FORCE LIMITING PRACTICES REVISITED

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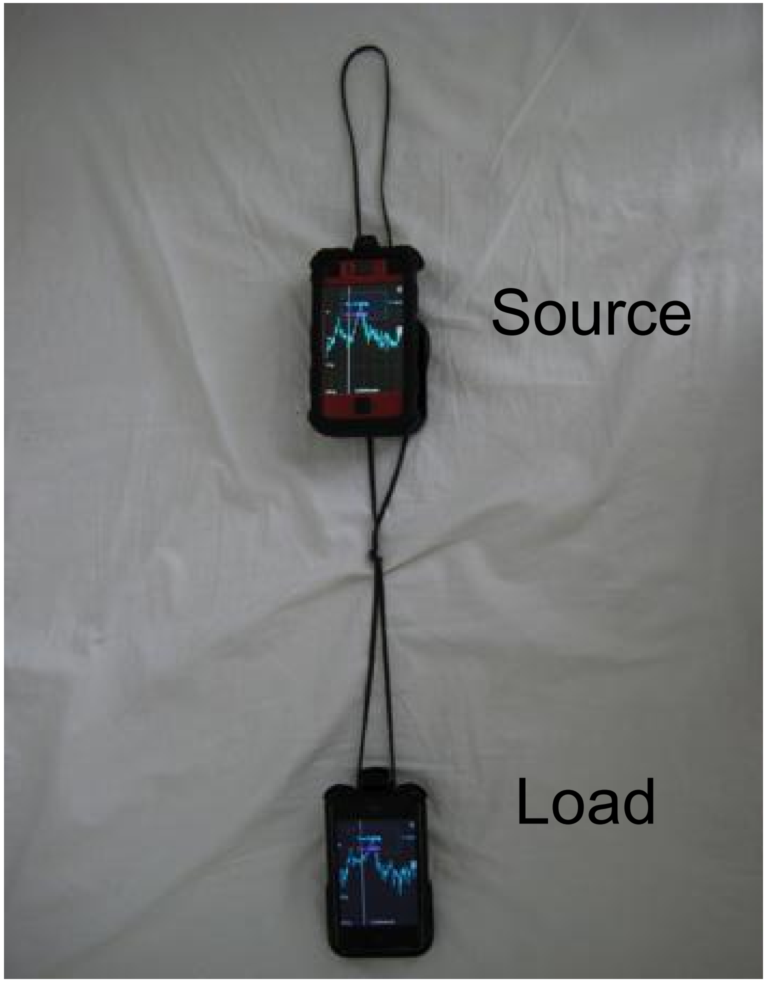
Outline

- Demo of TDOF System
- Review of Semi-empirical Method
- Review of TDOF Method
- Sweitzer’s Method
- How to Determine Apparent Mass
- Infinite System Apparent Mass
- Calculations from Flight C^2 Data and TDOF Model
- Tap Test Measurements
- FEM and BEM Analyses
- Status of Handbooks that Discuss Force Limiting
- Guidelines and Recommendations
- Force Limiting Background References – Backup

DEMO of TWO-DEGREE-OF-FREEDOM (TDOF) SYSTEM

- TDOF System Description
  - *Flight mounting structure, the **source**, e.g., a launch vehicle*
  - *Vibration test item, the **load**, e.g., a spacecraft*
- Load Vibration Test
  - *Wideband (enveloped) input*
  - *Large responses at fixed-base resonance frequency, f_o*
- Flight Mounting Configuration
  - *Two resonances: even mode below f_o, odd mode above f_o*
  - ***At f_o, vibration absorber effect reduces (notches) the input.***

Two iPhones connected with rubber bands

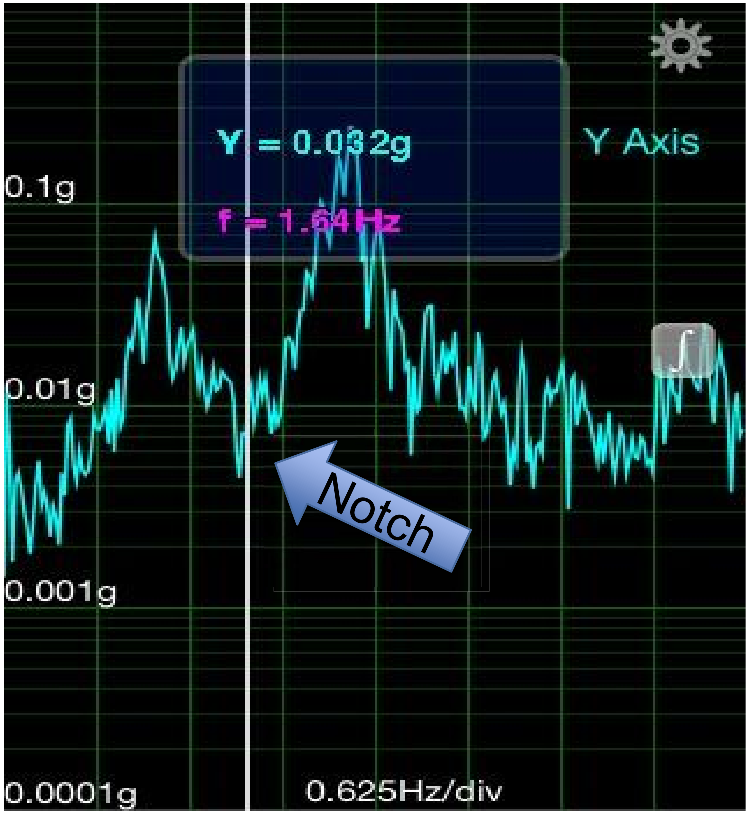


LOAD VIBRATION TEST

(lower iPhone by itself)

