-STD-5002: 4.2.4.2 Uncertainty Factors In Early Load Cycles)

NASA-STD-5002

LOAD ANALYSES OF SPACECRAFT AND PAYLOADS June 21, 1996

4.2.6 Verification of the payload mathematical model. Verification of the payload model by modal survey testing shall be performed to ensure the model is sufficiently accurate for load and deflection predictions (refer to NASA-STD-7002, *Payload Test Requirements*). Payload model verification may be accomplished by a ***combination of payload level and component level modal survey tests***.



*'Math Model' ≡ **NASTRAN** Coupled Loads Analysis (Reduced FEM's of payload & launcher)*

Minimum of two CLA submittals to the launch vehicle provider – *NASA-STD-5002*

also see: NASA Preferred Practice #1317 & #1318

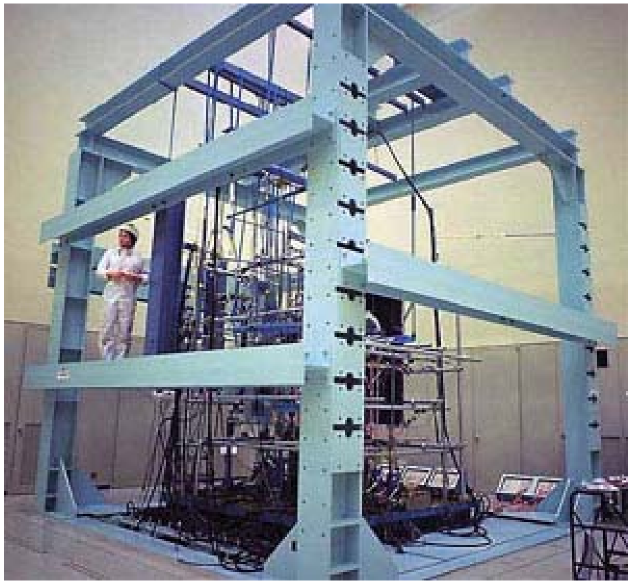
LIMIT LOADS TESTING

TRADITIONAL TEST METHODS

- CENTRIFUGE – Suited for Small & Medium Size Articles
- SINE BURST – Suited for Medium & Large Sized Articles
- STATIC or PROOF LOADS – Suited for Large Articles & Structures
- RANDOM VIBRATION is generally **NOT** an acceptable substitute for Limit Load

Asymmetric Axial Limits (+11G / - 3G)

- Provided for the Primary Mirror & its Bipods
  - Suggests a Static Loads Test Method
- Symmetric Tests (i.e. Sine Burst) to ±11G



Box (Unit) Design Limit Loads

A Launch Environment Description

- The bigger ground launched vehicles (Delta, Atlas, Titan) have a very high vibro-acoustic environment at liftoff but **very low mechanically transmitted random** (primarily because the vehicle acts as a low-pass mechanical filter).
- The high-frequency launch environment for the ground launched vehicles is **dominated by acoustics**. Therefore, we typically do not do a spacecraft level random vibration testing for payloads flying on the Delta or Atlas vehicles.
- The high-frequency observatory test for these vehicles is an **acoustic test**.

** Scott Gordon E-mail, Chief Engineer for Structures at GSFC, dated Feb. 8, 2005*

(TRANSIENT) ACOUSTIC LOADING

BOEING / DELTA IV Payload Planners Guide, Oct 1999

Acoustic Environment (4.2.3.3)

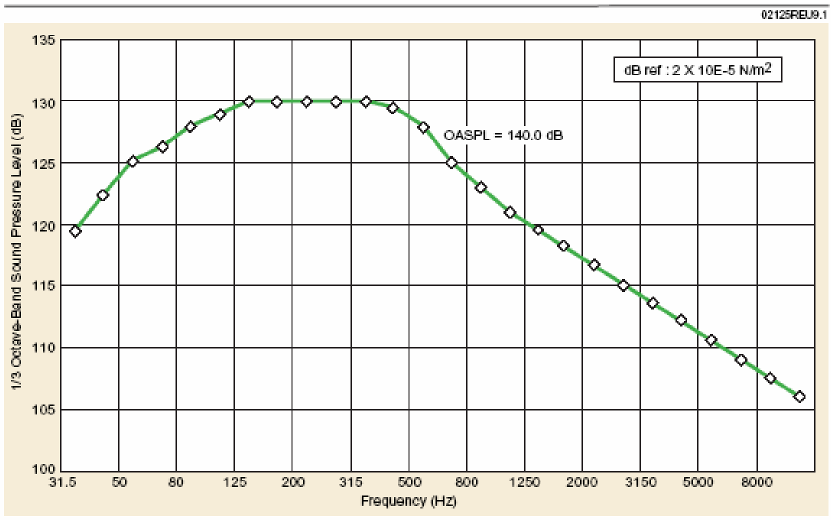


Figure 4-25. Delta IV-M and Delta IV-M+ (4-m Composite Fairing) Internal Payload Acoustics Typical 95 Percentile, 50% Confidence Predictions, 60% Fill Effect Included

