New Approaches in Force-Limited Vibration Testing of Flight Hardware

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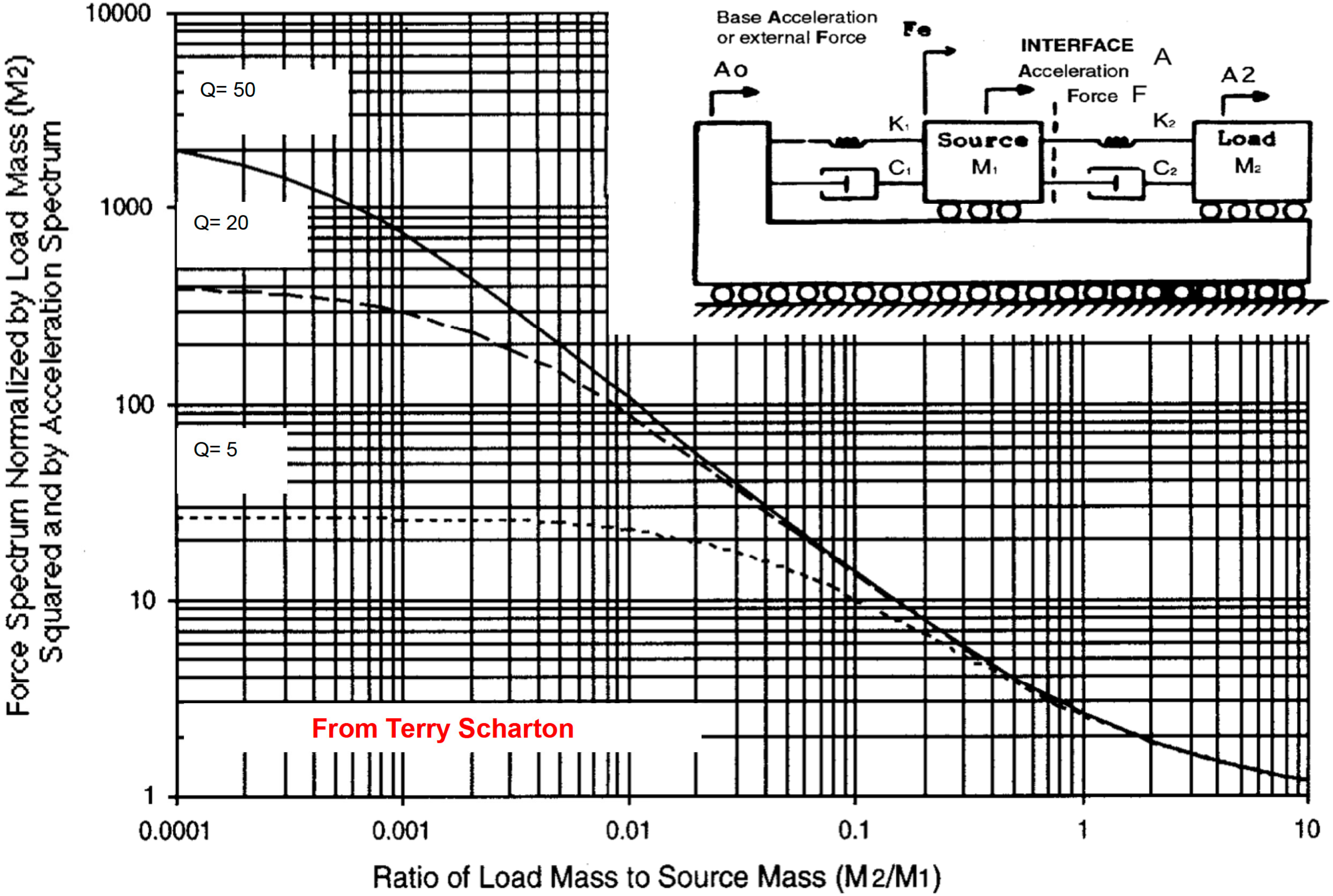
Force Limits: Existing Approaches

- To qualify flight hardware for random vibration environments the following methods are used to limit the loads in the aerospace industry:
  - *Response limiting and notching*
  - *Simple TDOF model*
  - ***Semi-empirical force limits***
  - *Apparent mass, etc.*
  - *Impedance method*
- In all these methods attempts are made to remove conservatism due to the mismatch in impedances between the test and the flight configurations of the hardware that are being qualified
  - *Assumption is the hardware interfaces have correlated responses*
- A new method that takes into account the un-correlated hardware interface responses are described in this presentation.

Force Limits Review: Response Limiting and Notching (1/4)

- In force limited vibration testing, base acceleration is considered an input and base force is a response
- Both acceleration and force specifications are needed.
  - *Force limits are proportional to the acceleration specification,*
  - *Force limits typically cover only first few modes*
- In force limiting, input is reduced (notched) at frequencies where force limits would be exceeded
  - *Notch depth depends on the force limit, and the damping of the resonance being limited in the test,*
  - *Notching is not nearly as effective in reducing rms response as reducing the input at all frequencies.*

Force Limits Review: Simple TDOF Model (2/4)



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Force Limits Review: Semi-empirical Force Limits (3/4)

- Semi-empirical force limit $S_{ff}(f)$ for random vibration test with input acceleration spectral density of S_{aa}:

$$S_{ff}(f) = C^2 M_o^2 S_{aa}(f), \qquad f < f_b$$

$$S_{ff}(f) = C^2 M_o^2 (f_b/f)^{2n} S_{aa}(f), \qquad f \geq f_b$$

  where C is dimensionless constant that depends on the flight mounting configuration, M_o is the total mass of the test item, f_b is a break frequency (often f_o), and n is a positive constant (often 2),
- Constant C, analogous to Q, determined from:
  - *Simple TDOF model,*
  - *Impedance analyses,*
  - *Finite element analysis of flight configuration, and*
  - *Flight or ground test data on similar configurations.*

Force Limits Review: Impedance method (4/4)

- Using Norton's/Thevinen's equivalent circuit theorem, the ratio of the acceleration (*A*) and force (*F*) at the interface of a coupled source (s) and load (l) to the free acceleration of the source (A_s) is:

$$\left|\frac{A(f)}{A_s(f)}\right| = \left|\frac{M_s(f)}{[M_s(f)+M_l(f)]}\right|, \text{ and}$$

$$\left|\frac{F(f)}{A_s(f)}\right| = \left|\frac{M_s(f)xM_l(f}{[M_s(f)+M_l(f)]}\right|,$$

where: M_s and M_l are the apparent masses of the source and the load, respectively.

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- Note that if a vibration test specification is used as the reference free acceleration $A_s(f)$ in these Equations, then the source and load apparent masses on the RHS must also be frequency averages or envelopes.

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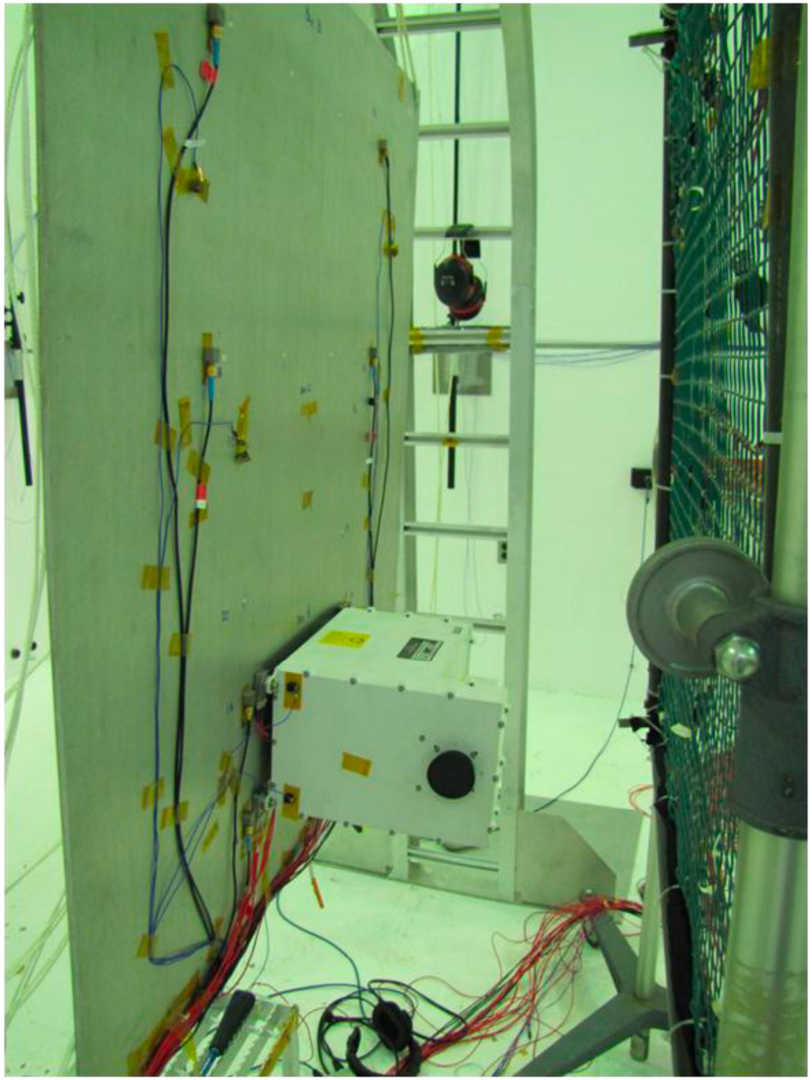
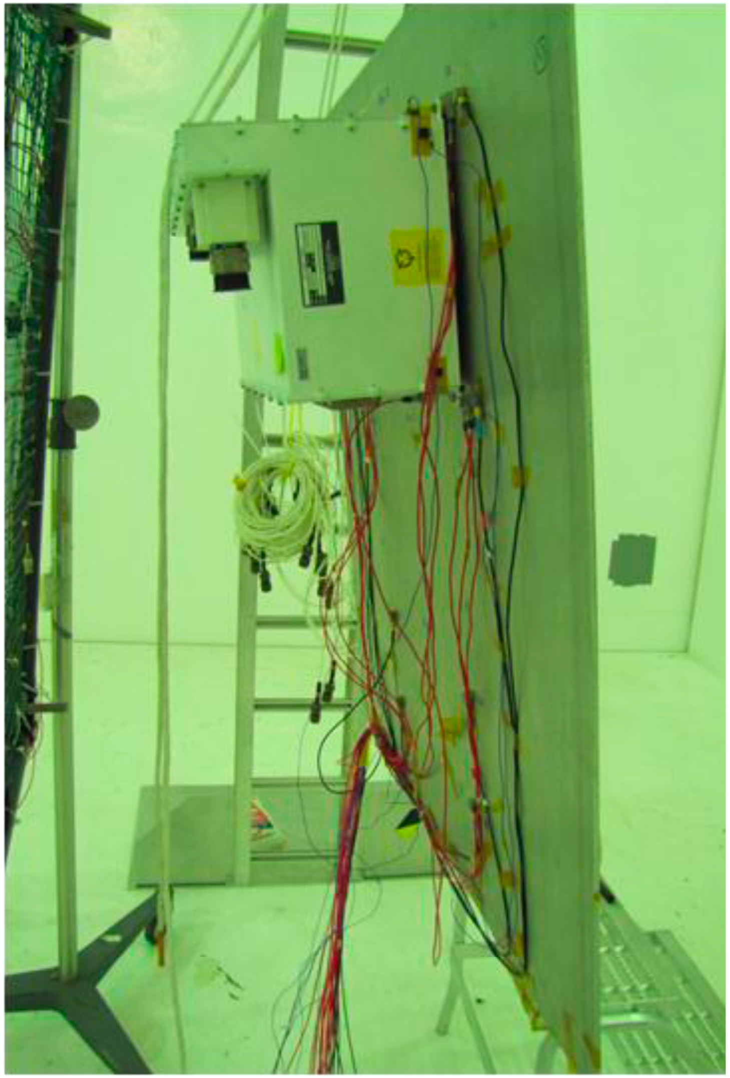
New Approaches in Force Limits