- Input is wideband, i.e., the result of enveloping or averaging data or analyses.
- *Large response at 1.64 Hz, which is the fixed-base resonance frequency (f_o) of the load, i.e., it's resonance frequency on a shaker.*

FLIGHT MOUNTING CONFIGURATION
(two coupled iPhones)



Source (upper iPhone)

Load (lower iPhone)

Object of Force Limiting: **Put back the notch!**

SEMI-EMPIRICAL METHOD (NASA-HDBK-7004B)

- For sinusoidal excitation, the force limit (F) is given by:

$$F(f) = \boldsymbol{C}\ M_o\, A(f), \qquad f < f_b$$

$$F(f) = \boldsymbol{C}\ M_o\, (f_b/f)^n A(f), \qquad f \geq f_b$$

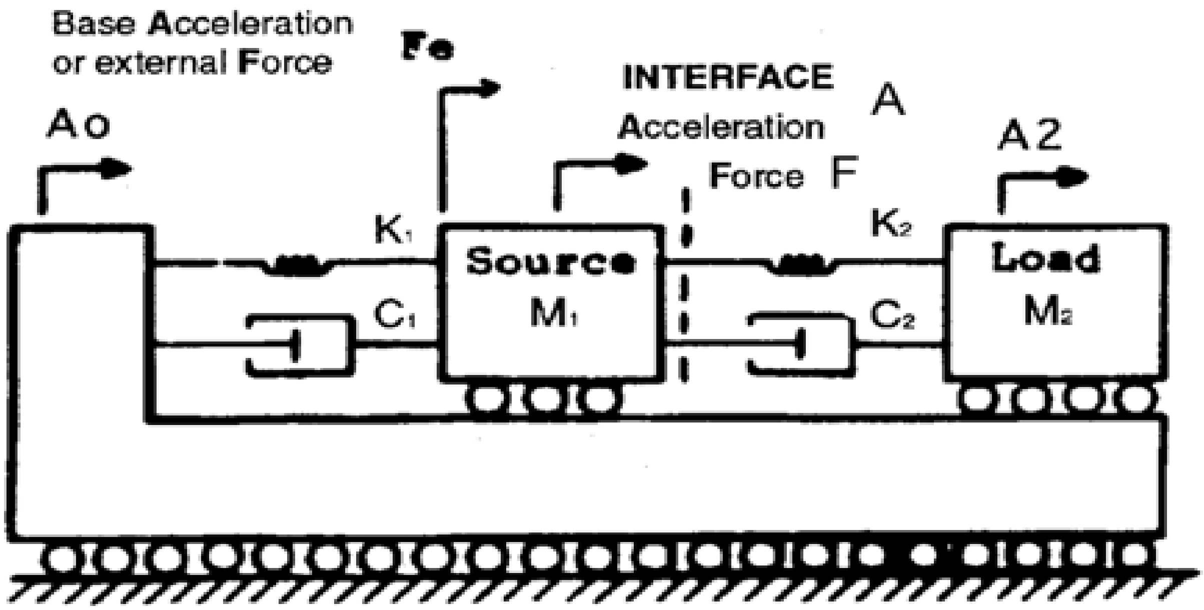
*where: **C** is a dimensionless constant, M_o is the total mass of the test item, f_b is a break frequency (often the test item first resonance frequency) and n is positive constant (often unity).*

(For random excitation, these quantities are squared)

- **C** replaces the resonance amplification factor $Q = 1/ 2\zeta$
- **C** depends on the ratio of the apparent mass of the test item to that of the **flight mounting structure.** (TDOF Method)
- **C should not be selected without adequate justification.**