Spectral Peak Amplitudes

Pressure - Time History

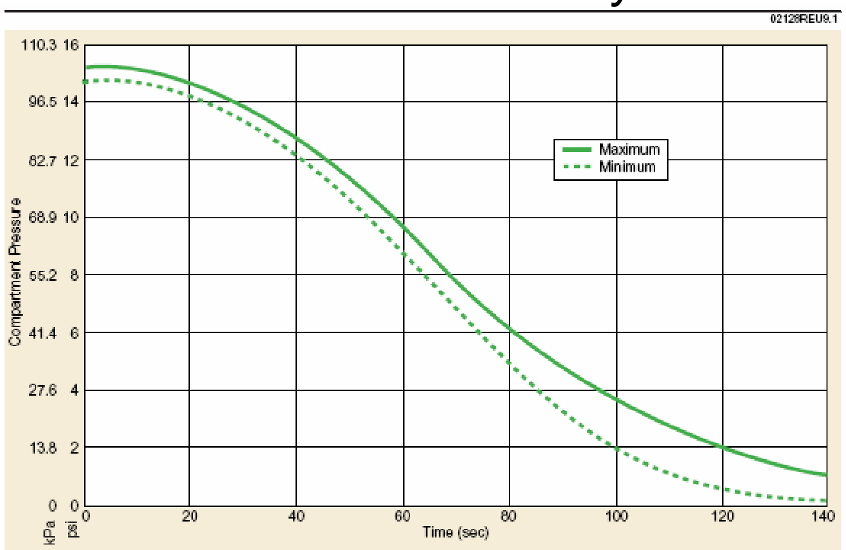
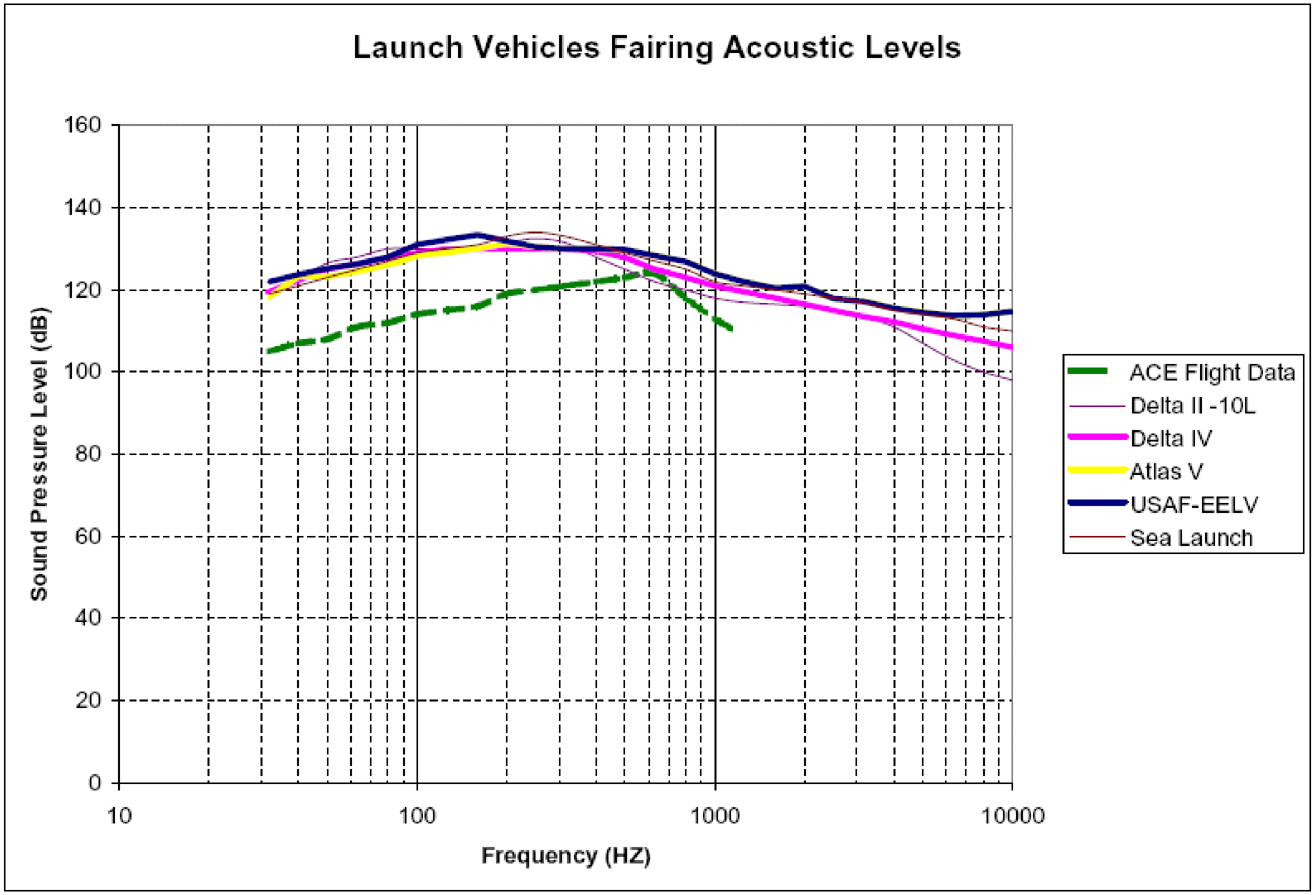


Figure 4-4. Delta IV Medium Absolute Pressure Envelope

Highest Level Acoustics lasts ~ 5 seconds (Delta II PPG)