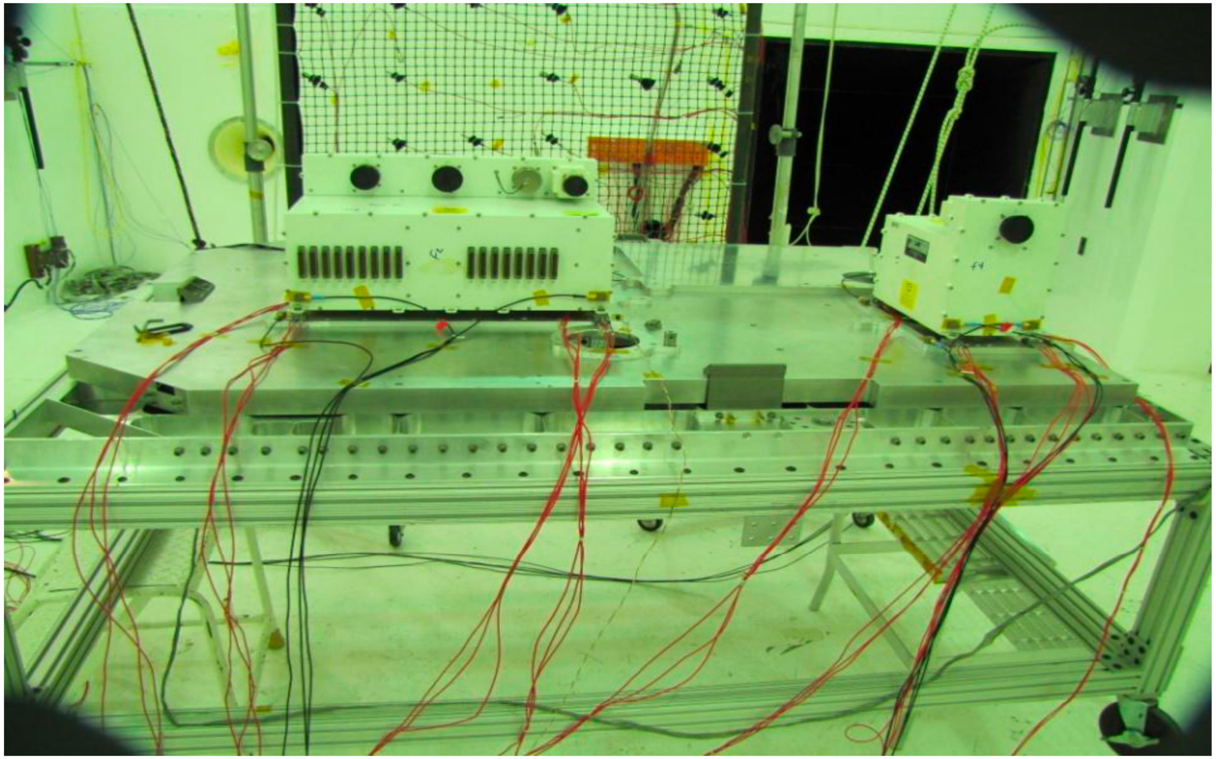
- Results from NESC Mass Loading Study are used to take a new look at force limiting approaches
  - *Acoustic tests performed using two boxes attached to panels are considered as flight-like data*
    - Acceleration responses at boxes interfaces are measured and enveloped to obtain input acceleration for each box
    - Boxes base shaked to inputs obtained from acoustic tests
    - Forces at boxes interfaces measured
  - *Semi-empirical approach was used to force limit the shaker testing of the boxes*
  - *The base shake test results are compared with the interface force responses measured from acoustic tests*

Acoustic Test: Al Panel and Boxes A&B





Acoustic Test: Rover Deck and Boxes A&B



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Box A and B Base Shake Test Setup

Box A

Box B

These boxes were base shaked to the input derived using Panel/Box interface responses from acoustic tests