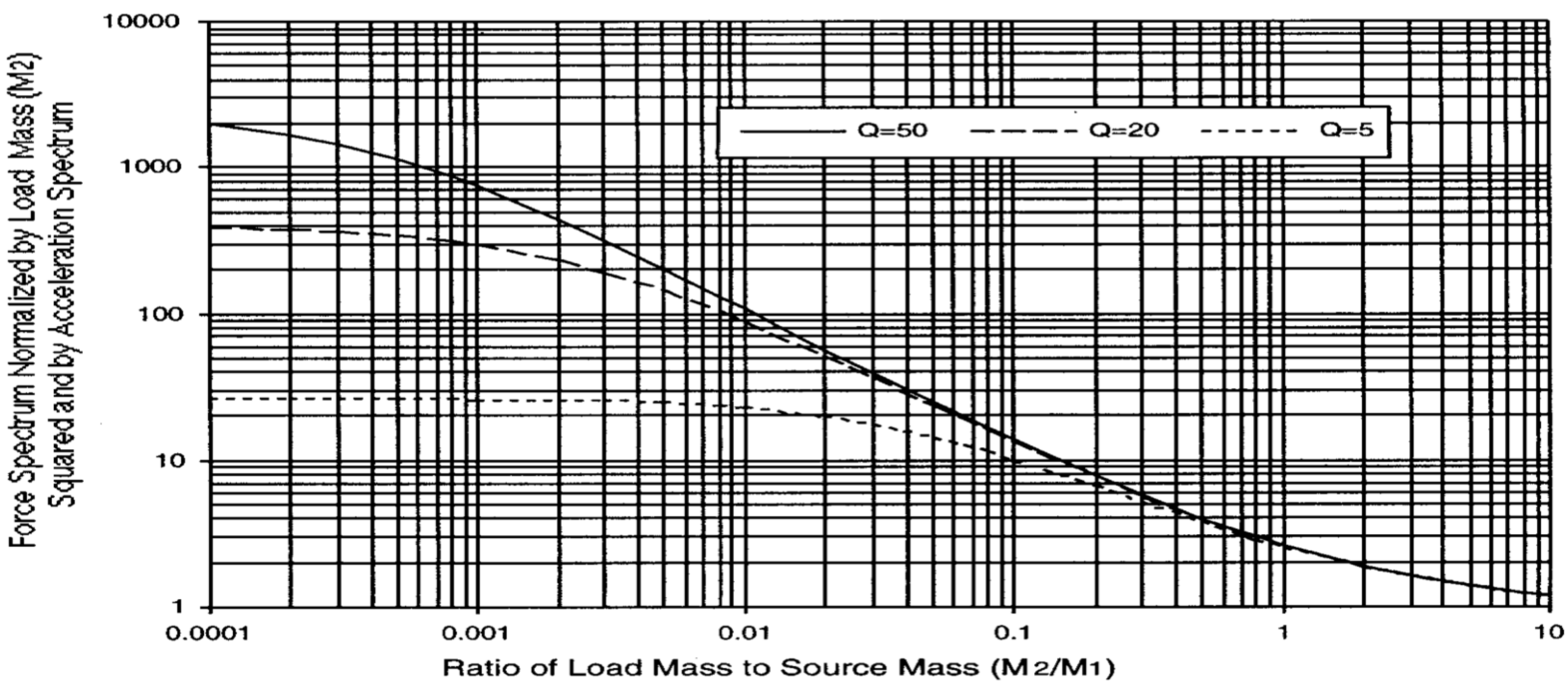
TWO-DEGREE-OF-FREEDOM METHOD
(NASA-HDBK-7004B)

- Simple TDOF model of vibration mode of flight mounting structure (source) coupled to mode of test item (load)
- Calculation of ratio of interface force (F) to acceleration (A), which is maximum when the uncoupled frequencies are equal



TWO-DEGREE-OF-FREEDOM METHOD (Cont.)

- Everyone who uses the semi-empirical method should be familiar with, **and refer to**, this graph, as its ordinate is $\mathbf{C^2}$
- The graph abscissa is the ratio of the apparent mass of test item to that of **the flight mounting structure,** evaluated at the dominant resonance frequency of the test item on the shaker.



SWEITZER'S METHOD

- Sweitzer's method (NASA-HNBK-7005, Section 6.5.3) of reducing overtesting, resulting from the very high structural impedance of shakers, is to replace the amplification factor (Q) measured in the test by its square root, i.e., $C= Q^{1/2}$, e.g., 20 dB peak becomes 10 dB notch and 10 dB peak.
- The advantage of Sweitzer's method is that it can be implemented without force gages, if Q can be accurately measured with accelerometers, which may be problematic.
- The disadvantage is that there is no quantitative rationale to support this choice of C, however it may provide a useful guideline for the choice of C in the semi-empirical method.
- In this regard, it may be seen from the TDOF that $C= Q^{1/2}$ corresponds to an apparent mass ratio of $M_2/M_1 = 0.3$ for Q =5, to $M_2/M_1 = 0.06$ for Q =20, and to $M_2/M_1 = 0.02$ for Q =50

HOW TO DETERMINE APPARENT MASS

- Apparent mass is the frequency response function (FRF), defined as the ratio of force to acceleration.
- Ratio of test item to flight mounting structure apparent masses is key parameter for calculating force limits. (see TDOF Method)
- Test item apparent mass may be calculated from a FEM, and verified in the preliminary vibration test with force transducers.
- Flight mounting structure apparent mass may be determined with one of the following methods, which are discussed herein:
  - *Infinite system model of flight mounting structure*
  - *Scale from flight or ground test measurements of* C^2 *and TDOF model*
  - *Tap tests of the flight mounting structure at the test item interface*
  - *FEM of flight mounting structure driven at the test item interface*

    (The test item is absent for these latter two methods.)

