# Application of the Semi-Empirical Force-Limiting Approach for the CoNNeCT SCAN Testbed

The semi-empirical force-limited vibration method was developed and implemented for payload testing to limit the structural impedance mismatch (high force) that occurs during shaker vibration testing. The method has since been extended for use in analytical models. The Space Communications and Navigation Testbed (SCAN Testbed), known at NASA Glenn Research Center (GRC) as, the Communications, Navigation, and Networking re-Configurable Testbed (CoNNeCT) project utilized force-limited testing and analysis following the semi-empirical approach. This presentation presents the steps in performing a force-limited analysis and then compares the results to test data recovered during the CoNNeCT force-limited random vibration qualification test that took place at NASA Glenn Research Center (GRC) in the Structural Dynamics Laboratory (SDL) December 19, 2010 – January 7, 2011. A compilation of lessons learned and considerations for future force-limited tests is also included.

# Application of the Semi-Empirical Force-Limiting Approach for the CoNNeCT SCAN Testbed

Lucas Staab, Mark McNelis, Trevor Jones, James Akers, and Vicente Suarez
NASA Glenn Research Center

DEV/Structural Systems Dynamics Branch
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Lucas.D.Staab@nasa.gov
216-433-6513

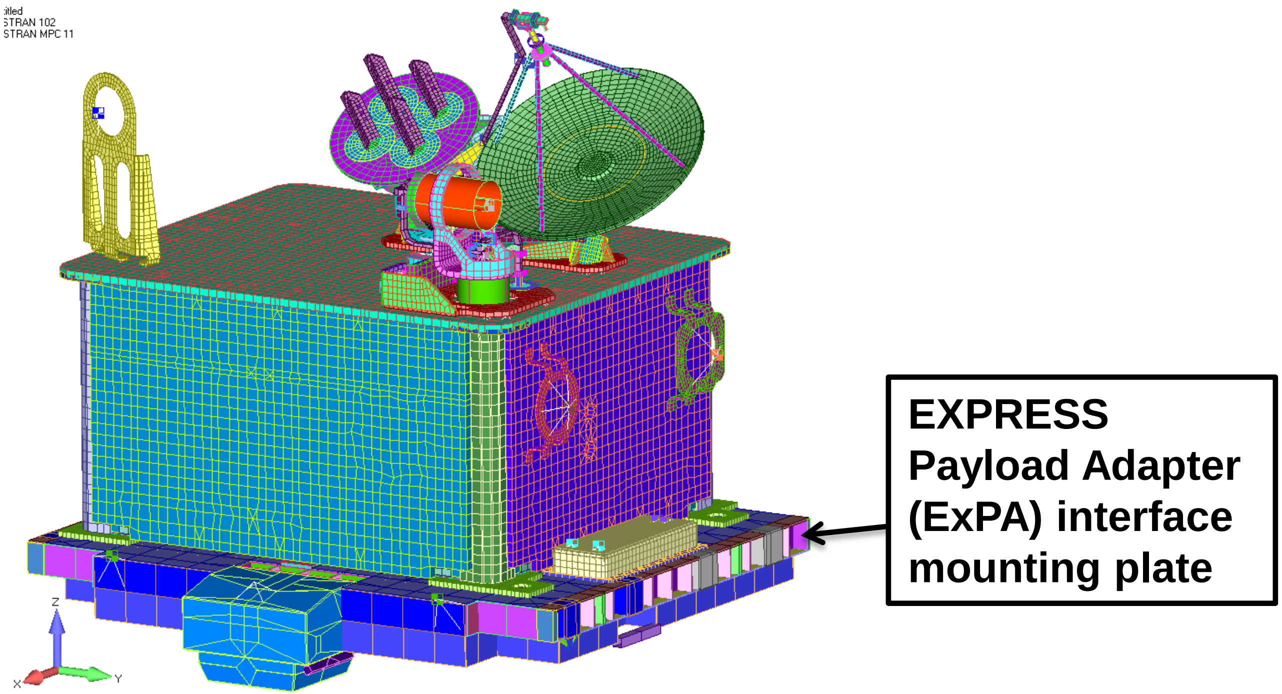
# Agenda

- CoNNeCT Background
- Force-Limiting Theory
- Implementation of Force-Limiting Analysis in NASTRAN
- Impedance Analysis and Force-Limited Test Results
- Lessons Learned
- Conclusions

# Communication, Navigation, Networking, Re-Configurable Testbed (CoNNeCT) Background

# Background
## CoNNeCT Testbed

- The CoNNeCT Testbed is an International Space Station (ISS) national lab that uses software defined radios to advance technologies and demonstrate future mission capabilities for communications, networking and navigation.
- CoNNeCT is a payload that was designed, developed and tested at NASA Glenn Research Center (GRC) and is planned for launch January 2012 on the JAXA H-II Transfer Vehicle (HTV) to the ISS.