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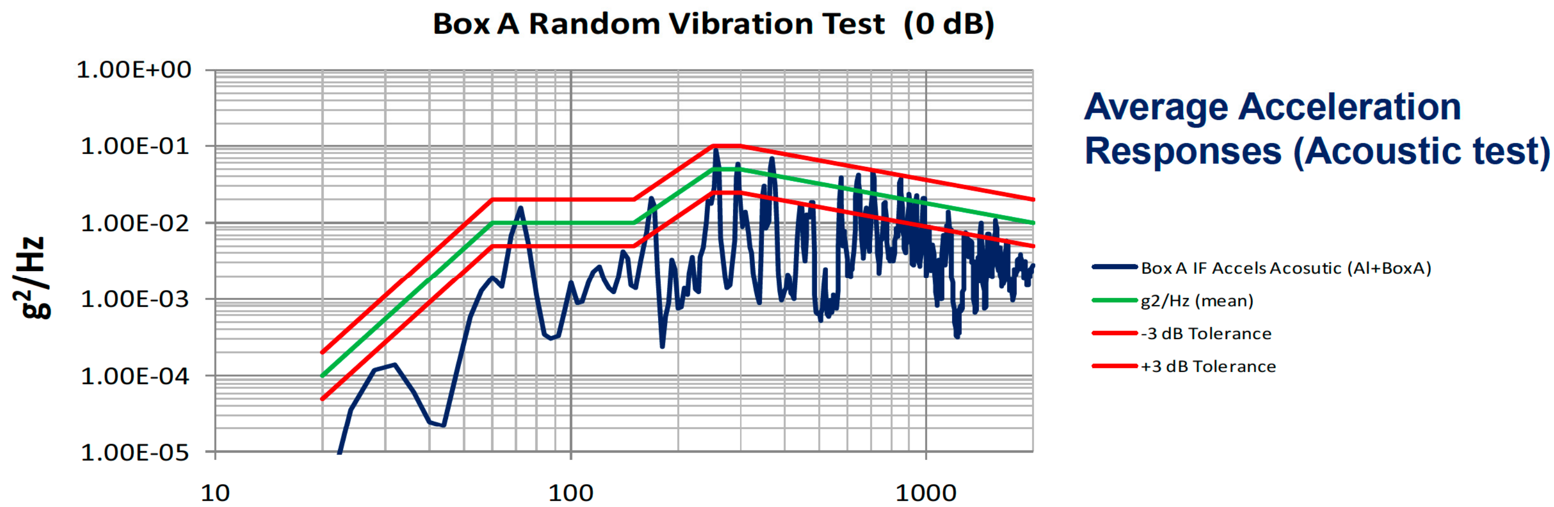
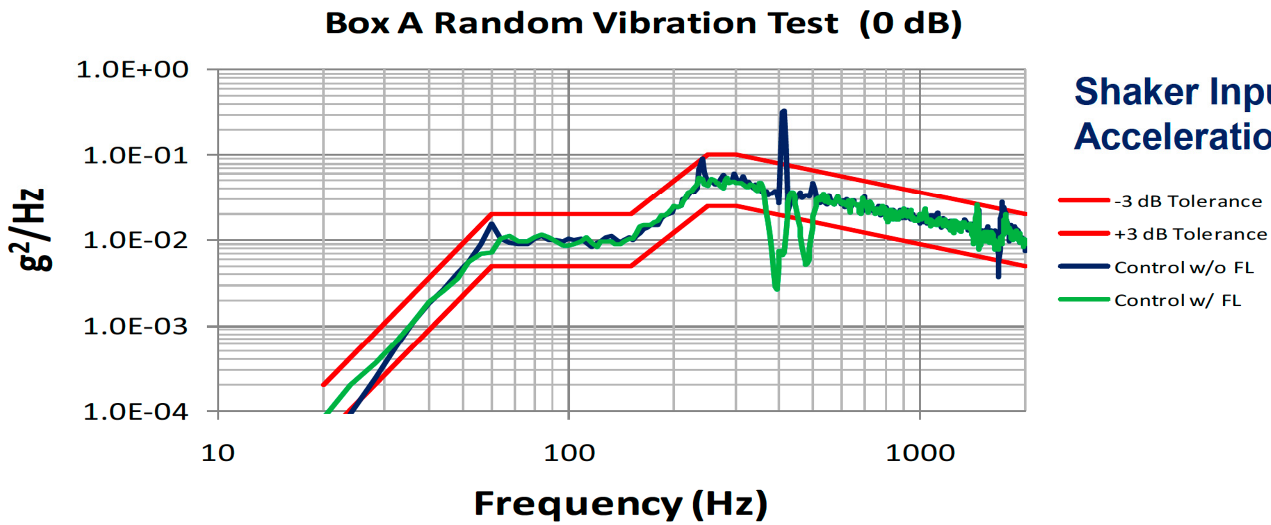
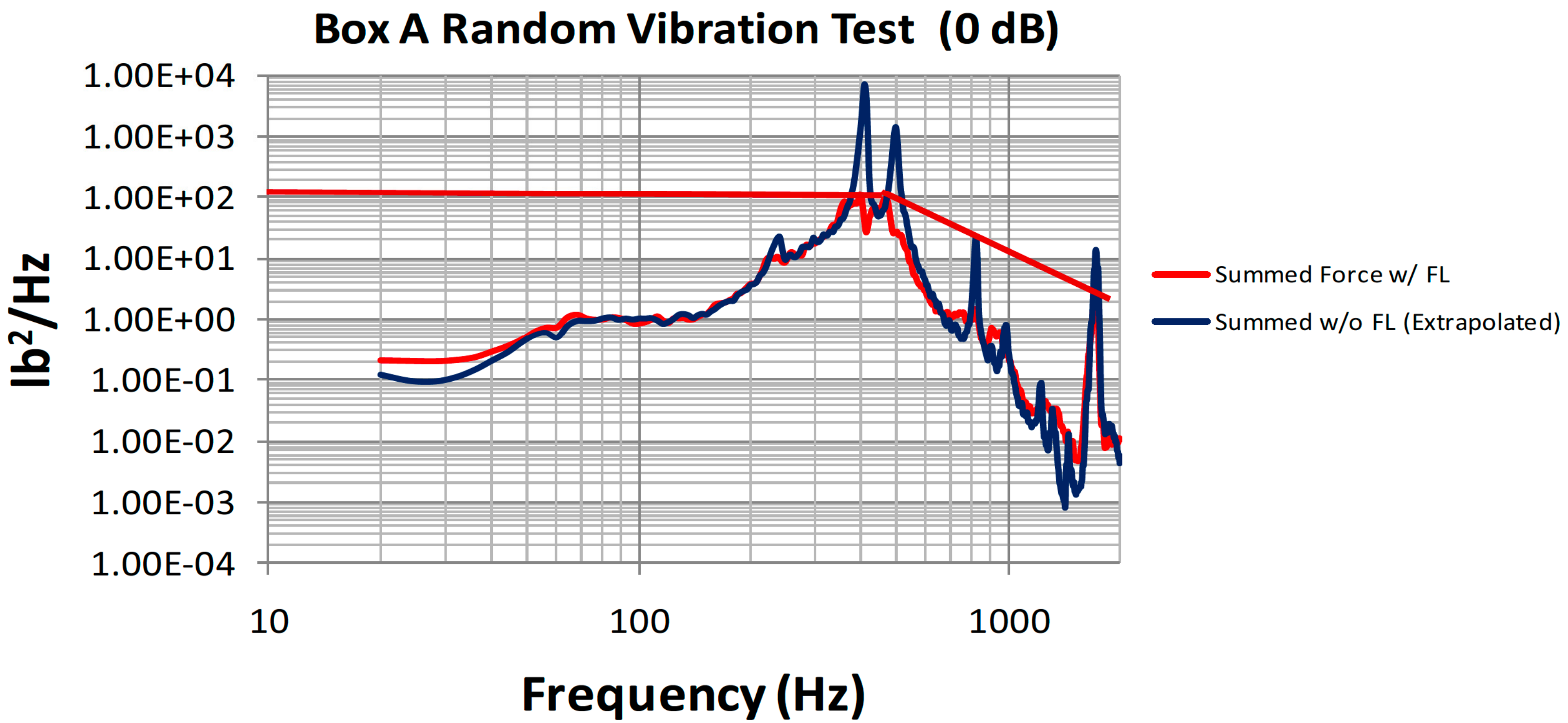
Input Acceleration Specification for Box A Shaker Test





The average Box A acceleration responses from acoustic test (AI +Box A) is used to derive the base shake input

Box A Shaker Test Force Limit: Semi-Empirical Method



Force Limit using semi-empirical method with C^2 of 4: Accounts for mismatch in impedances of Box's correlated interface responses

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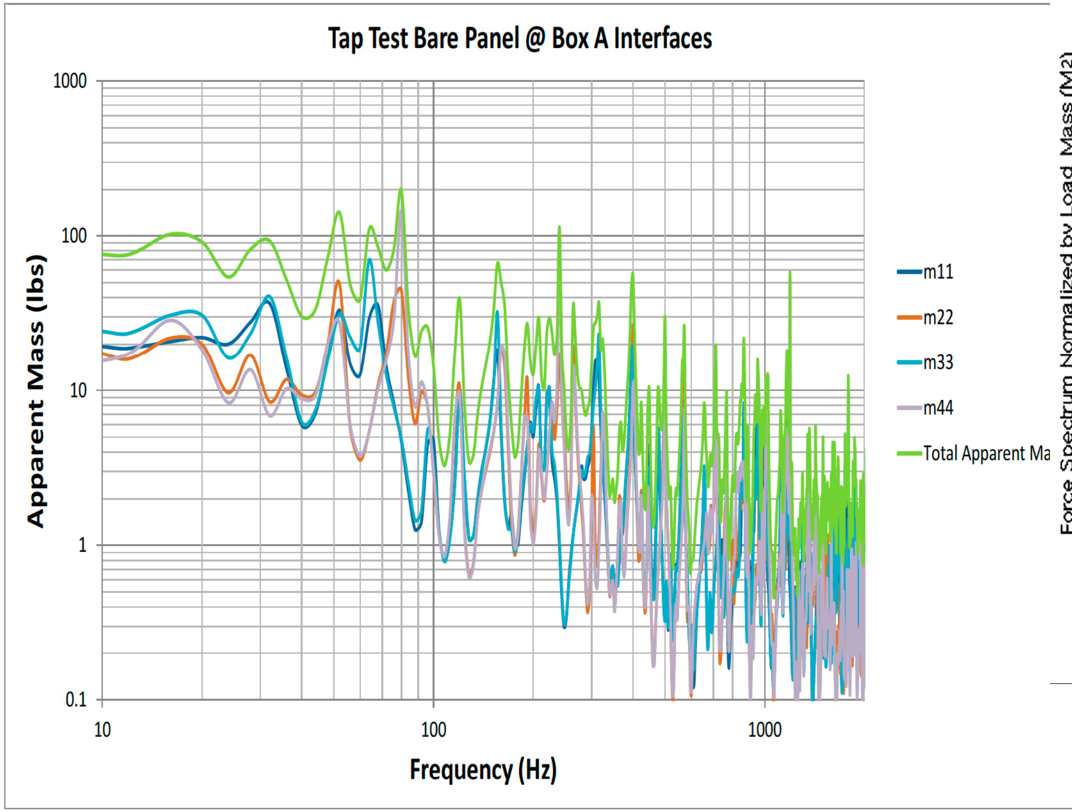
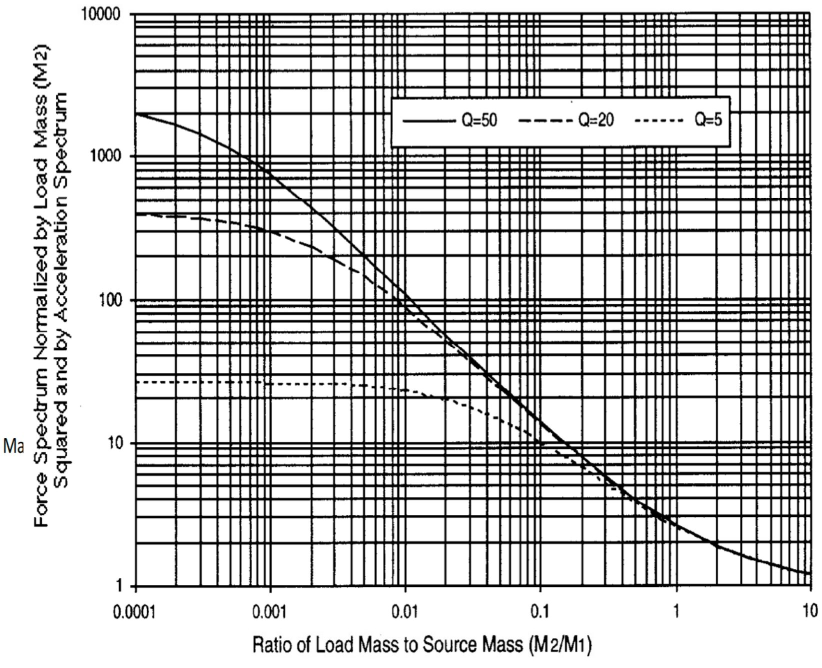
C^2 Estimate Using Apparent Mass (Box A) Source Structure: Al Panel