INFINITE SYSTEM APPARENT MASS

- Asymptotic apparent masses derived from:
  1) frequency averaging,
  2) critical damping, and
  3) infinite system.
- Approximate apparent mass as $1/f^n$ above first resonance. (n=1 for infinite plate bending and rod extension and n=0.5 for beam bending)
- Delta II L/V example:

  M_o ~ 500 kip and $f_{long.}$ ~ 6 Hz, so for 10 kip S/C with f_o= 30 Hz, M_1/M_2 ~ 0.1 and C ~ 4 (TDOF)

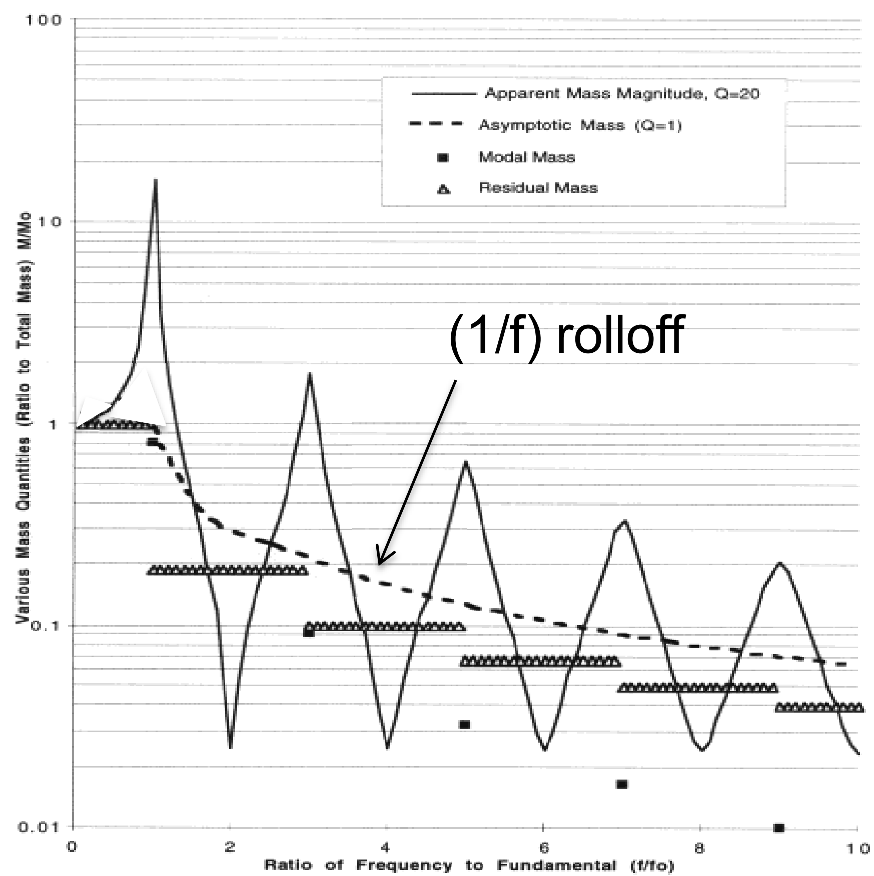


FIGURE 4. Apparent Mass, Asymptotic Mass, Modal Mass, and Residual Mass of Longitudinally Vibrating Rod, Excited at One End and Free at Other End

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CALCULATIONS USING FLIGHT C^2 DATA in NASA-HNBK-7004

- GLAST SPACECRAFT (9631 lb)
  - *5099 lb axial force; 0.06 G @32 Hz*
  - *Semi-empirical method:*