FAIRING ACOUSTIC SPECIFICATION OVERLAYS

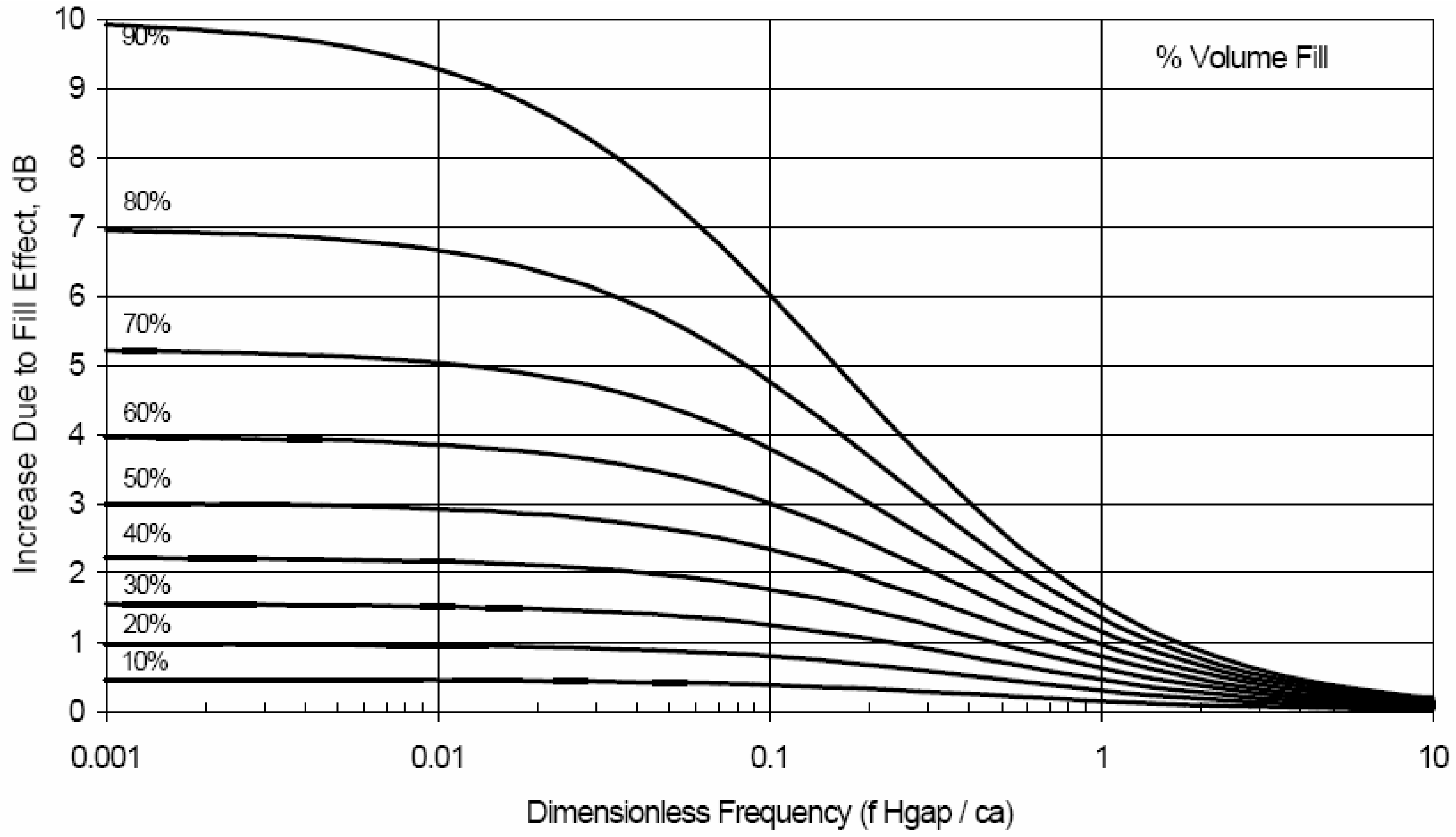


10 dB is
10x amplitude
√10x RMS

NASA-STD-7001 (4.2.4) + GEVS (A2) also describe a **"Fairing Fill Factor"** Modifier

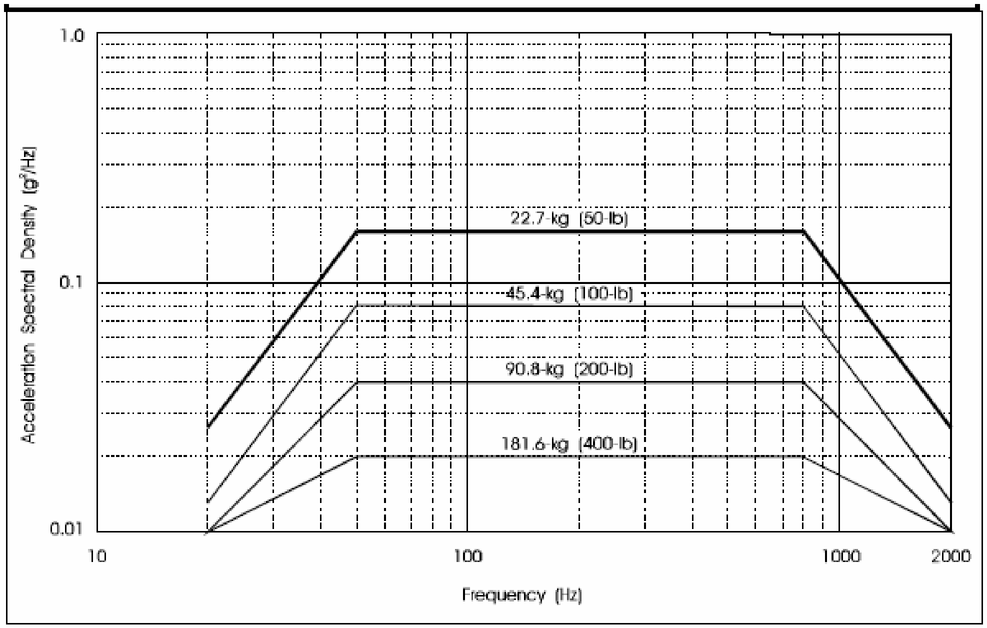
FAIRING ACOUSTICS "FILL FACTOR"

from NASA-STD-7001 (4.2.4)



Box Environments Documentation

- **“DEFAULT” UNIT (or box) TEST REQUIREMENTS**
- The conservative 14.1G GEVS “default” test prescribed by NASA Goddard:



Frequency (Hz)	ASD Level (G^2/Hz)	
	Qualification	Acceptance
20	0.026	0.013
20-50	+6 dB/oct	+6 dB/oct
50-800	0.16	0.08
800-2000	-6 dB/oct	-6 dB/oct
2000	0.026	0.013
Overall	14.1 G_{rms}	10.0 G_{rms}

The acceleration spectral density level may be reduced for components weighing more than 22.7-kg (50 lb) according to:

	Weight in kg	Weight in lb	
dB reduction	= 10 log(W/22.7)	10 log(W/50)	
$ASD_{(50\text{-}800\ Hz)}$	= 0.16•(22.7/W)	0.16•(50/W)	for protoflight
$ASD_{(50\text{-}800\ Hz)}$	= 0.08•(22.7/W)	0.08•(50/W)	for acceptance

Where W = component weight.

The slopes shall be maintained at + and - 6dB/oct for components weighing up to 59-kg (130-lb). Above that weight, the slopes shall be adjusted to maintain an ASD level of 0.01 G^2/Hz at 20 and 2000 Hz.

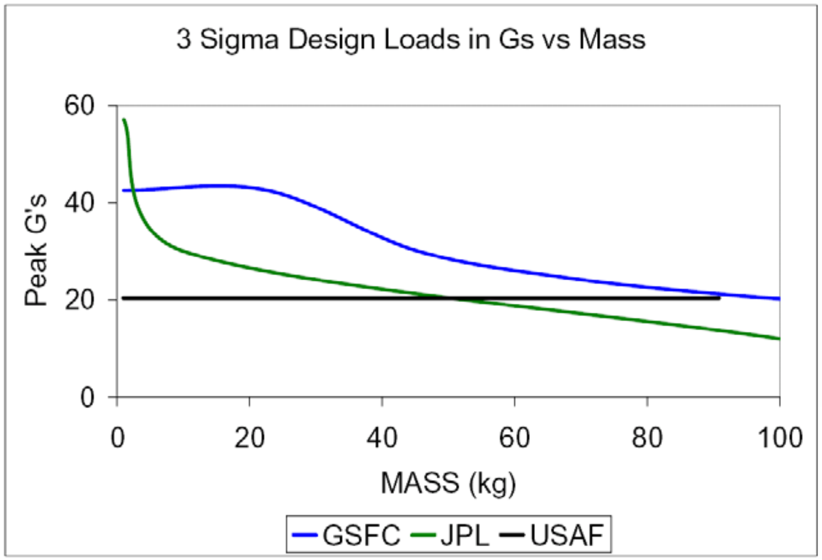
For components weighing over 182-kg (400-lb), the test specification will be maintained at the level for 182-kg (400 pounds).

- ***Widely accepted by aerospace avionics suppliers***
- The leads to the conservative ***“UCB/SSL rule of thumb for boxes”***
  - **OLD: 14 Grms → 42Gpeak (3σ) * 2.0 (min safety factor → *more later*) ≈ 100 Gpeak**
  - **NEW: 14 Grms → 70Gpeak (5σ) * 1.4 (min safety factor → *more later*) ≈ 100 Gpeak**