M_2/M_1 ~ 17.5/30 ~0.5 w/ C^2 of ~4

The apparent mass estimated by tapping Al panel w/o boxes @ four Box A interfaces
Box A Mass (M_2) ~17.5 lbs
The Source Mass (M_1) estimated to be ~ 30 lbs

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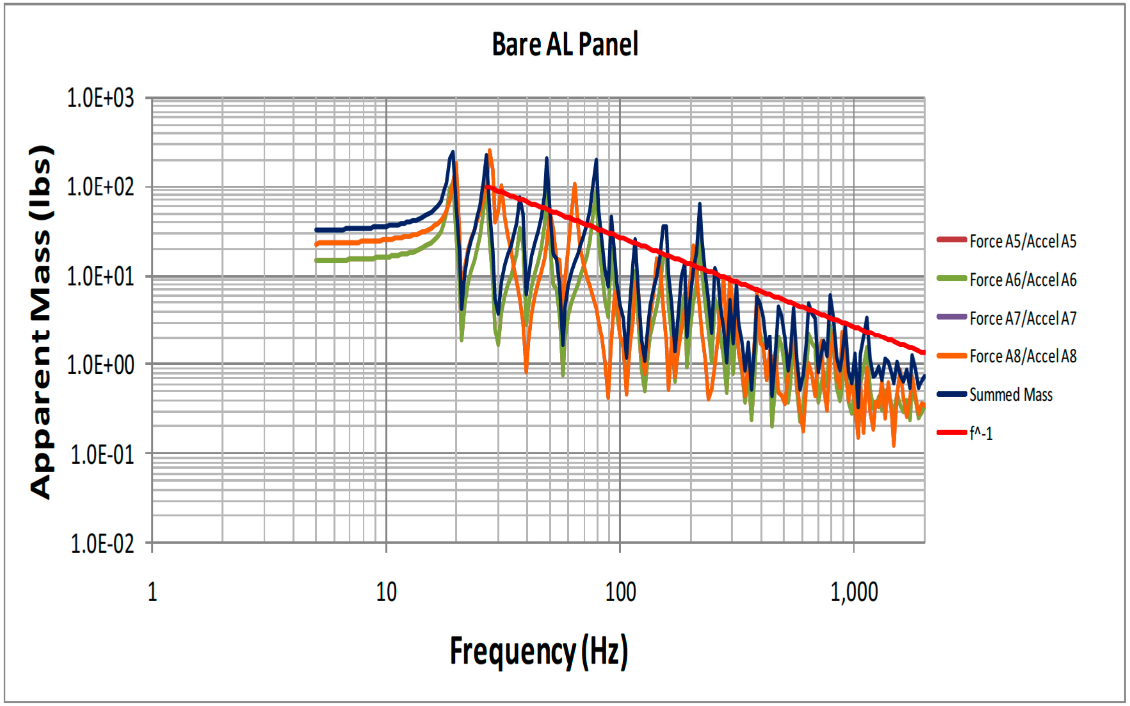
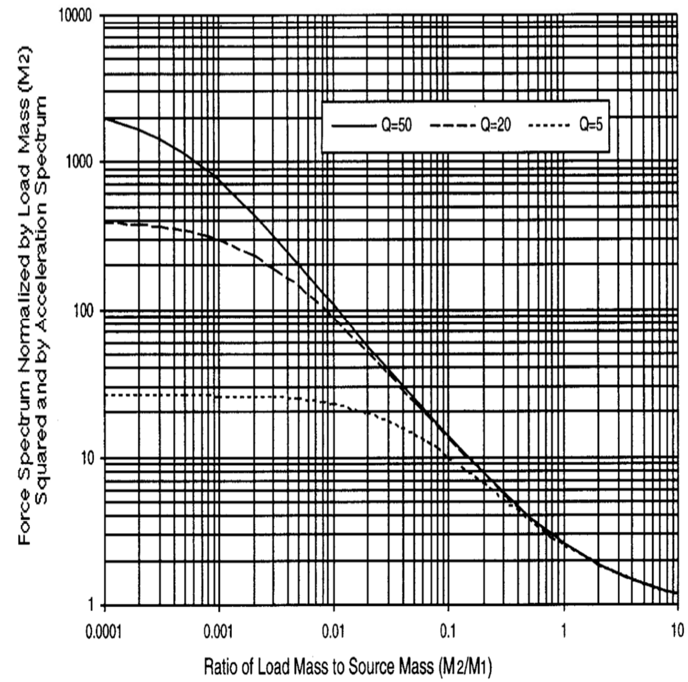
C^2 Estimate Using Apparent Mass (Box A) Source Structure: Al Panel





The apparent mass estimated using FEM of Al panel w/o boxes by applying white-noise force @ four Box A interfaces

Box Mass (M_2) ~17.5 lbs

The Source Mass (M_1) estimated to be ~ 10 lbs

M_2/M_1 ~ 17.5/10 ~2 w/ C^2 of ~2

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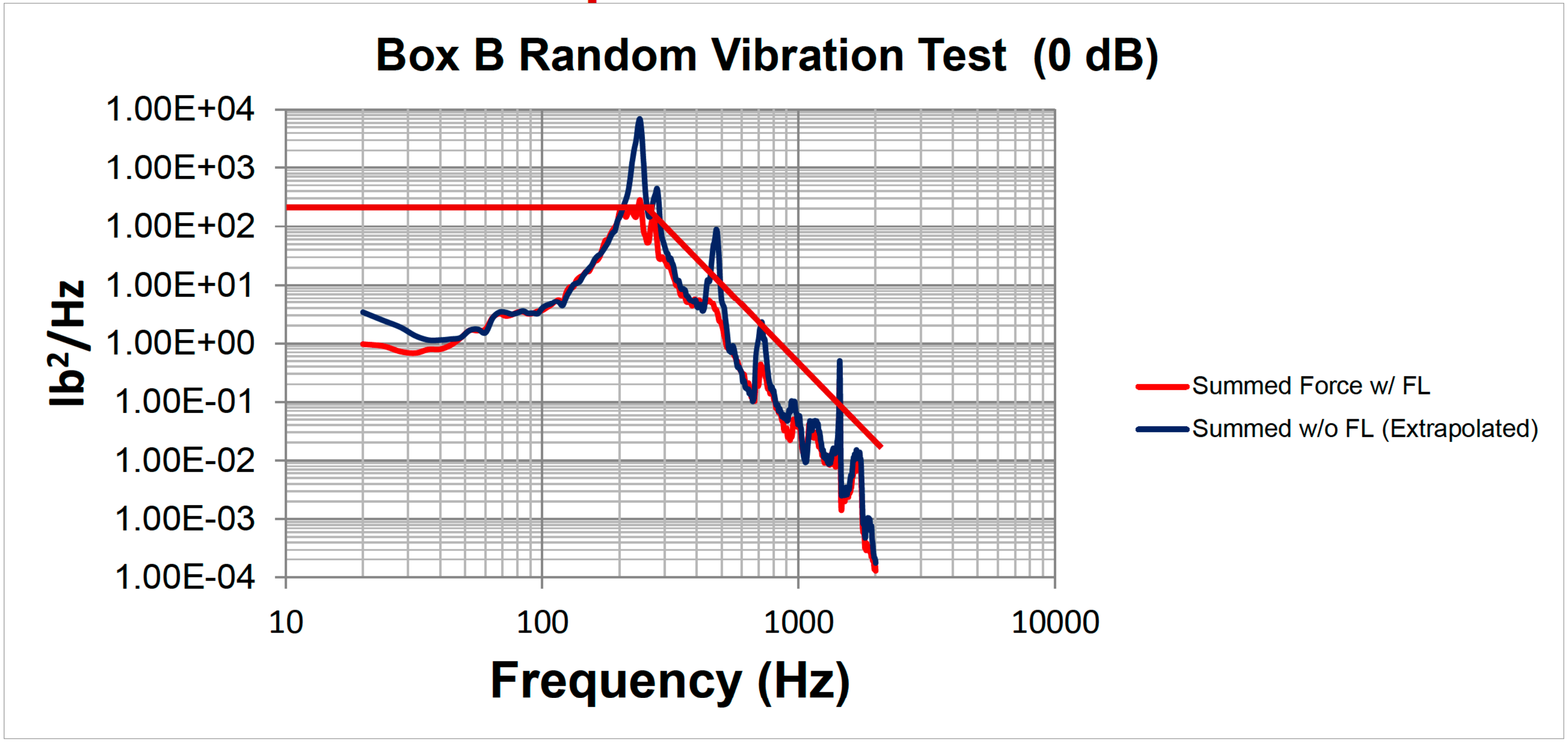
Box B Shaker Test Force Limit: Semi-Empirical Method



Force Limit using semi-empirical method with C^2 of 4: Accounts for mismatch in impedances of Box's correlated interface responses