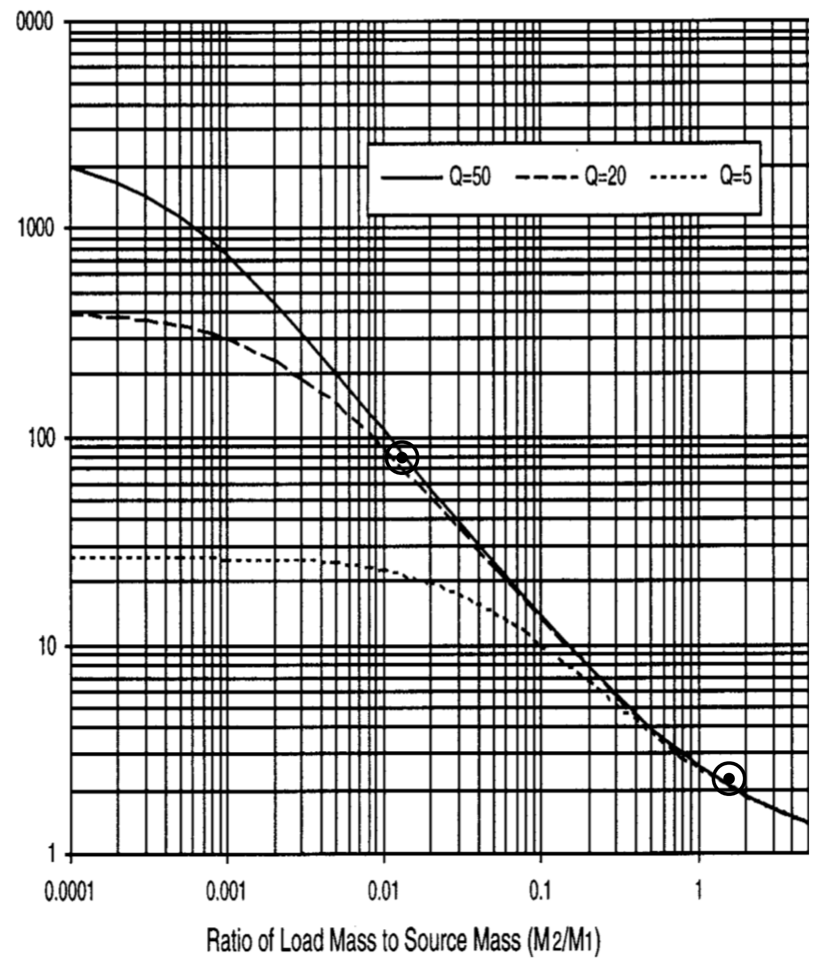
  C = [(5099 lb/9631 lb)/0.06 g] = 9,

  so by TDOF method, $M_2/M_1 \approx 0.02$

  (This does not compare well with infinite system Delta II calculation.)

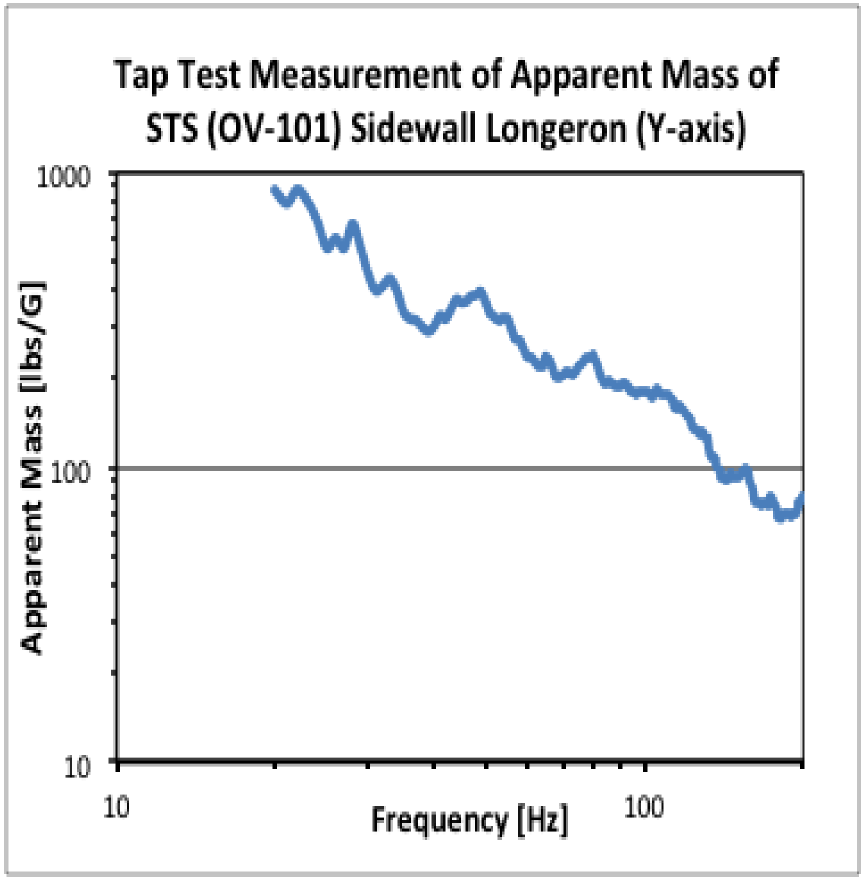
- SVF(230 lb) HITCHHIKER
  - *Semi-empirical method (ratio of flight force to acceleration @130 Hz divided by total mass): C = 1.4, so by TDOF method, $M_2/M_1 \approx 2.0$*

  (See tap test data in following chart)



TAP TEST MEASUREMENT OF APPARENT MASS OF FLIGHT MOUNTING STRUCTURE: Shuttle Longeron

- For uniform motion of multiple attachments (as on shaker)
  - *Exact formulation requires summing all elements of apparent mass matrix, obtained by inverting measured accelerance matrix*
  - *Approximation is to use inverse of measured single point accelerance (correlated), or to multiply this by # of attachments (uncorrelated)*
- Sidewall-mounted SVF Hitchhiker
  - *Tap test-single point apparent mass measured on STS sidewall longeron: approx. 100 lb @ 150 Hz SVF freq.*
  - *So, ratio of mass of 230 lb SVF test item to mounting structure mass is 2.3 for correlated motion, or 0.6 for uncorrelated motion of 4 points.*
  -