**CoNNeCT Flight Configuration FEM**

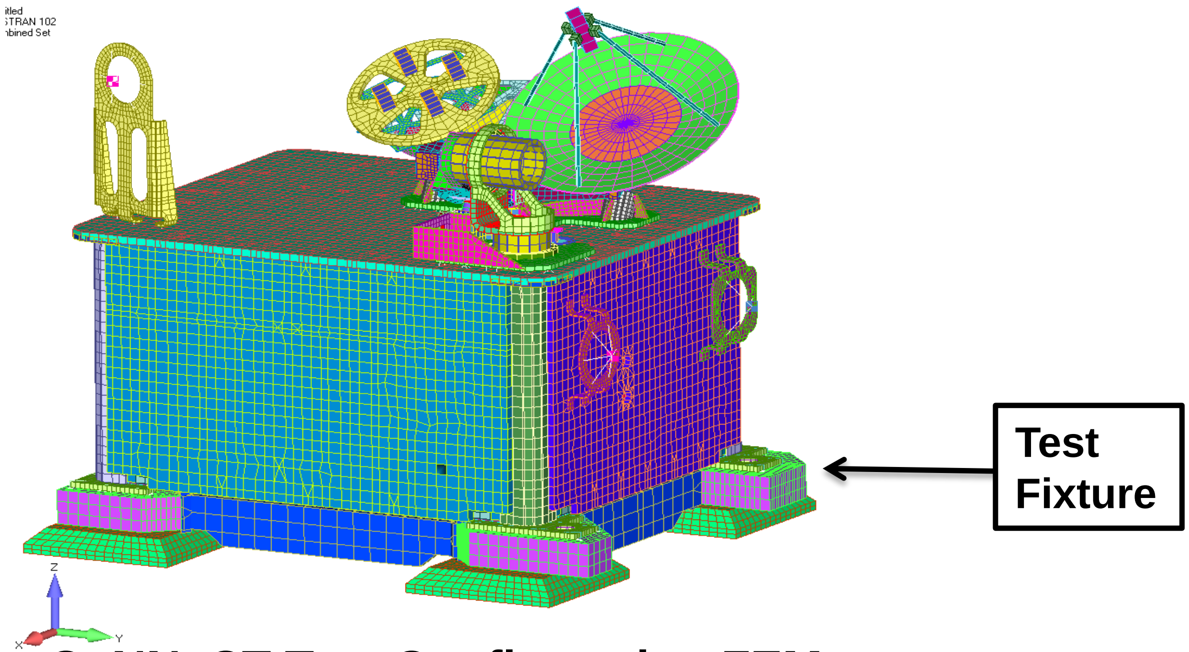
Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch

# Background
# CoNNeCT Force-Limiting Protoflight Testing

- The CoNNeCT payload was protoflight random vibration tested to qualify the payload for flight. The EXPRESS Payload Adapter (ExPA) flight interface mounting hardware was not available for testing.

- For a traditional base shake random vibration test/analysis, the correct flight interface impedance between the payload and the launch vehicle is not represented.

- The impedance mismatch results in a conservative estimate of the flight response. Force-limiting testing/analysis accounts for this impedance mismatch providing a more realistic flight response.




**CoNNeCT <u>Test</u> Configuration FEM**

Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch



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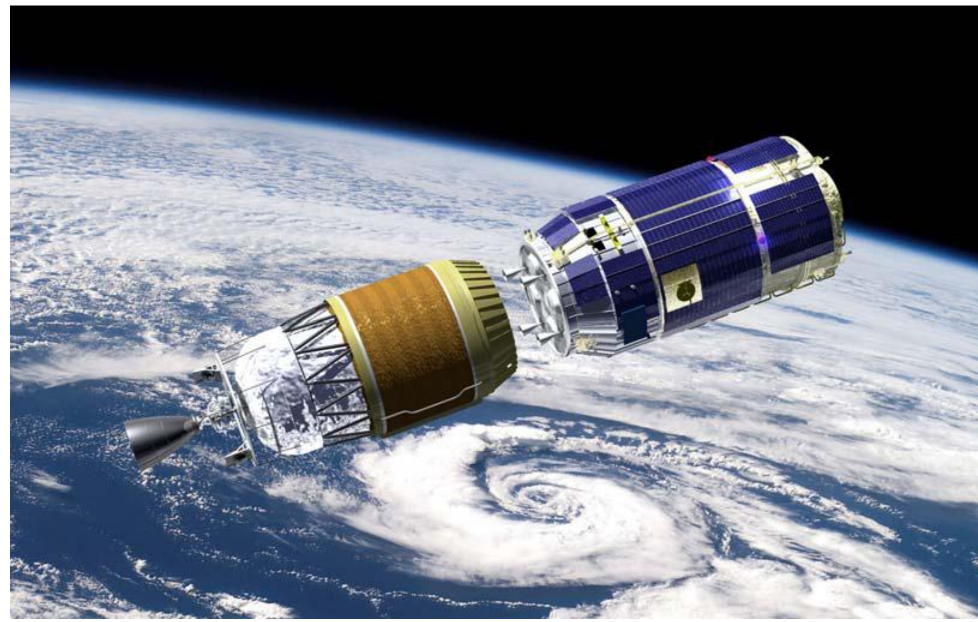
# Background
## H-II A Rocket and HTV