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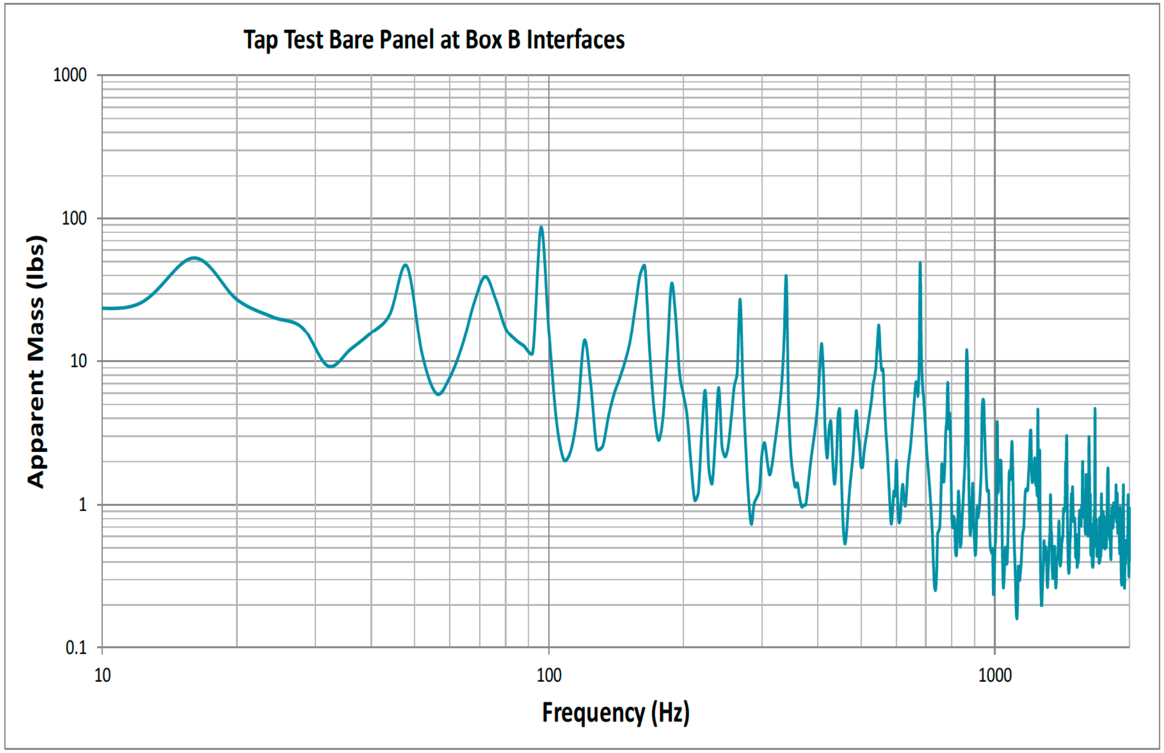
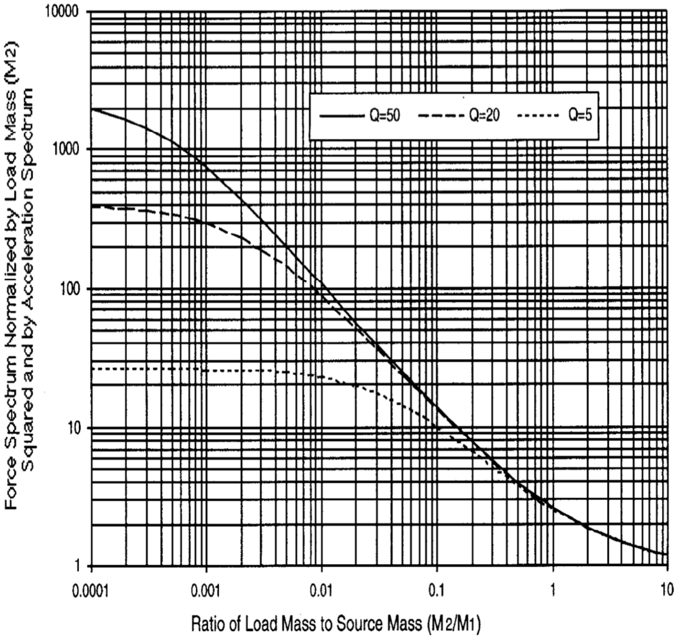
C^2 Estimate Using Apparent Mass (Box B) Source Structure: AL Panel





M_2/M_1 ~ 45/8 ~5 w/ C^2 of ~1.5

The apparent mass estimated by tapping Al panel w/o boxes @ four Box B interfaces
Box B Mass (M_2) ~45 lbs
The Source Mass (M_1) estimated to be ~ 8 lbs

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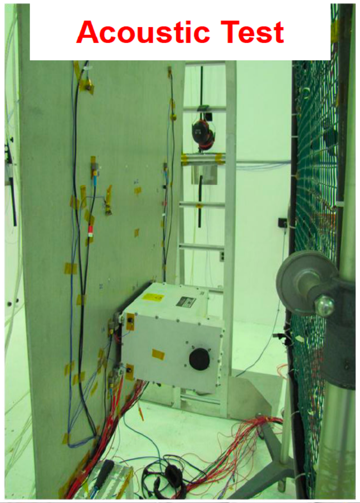
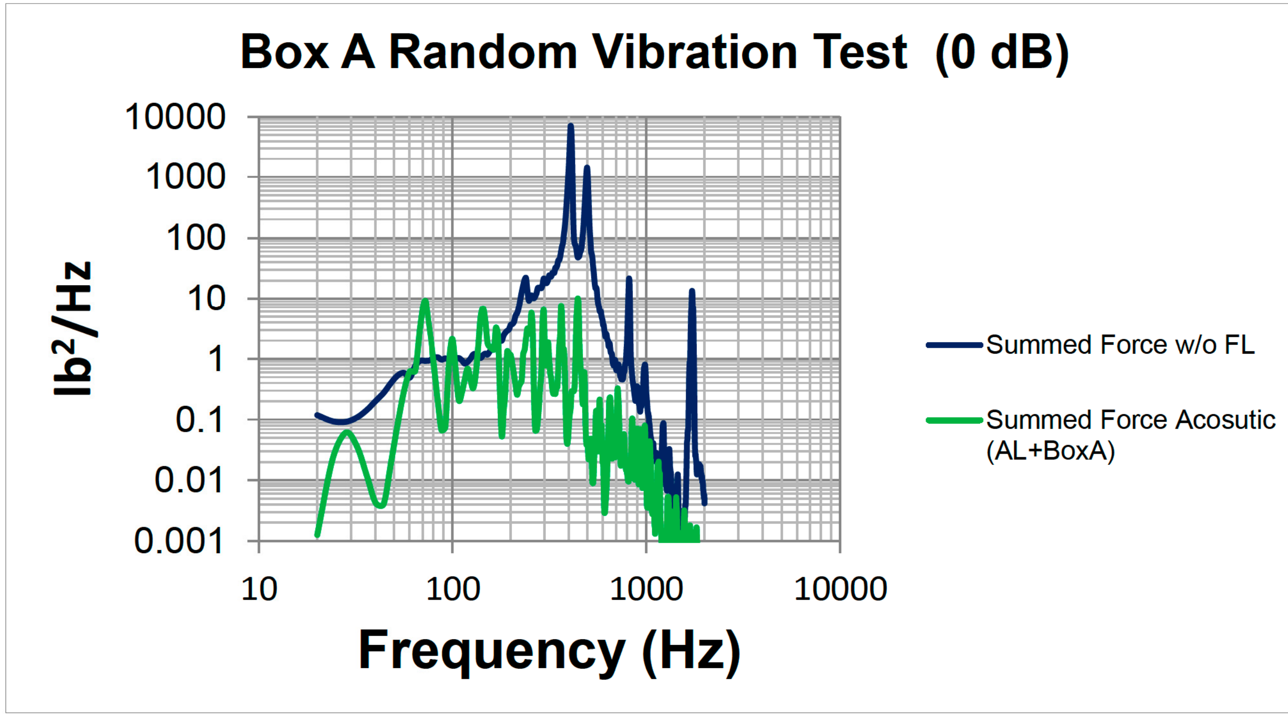
Box A: Force Response Comparisons





Summed forces measured at Box A interfaces:

- **Random vibe test on shaker head (Vertical axis)**
- **Acoustic test of Box A mounted on AL Panel (free-free B.C.)**