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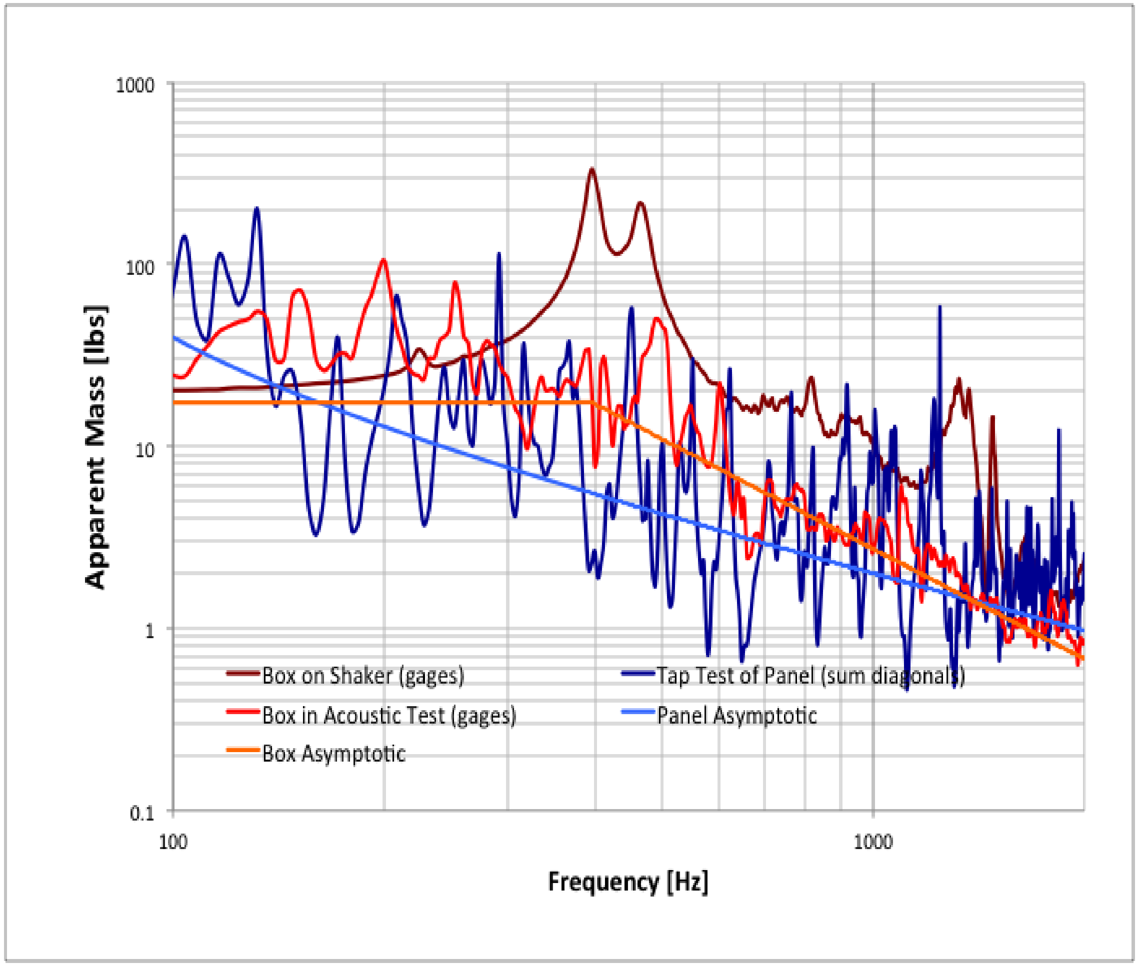
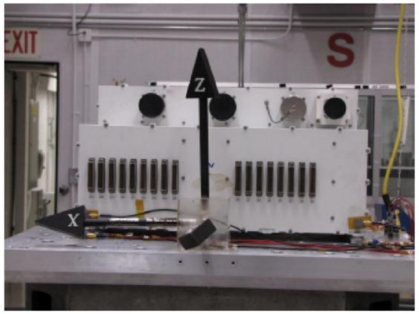
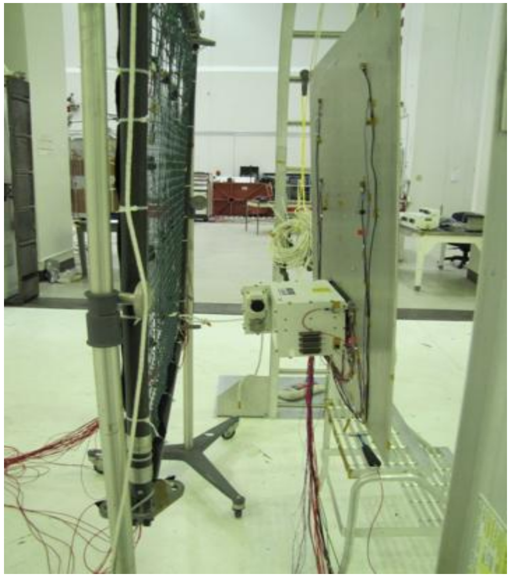
APPARENT MASSES OF PANEL (38.4 lb) and BOX (17.4 lb)