Box Environments Documentation

A COMPARISON OF GOVERNMENT AGENCY TEST PRACTICES

A Test Requirements Overlay



JPL's MER Mass Acceleration Curve

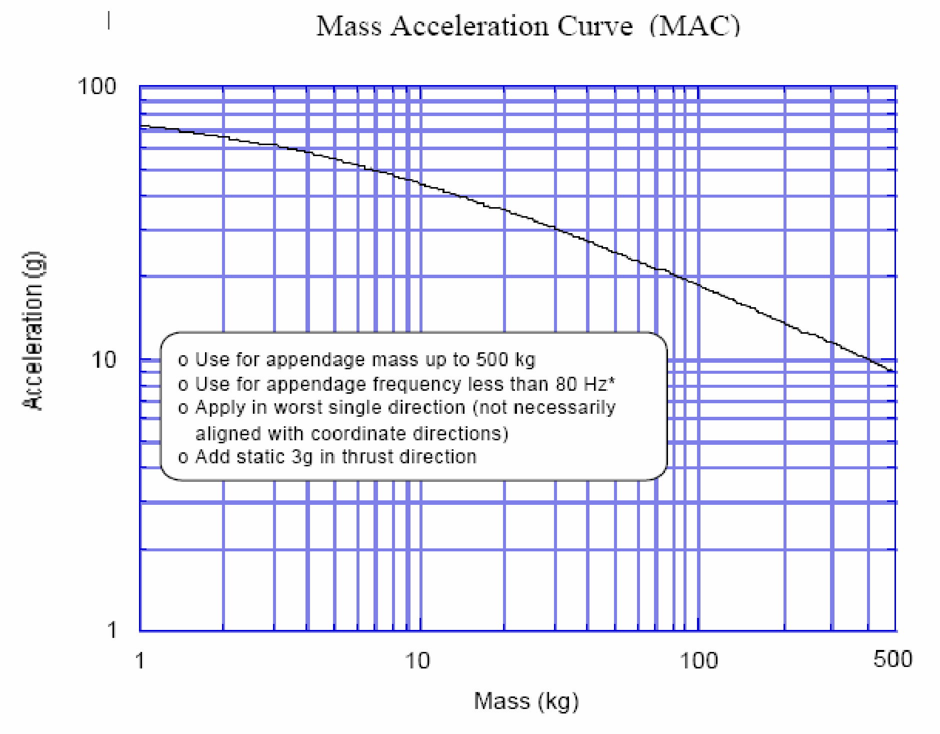


Figure 3. Mass Acceleration Curve

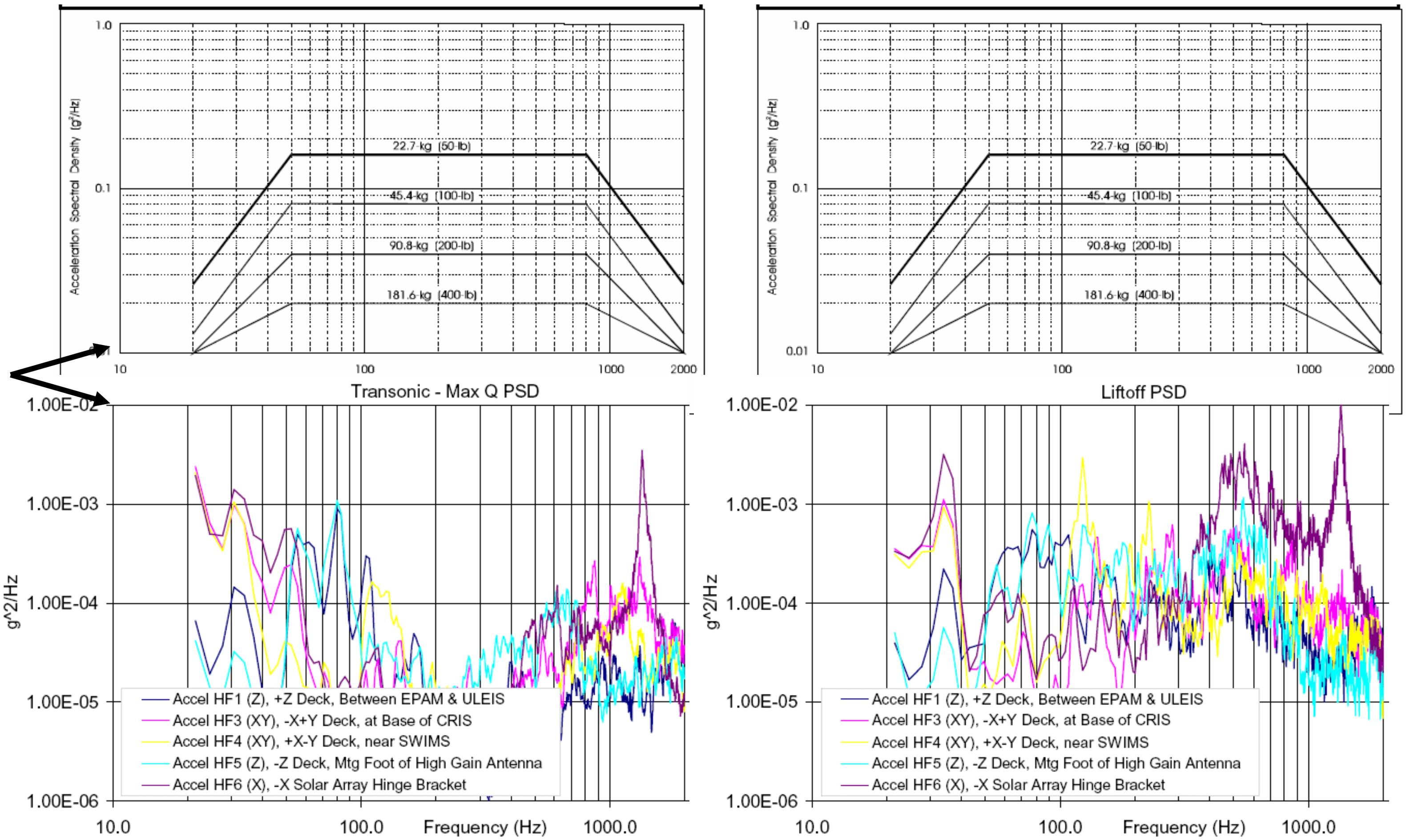
- *NASA-STD-5002 para. 5.4*
- *NASA Preferred Practice #1211*

The ELV Box Environments Reality

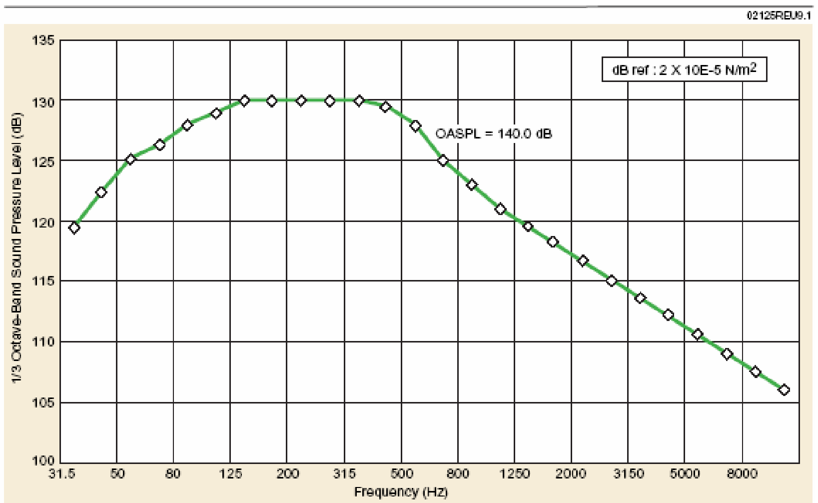
GEVS Random Test "DEFAULTS" vs. ACE Flight Data (Delta II)