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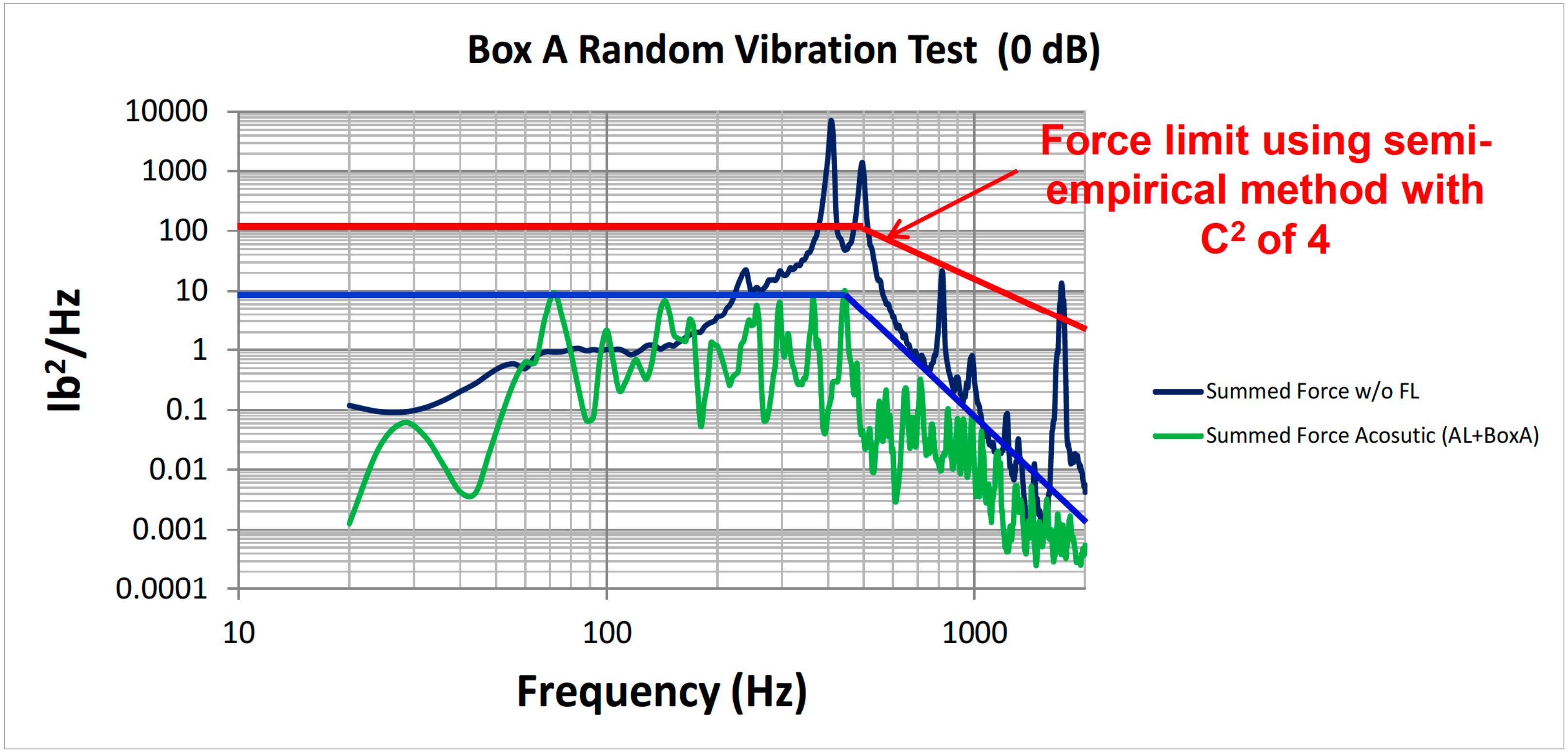
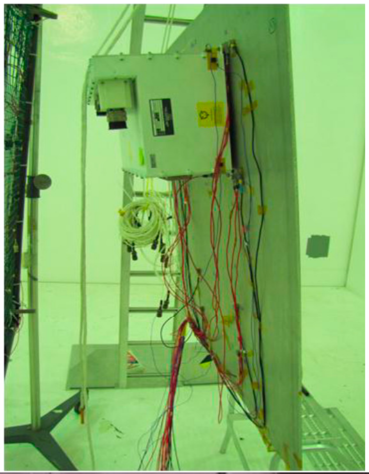
Semi-Empirical Force Limit vs. Acoustic Test (flight-like)

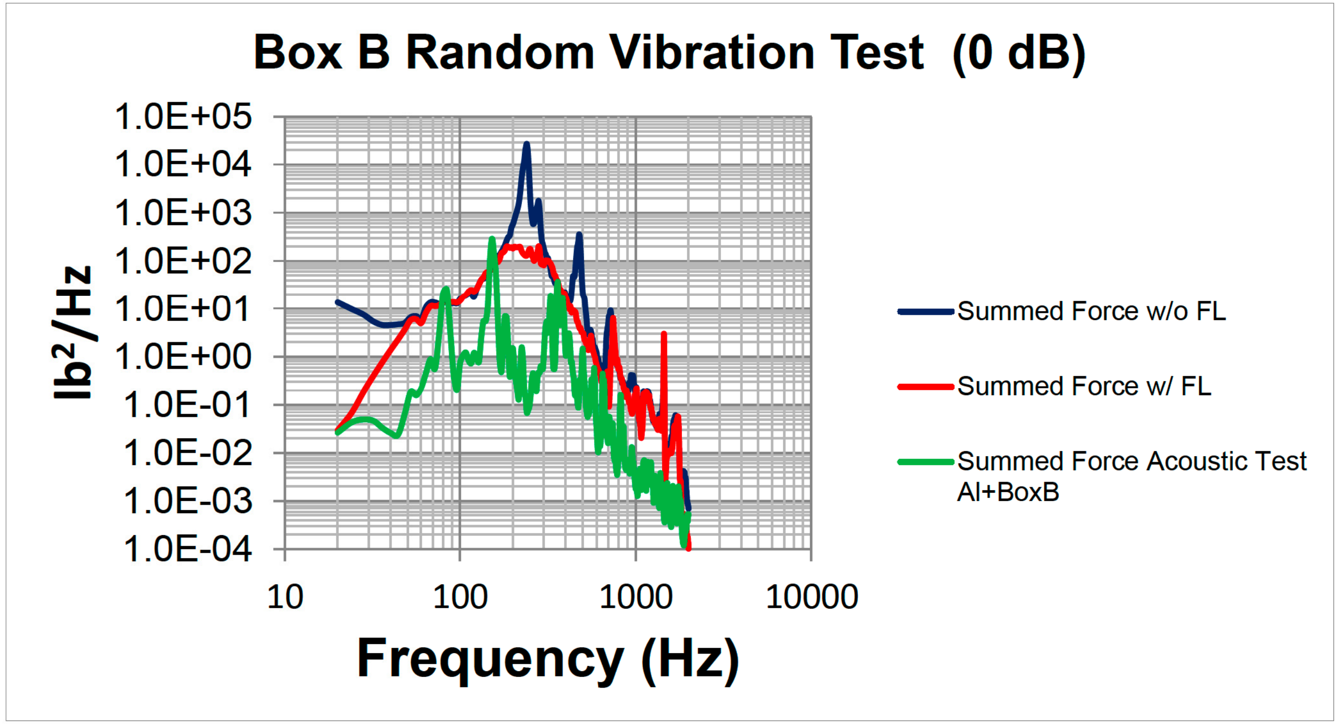


Force Limit using acoustic data (Flight-like): Accounts for mismatch in impedances of Box's un-correlated interface responses

Semi-Empirical Force Limit vs. Acoustic Test (flight-like) Box B and AL Panel

Acoustic Test





Force Limits: Acoustic Test vs. semi-empirical method with C^2 of 4.
@ f_0 more than 50 dB over test!

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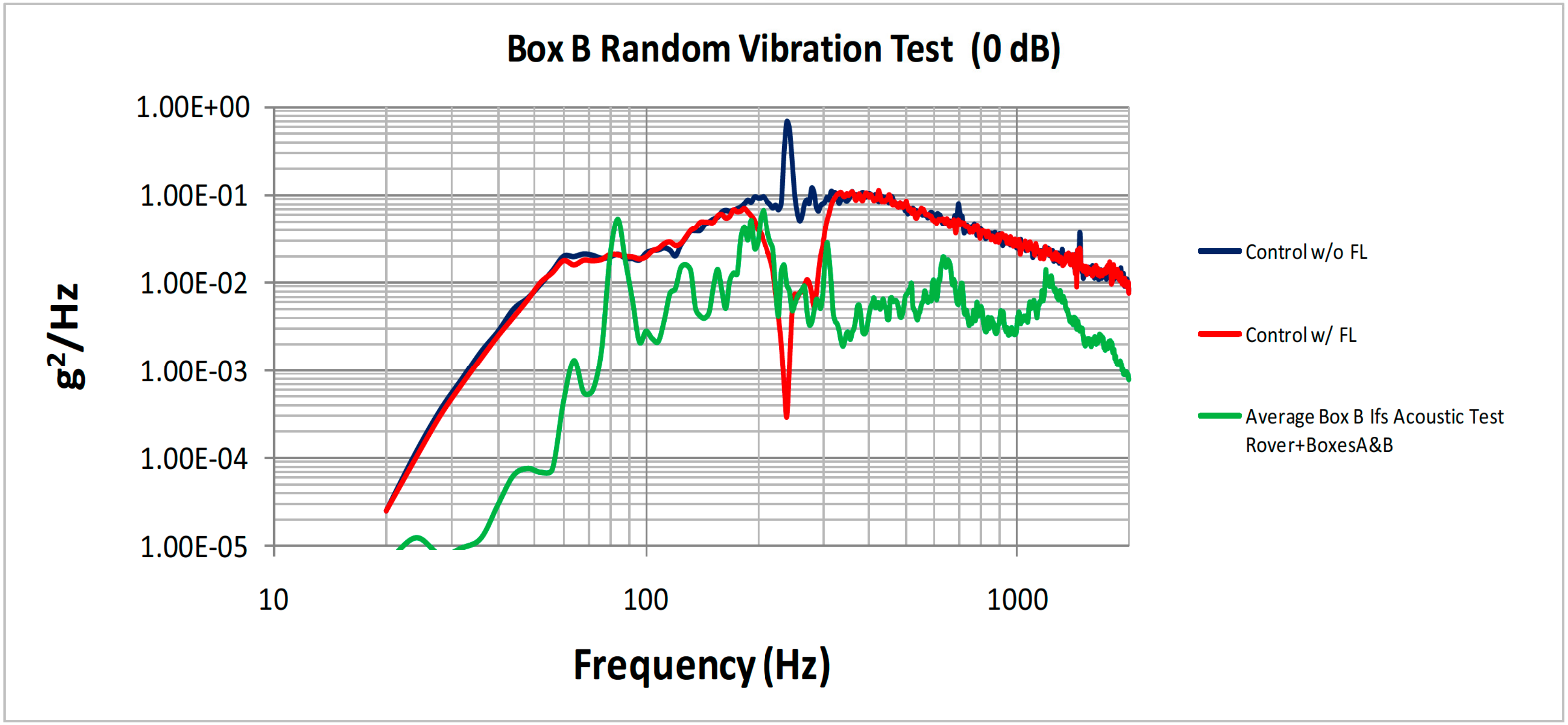
Input Acceleration Specification for Box B