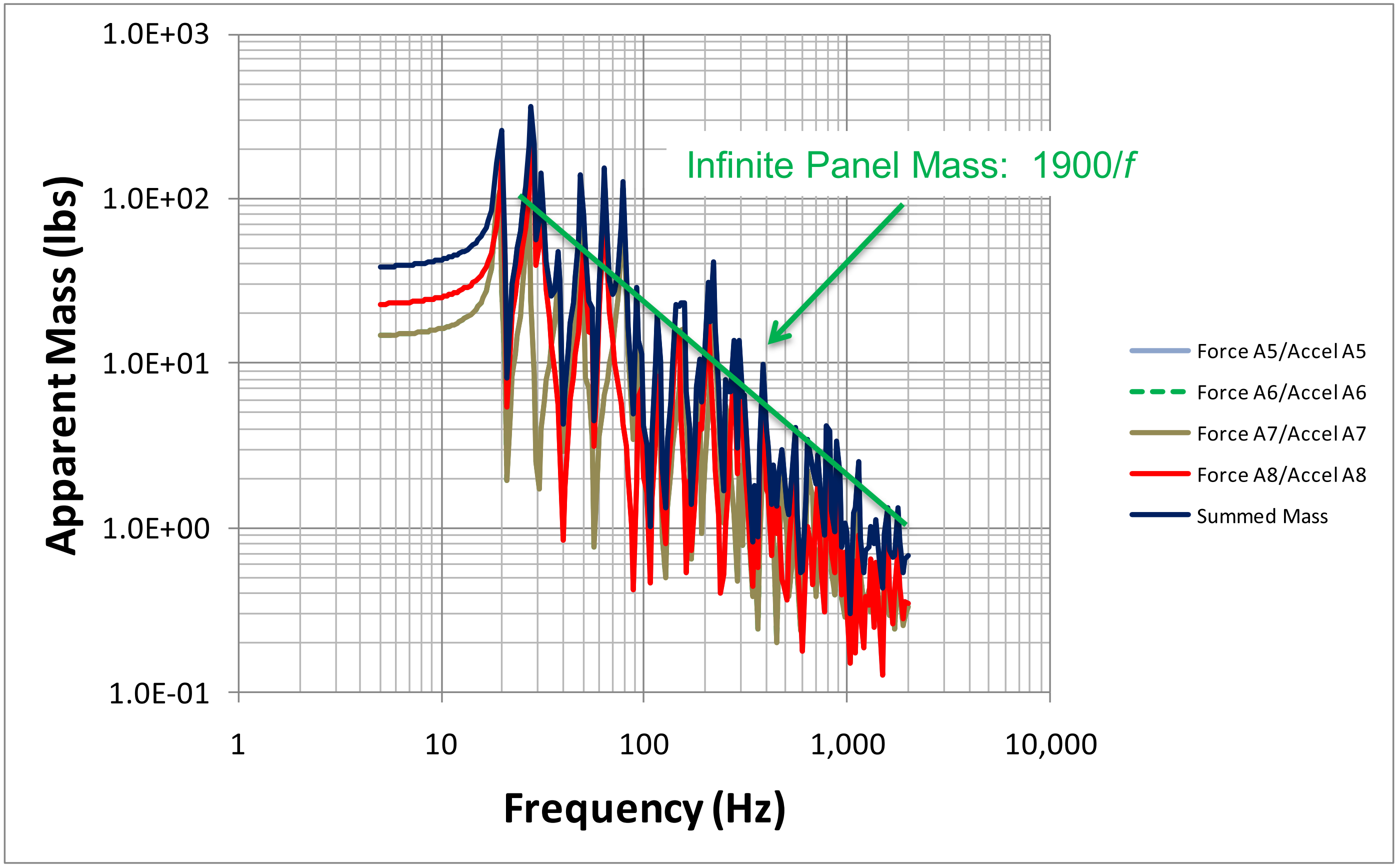






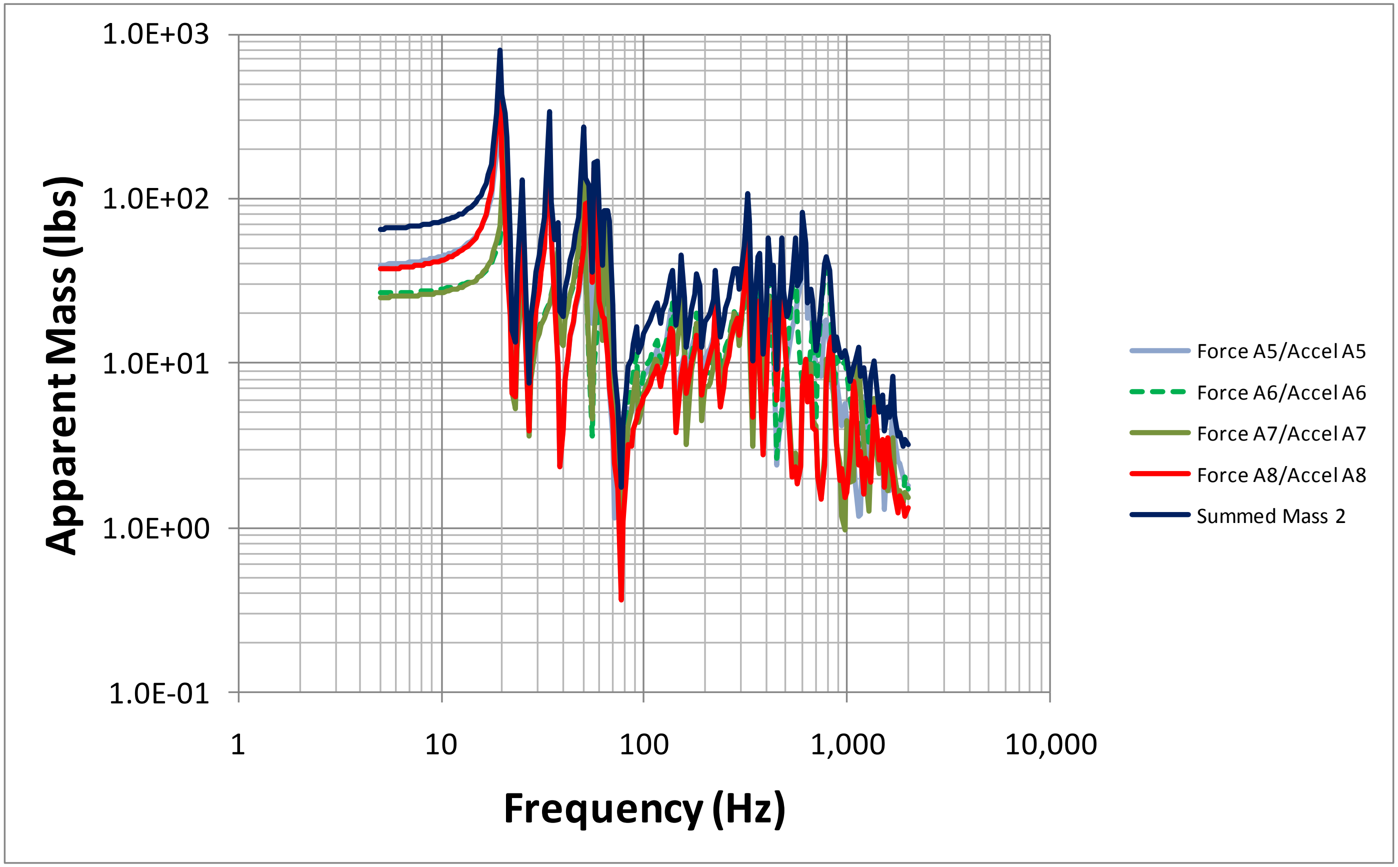
- Note difference in apparent masses (total force/average acceleration) of box A mounted on shaker (@ 4 points) and on panel, where it does not move uniformly.
- Note that asymptotic masses generally average through detailed apparent masses

FEM: APPARENT MASS OF BARE PANEL (38.4 lb)



- Apparent mass is computed by applying white-noise at each box IF without the box

FEM: APPARENT MASS OF PANEL (38.4 lb) and BOX (17.4 lb)



- Apparent mass is computed by applying white-noise at each box IF

GUIDELINES

- Three Guidelines (from NASA-HDBK-7004C draft)
  1. *Use force limiting only for highly resonant test articles.*
     - Don't use if C<2, i.e., less than 6 dB resonance peak.
     - Consider reducing acceleration specification, as an alternative.
  2. *Use appropriate rationale for deriving force limits.*
     - Simple TDOF method
     - Equivalent circuit method
     - FEM of flight mounting configuration
     - Reference to C values **measured** in flight or ground tests
  3. *Avoid excessive notching.*
     - Seek concurrence for notch depths greater than 14 dB
     - Compare with Sweizter's criterion for highly resonant test items, e.g., 20 dB resonance becomes 10 dB notch and 10 dB resonance.

RECOMMENDATIONS

- Always consider the ratio of the test item apparent mass to that of the flight mounting structure (see TDOF method)
- The apparent mass of the flight mounting structure may be determined with one of the following methods:
  - *Infinite system model of flight mounting structure*
  - *Scale from flight or ground test* ***measurements*** *of* C^2 *and TDOF model*
  - *Tap tests of unloaded flight mounting structure*