- *please take note of the log-log scales !*

0.01 G^2/Hz



GENERATING RANDOM VIBRATION TEST REQUIREMENTS



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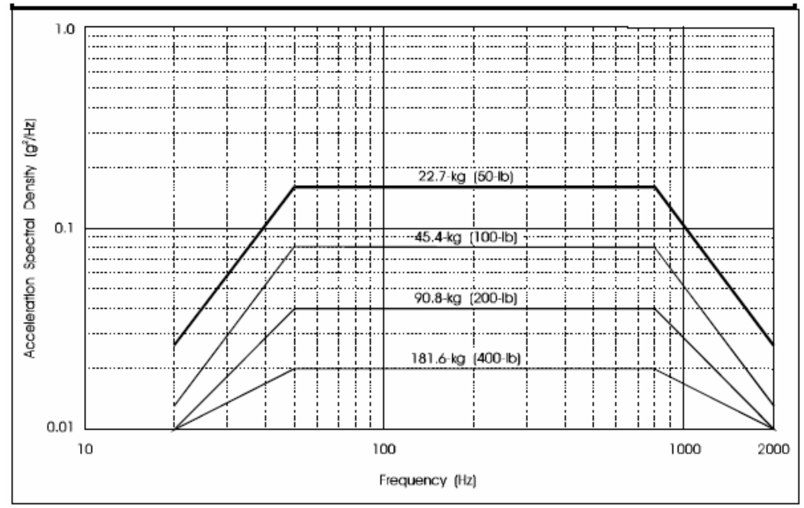


NASA-STD-7001

- A.2.1 **Statistical Energy Analysis** (SEA) is a technique to analyze and predict the vibro-acoustic response of a complex system by calculating the energy flow between subsystems.
  - SEA covers… (typically **100 Hz and higher**), whereas FEM is suited to lower frequencies.

SEA METHODS

Preliminary SEA of Bottom Deck

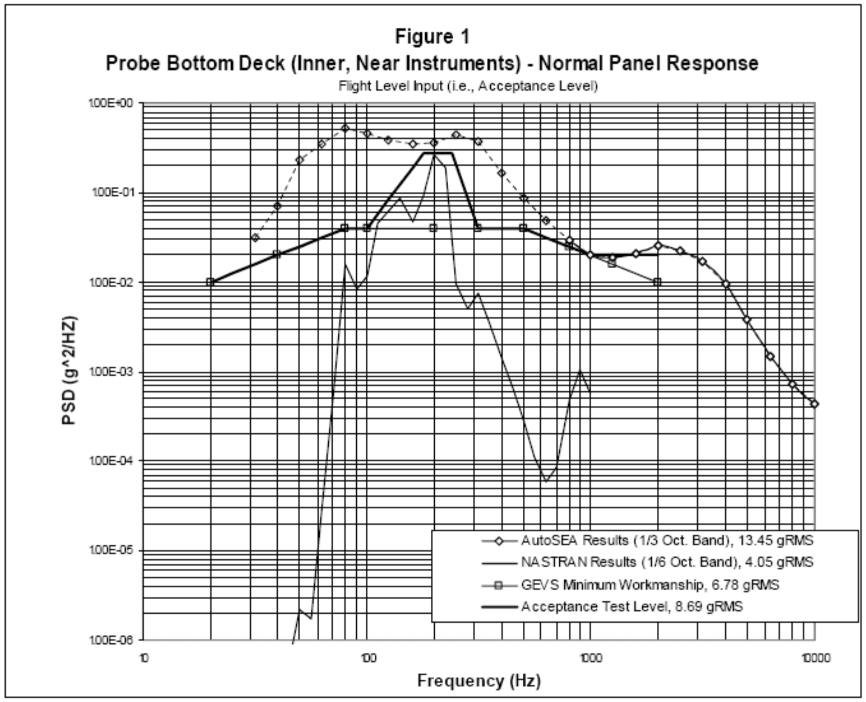
Basic SEA Equations for Plate (2) Excited by Acoustics (1)

- Energy balance: $E_2/E_1 = (n_2/n_1)[2\eta_{21}/(\eta_2 + 2\eta_{21})]$
  (where E is space-time average energy, n is modal density, n_{21} is the one-sided radiation loss factor, and n_2 the internal loss factor of the plate)
- Energy parameters: plate, $E_2 = [\rho_s * S/(2\pi f)^2] <A^2>_{s,t}$
  acoustics, $E_1 = [V/(\rho_o * c_o^2)] <p^2>_{s,t}$
  (where ρ_s is surface density, S area, f frequency, and A acceleration of the plate; and V is volume, ρ_o density, c_o speed of sound, and p pressure in the acoustic medium)
- Modal densities: plate, $n_2 = S/(2\kappa * c_l)$
  acoustics, $n_1 = (4\pi f^2)V/c_o^3$
  (where κ is the radius of gyration and c_l the speed of longitudinal waves in the plate)

$$<A^2>_{s,t} / <p^2>_{s,t} = [2/\rho_s^2] * [\pi\rho_s c_o/(4\kappa\rho_o c_l)] * [2\eta_{21}/(\eta_2 + 2\eta_{21})], \quad \text{Eq. 1}$$

$=$ random incidence mass law * max. resonant * damping effect

Combining FEM & SEA Modeling



FEM ← | → SEA

The often used software platform is "AutoSEA2"

http://www.esi-group.com/SimulationSoftware/Vibro_acoustics

Box Environments & Safety Factors

NASA-STD-5001: **STRUCTURAL DESIGN AND TEST FACTORS OF SAFETY FOR SPACEFLIGHT HARDWARE**, June 21, 1996

TABLE I. Minimum Design and Test Factors for Metallic Structures

Verification Approach	Ultimate Design Factor	Yield Design Factor	Qualification Test Factor	Acceptance or Proof Test Factor
Prototype	1.4	1.0 *	1.4	NA or 1.05 **
Protoflight	1.4	1.25	NA	1.2

NOTES:
* Structure must be assessed to prevent detrimental yielding during flight, acceptance, or proof testing.
** Propellant tanks and solid rocket motor cases only.