Input accelerations: Random vibration of Box B w/ and w/o force limit and acoustic test of Box B attached to Rover deck

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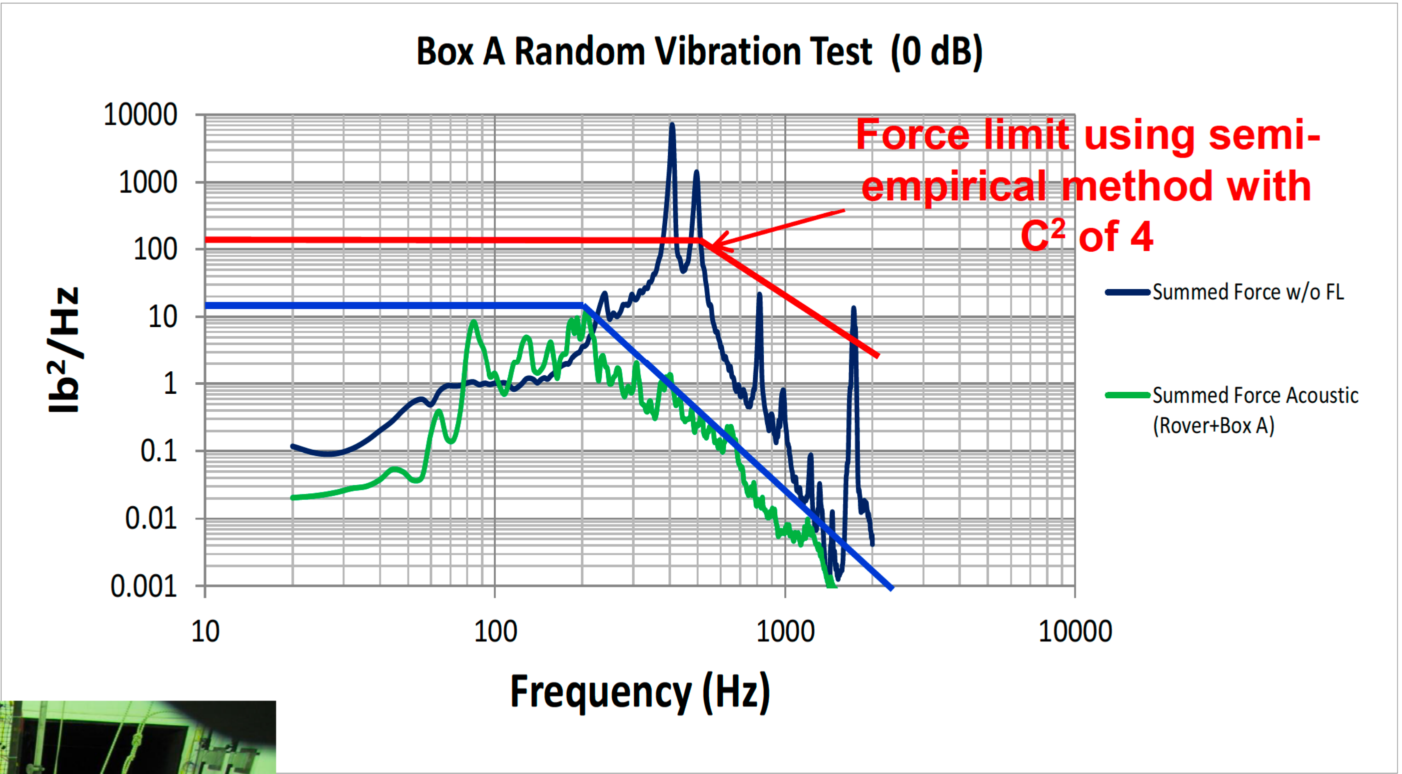
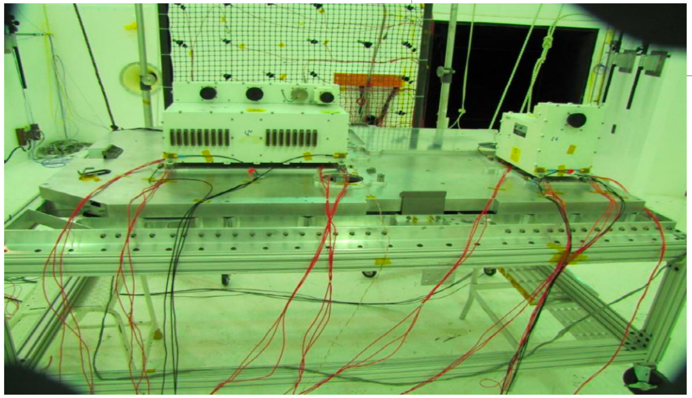
Semi-Empirical Force Limit vs. Acoustic Test (flight-like) Box A and Rover Deck (Fixed-fixed BC)

Comparison of the summed forces measured at Box A interfaces: random vibe test and acoustic test of Box A mounted on Rover Deck



Acoustic Test



Shaker Test

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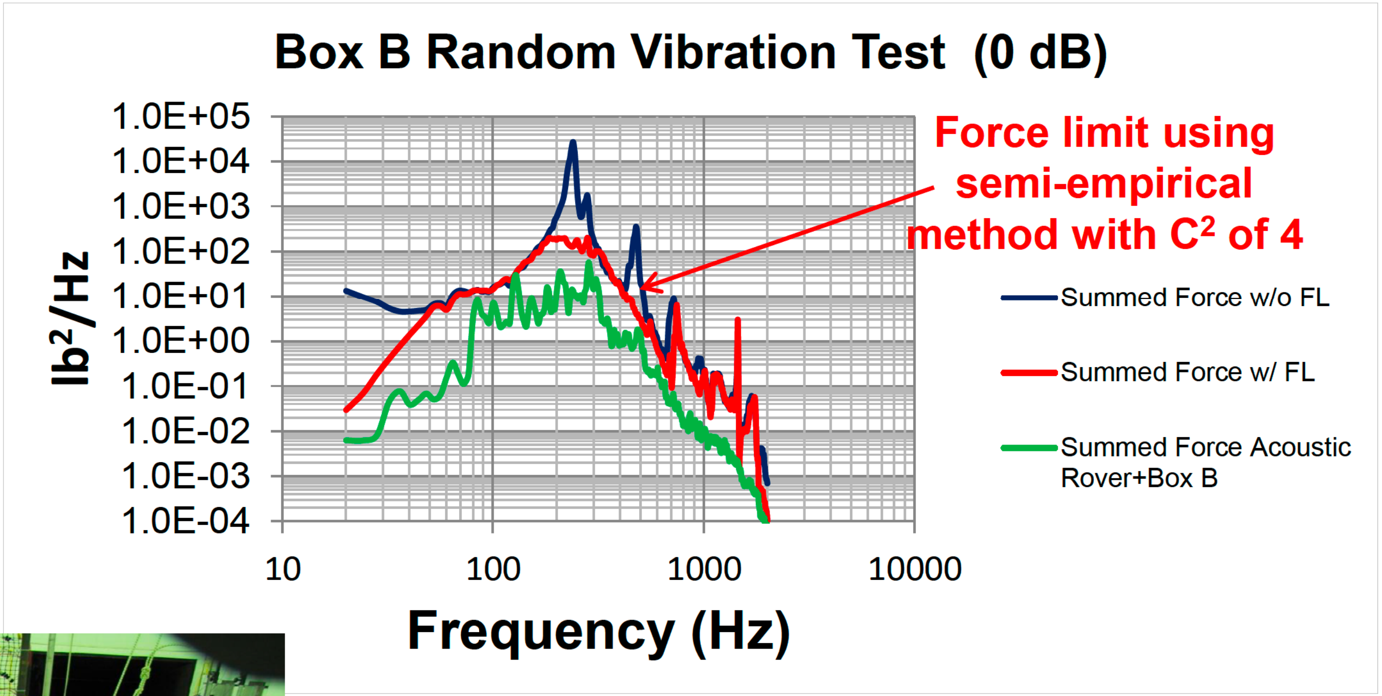
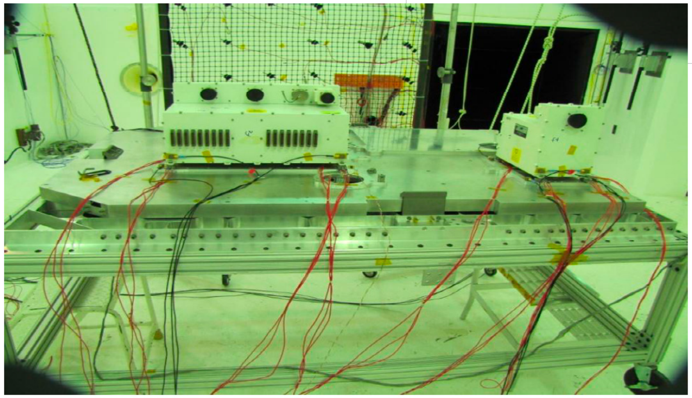
Semi-Empirical Force Limit vs. Acoustic Test (flight-like) Box B and Rover Deck (Fixed-fixed BC)

Comparison of the summed forces measured at Box B interfaces: random vibe test and acoustic test of Box B mounted on Rover Deck