  - *FEM of flight mounting structure driven at the test item interface*
- Asymptotic apparent mass provides frequency dependence
- Encourage suppliers of flight mounting structure, i.e., L/V or S/C, to provide FEM analysis of apparent mass at test item attachment interface. (for L/V, this is available from CLA)

Backup Charts

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1. **General References (24) -** Documents that provide a basic discussion of mechanical Impedance and Its applications (including in some cases applications to the vibration testing problem), but which do not present or suggest specific vibration test procedures.

2. **Input Force Control Procedures (12) -** Documents that suggest and/or

   detail vibration test procedures based upon control of the measured or predicted input force to the test Item.

3. **Response Control Procedures (9) -** Documents that suggest and/or detail vibration test procedures based upon control of the response of the test Item.

4. **Impedance Correction Procedures (7) -** Documents that suggest and/or detail vibration test procedures based upon corrections to the motion Input derived from the mounting point Impedance as well as the impedance of the test Item.

FORCE LIMITING BACKGROUND REFERENCES (2)

5. **Impedance SImulation Procedures (7)** – Documents that suggest detail test procedures using either the shaker or special fixtures to simulate the mounting point impedance for the test item.
6. **Acoustic Testing Procedures (5)** – Documents that discuss the illustrate the differences between acoustic-induced and shaker–induced vibration responses of the test items and generally recommend acoustic tests for items subjected to acoustic excitation in practice.

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Thank you