TABLE II. Minimum Design and Test Factors for Fasteners and Preloaded Joints

Verification Approach	Design Factors			Test Factors	
	Ultimate Strength	Joint Separation		Qualification	Acceptance or Proof
		Safety Critical *	Other		
Prototype	1.4	1.4	1.2	1.4	NA
Protoflight	1.4	1.4	1.2	NA	1.2

NOTE:
* Joints that maintain pressures and/or hazardous materials in a safety-critical application.

TABLE III. Minimum Design and Test Factors for Composite/Bonded Structures

Verification Approach	Geometry of Structure	Ultimate Design Factor	Qualification Test Factor	Acceptance or Proof Test Factor
Prototype	Discontinuities	2.0 *	1.4	1.05
	Uniform Material	1.4	1.4	1.05
Protoflight	Discontinuities	2.0 *	NA	1.2
	Uniform Material	1.5	NA	1.2

NOTE:
* Factor applies to concentrated stresses. For non-safety critical applications, this factor may be reduced to 1.4 for prototype structures and 1.5 for protoflight structures.

- **1.4 safety factor given 1.25 test factor is extraordinarily non-conservative**
  - Analyses need to be extremely detailed for these small margins !

- *Design Texts, ASME, & AIAA often suggest starting with safety factor of* ***4***