Acoustic Test



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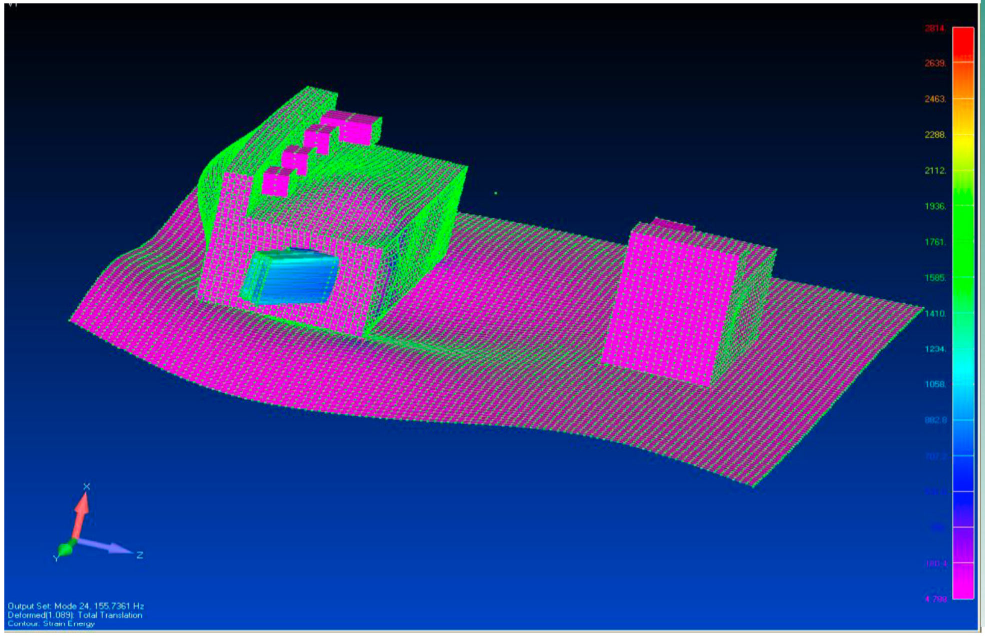
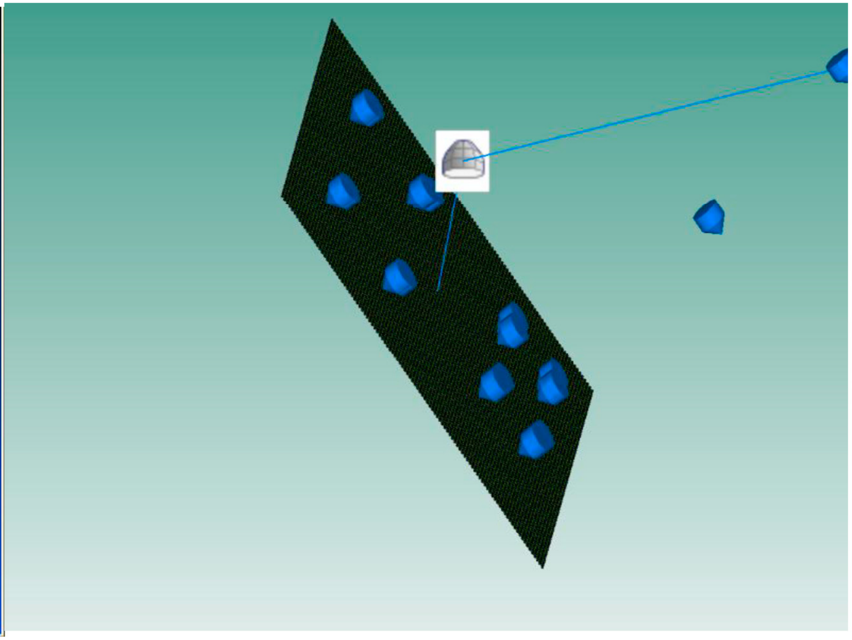
Force Limiting Specification Using Boundary Element Method (BEM)

FEM/BEM: AL +Boxes A&B



FEM Mesh



BEM Mesh

The FEM model of the Al panel loaded with boxes A and B was used to compute the Eigen frequencies and to generate a BEM mesh (fluid mesh) as shown. The vibro-acoustic analysis was performed over the entire structural response frequency range, i.e. up to 2000 Hz. The force responses in three orthogonal axes of the panel at box interfaces were obtained and are used to derive the force limiting specification.

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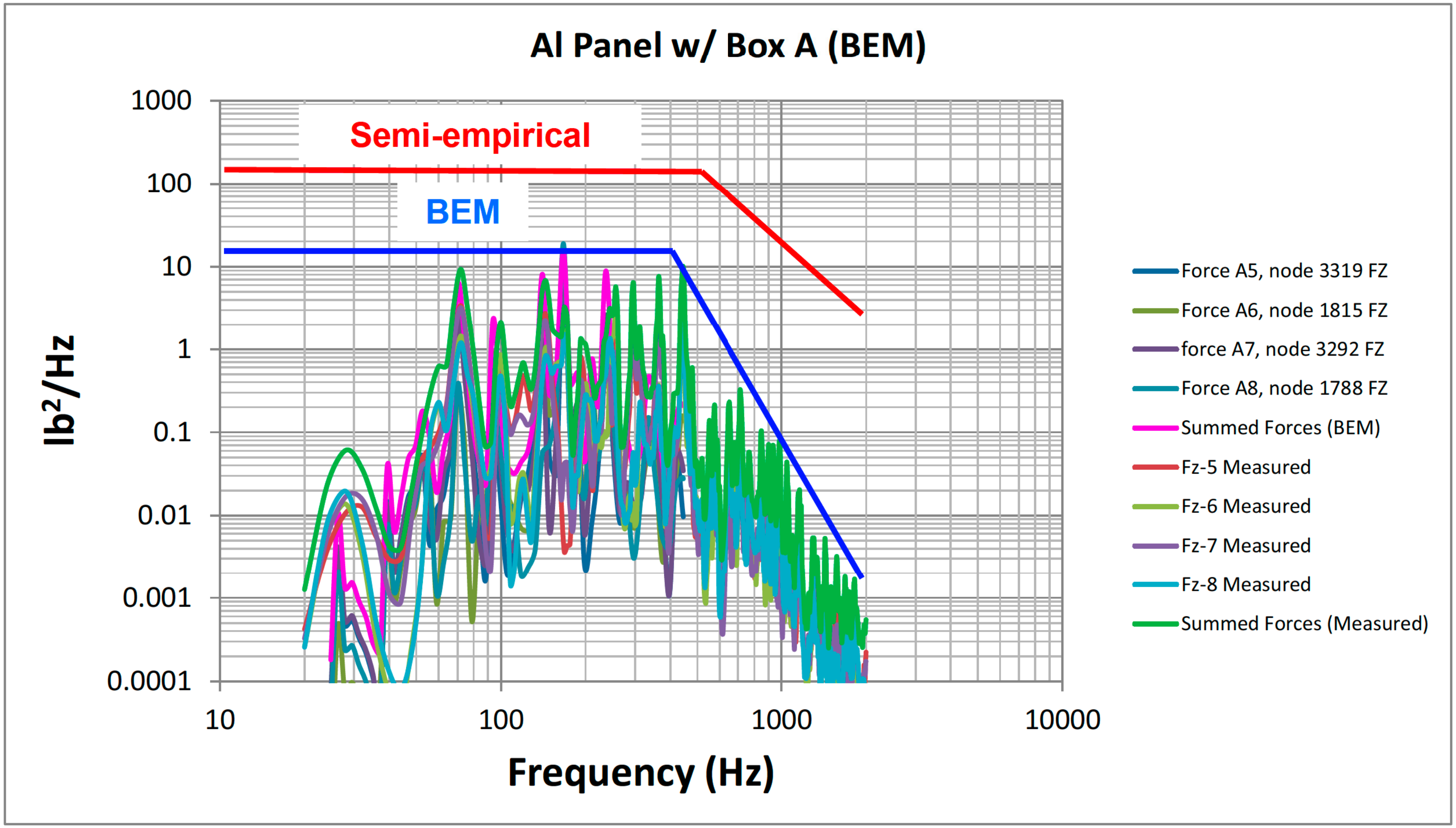
BEM vs. Semi-Empirical Force Limit
Al Panel + Box A



Semi-empirical: ~122 lb^2/Hz vs BEM ~15 lb^2/Hz

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Summary and Recommendations

- Existing force limiting methods outlined in NASA-HDBK-7004 are used to notch the input acceleration of the test hardware
  - *Accounts for mismatch in impedances between testing and flight configurations,*
  - *Assumes the hardware interface responses are correlated*
- Recent detailed acoustic tests conducted using two electronics boxes and panels used to re-assess the existing force limiting approaches
  - *The data from these tests treated as flight-like cases,*
  - *The acceleration responses at boxes' interfaces measured in the acoustic tests used to derive the box input specifications*
  - *Boxes base shaked using the input from acoustic tests*
  - *Boxes interface force responses measured during the base shake and acoustic tests provide a clear evidence of over testing of the components*
- Current force limiting techniques account for correlated interface responses
  - *Most commonly used method is the semi-empirical method with C^2 in general obtained based on experience and engineering judgments (often FEM or TDOF system are used to obtain C^2)*
- The knowledge of the component un-correlated interface responses provide more accurate force spectrum that can be used to limit the input accelerations
  - *These can be obtained using*
    - Flight Data
    - FEM with white-noise applied at each interface,
    - BEM to recover forces at the interfaces
    - GMA, a classical RV analysis approach
- The new approach is being further investigated

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Thank you