- The CoNNeCT payload will be launched in January 2012 aboard the JAXA H-II Transfer Vehicle (HTV) to the International Space Station.

**JAXA Tanegashima Space Center**



**H-IIB Launch Vehicle (Second Stage) and HTV**

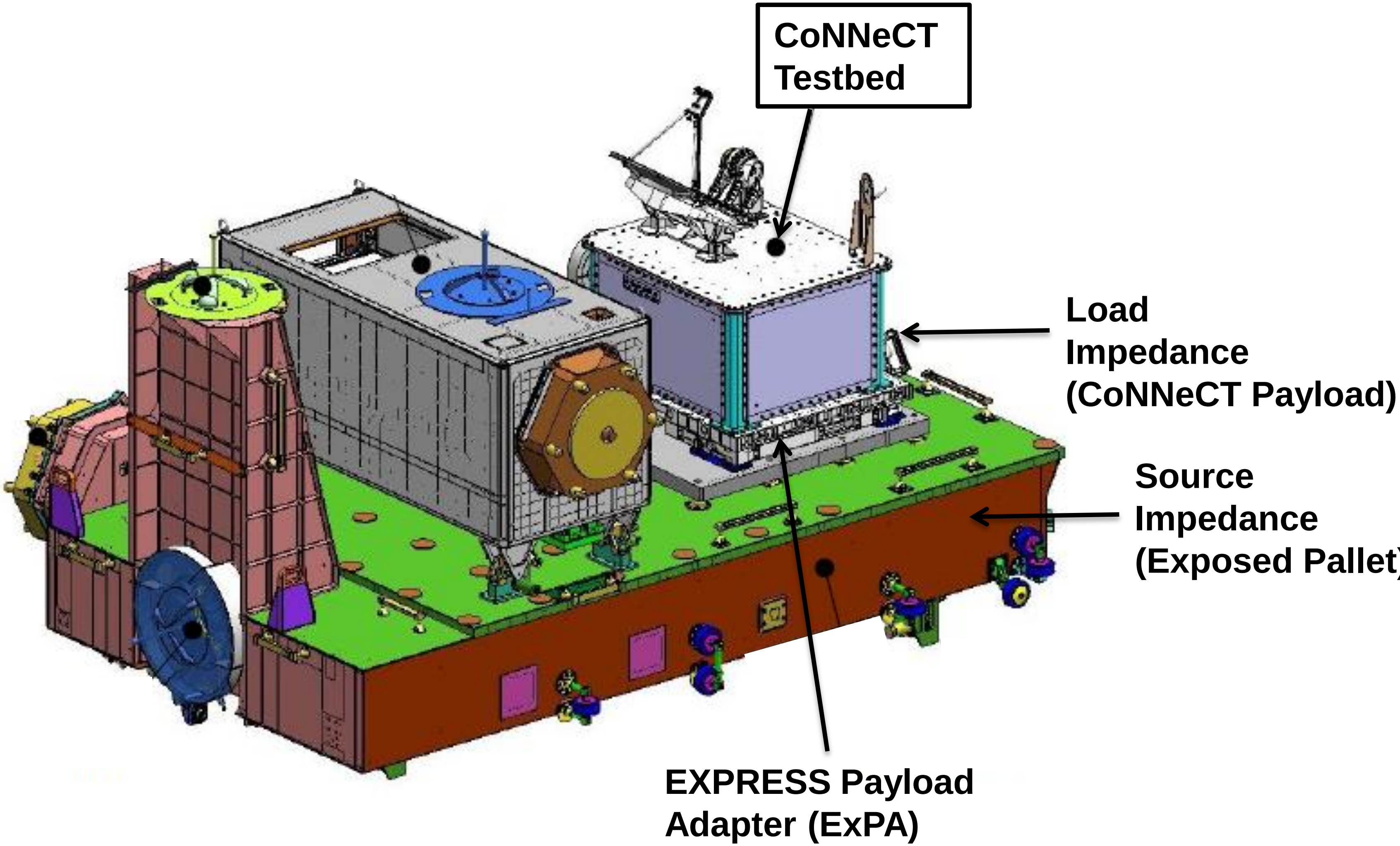
Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch