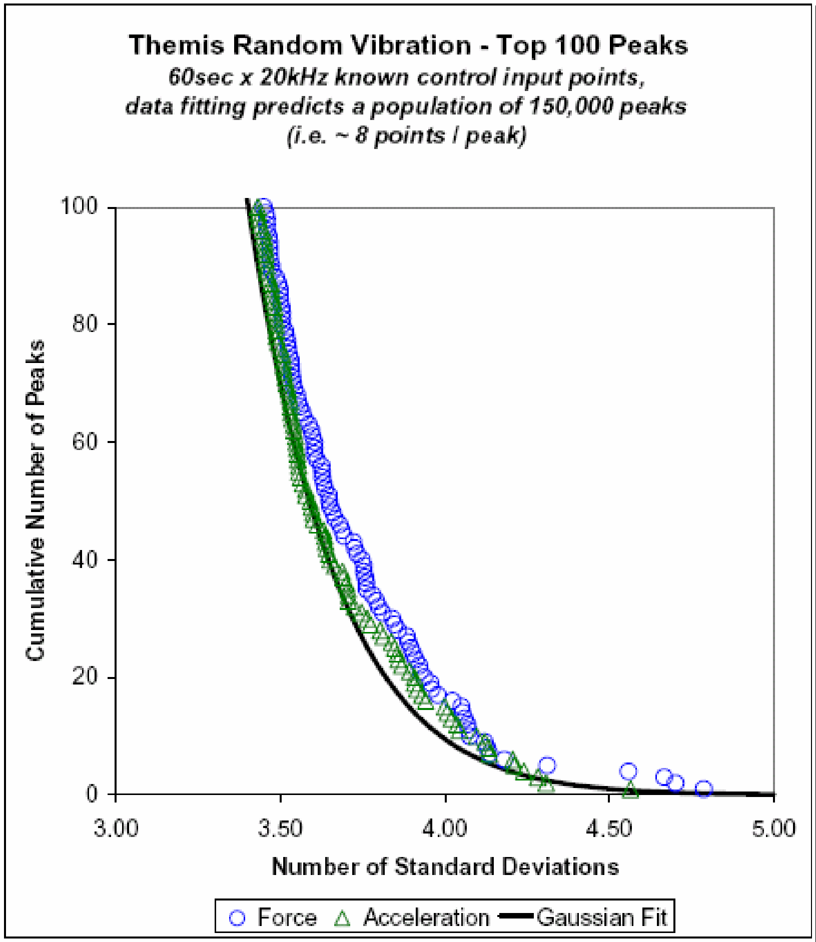
BACKUP SLIDES

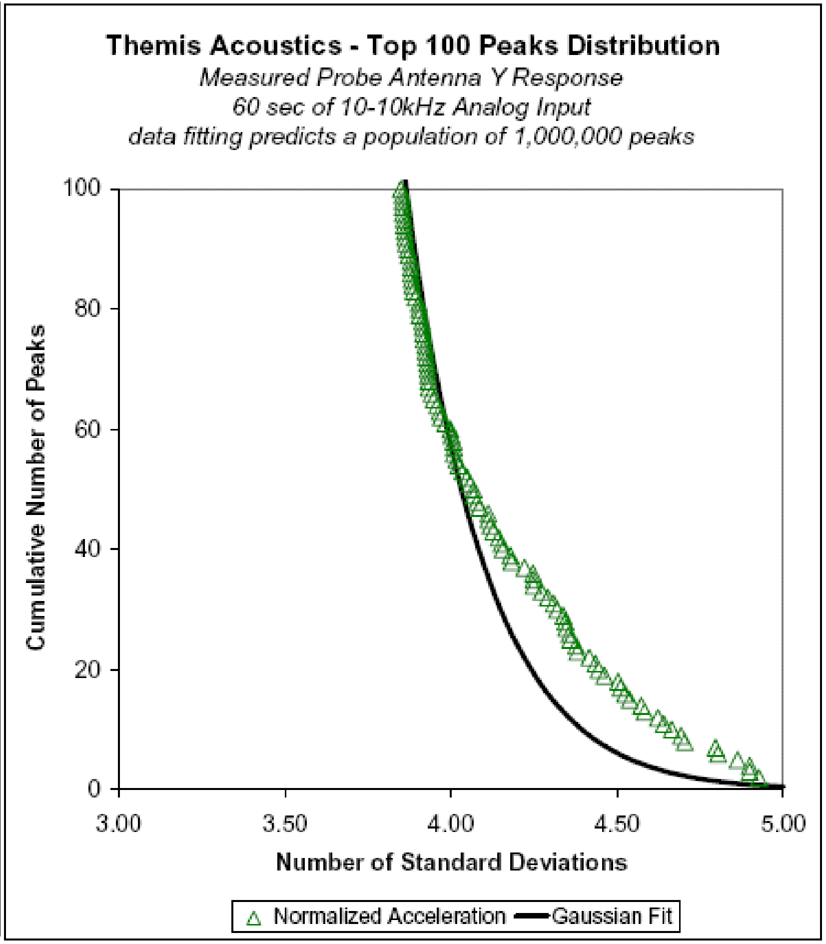
RECENT DEVELOPMENTS – RANDOM VIBRATION

- **NASA-STD-5002 states** *... Random vibration limit loads are typically taken as the 3-sigma load (obtained by* ***multiplying the rms load by 3****)... (pp. 5.3.3)*

Box Environments & Safety Factors

Measured Extreme Peaks in 60 sec. Random Vibration & Acoustics Tests

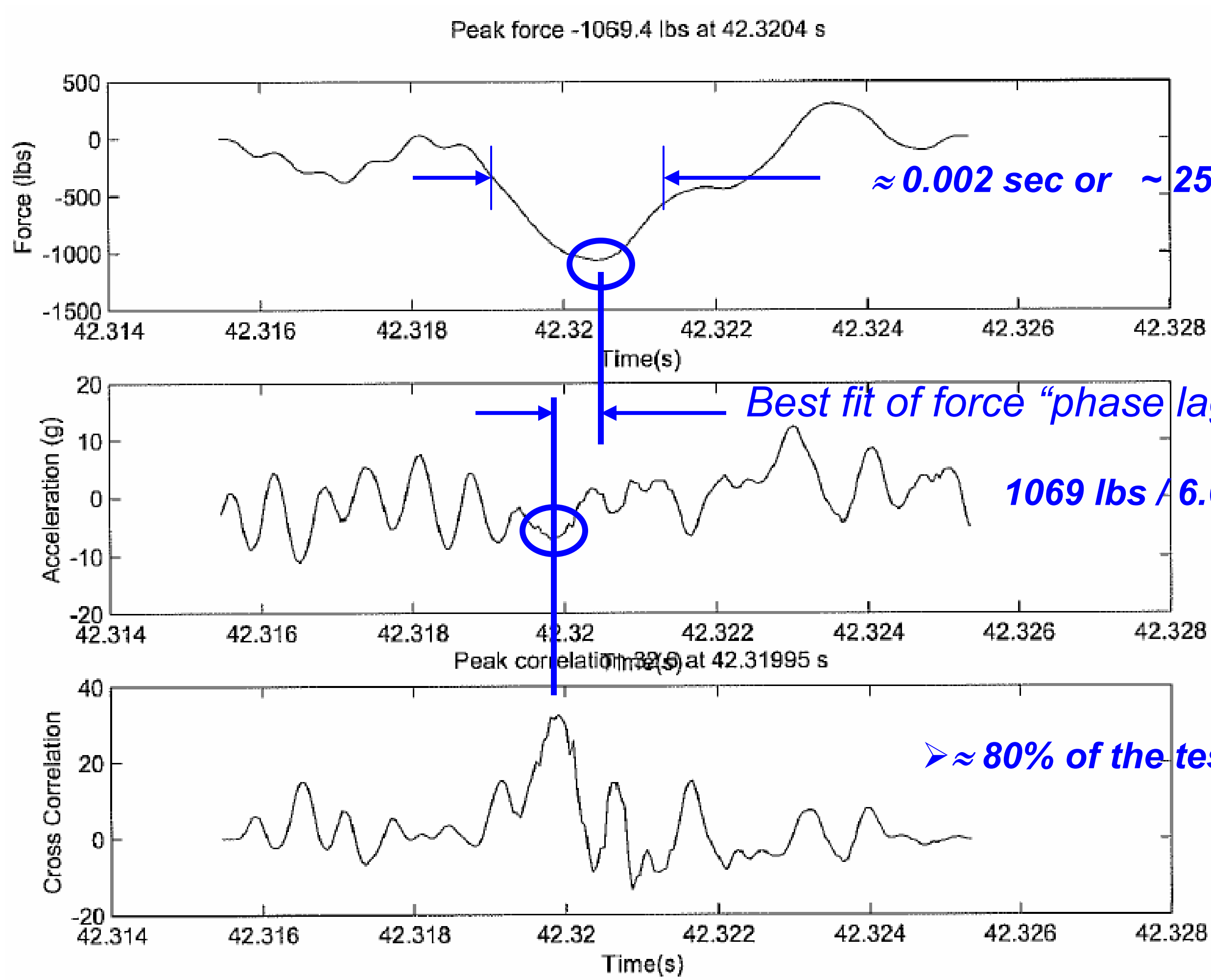




See Scharton & Pankow at: http://www.aero.org/conferences/sclv/2006proceedings.html

Box Environments & Safety Factors

This SINGLE 5 SIGMA PEAK: *"Is it Real, or is it Memorex"*



≈ 0.002 sec or ~ 250 Hz

Best fit of force "phase lag" @ 6.63 G peak

1069 lbs / 6.63 Gs = 161 lbs. (effective)

- ***197 lb actual mass***

- ***≈ 80% of the test article is being stressed***