# Background
# HTV Configuration and Exposed Pallet

HTV Configuration

Exposed Pallet

# Background
## CoNNECT Testbed
## Mounting Configuration on the Exposed Pallet




Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch



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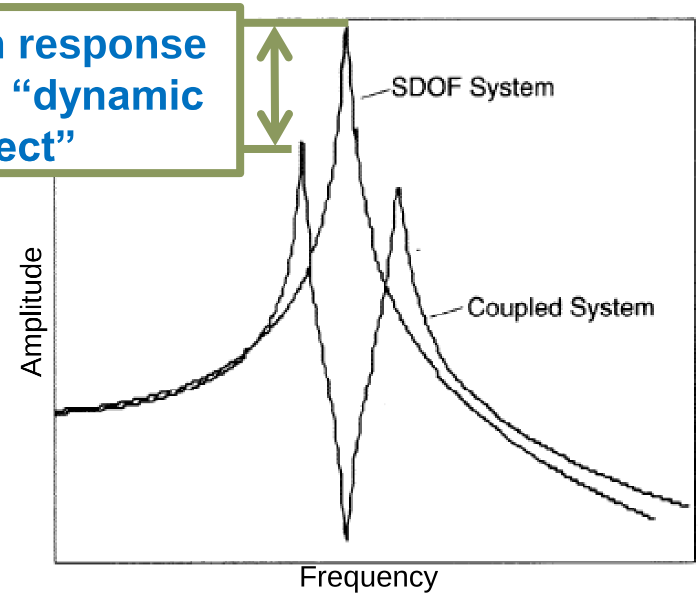
# Force-Limiting Theory

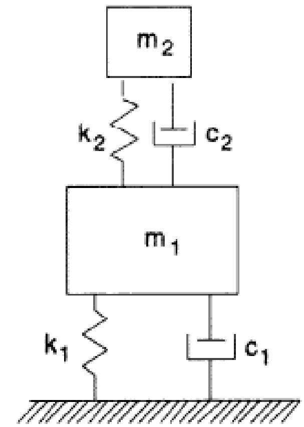
# Force-Limiting Theory
## Dynamic Absorber Effect*

**Reduction in response is due to the "dynamic absorber effect"**

$$\frac{x_1 k_1}{F_0} = \frac{\left[1-\left(\frac{\omega}{\omega_2}\right)^2\right]}{\left[\left[1+\frac{k_2}{k_1}-\left(\frac{\omega}{\omega_1}\right)^2\right]\left[1-\left(\frac{\omega}{\omega_2}\right)^2\right]-\frac{k_2}{k_1}\right]}$$

**Coupled System Transfer Function**




- For a traditional base shake random vibration test/analysis, the correct flight interface impedance between the payload and the launch vehicle is not represented.
- Force-limiting testing/analysis accounts for the impedance mismatch providing a more realistic flight response. The reduction in the response of the coupled system (payload and launch vehicle) is due to the dynamic absorber effect.
- The amount of dynamic interaction is heavily dependent on the relative ratio of natural frequency and stiffness of each separate single degree of freedom (DoF) system.
- The amount of separation between these two peaks of the coupled system is dependent on the relative mass ratios.

***Reference: "**Why You Can't Ignore Those Vibration Fixture Resonances," by Dr. Peter Avitabile, University of Massachusetts Lowell, Lowell, Massachusetts, Sound and Vibration Magazine, March 1999.

# Force-Limiting

- Force-Limiting theory can be implemented by various methods (accelerance, bias, Q, semi-empirical). CoNNeCT used the semi-empirical method.

- NASA-HDBK-7004B outlines a semi-empirical approach for force-limiting:

$$S_{FF} = C^2 M_o^2 S_{AA} \quad , \quad f < f_o \qquad \textbf{(Eq. 1a)}$$

$$S_{FF} = C^2 M_o^2 S_{AA} (f_o/f)^2 \quad , \quad f \geq f_o \qquad \textbf{(Eq. 1b)}$$

  - *$f_o$ is the fundamental frequency*
  - *$S_{FF}$ is the force spectral density*
  - *$S_{AA}$ is the acceleration spectral density*
  - *C is the dynamic amplification factor, defines the depth of notch.*
  - *$M_0$ is the total mass of the payload*
  - *The exponent of the rolloff factor $(f_o/f)^2$ can be tailored*

- The semi-empirical approach creates a notch in the input acceleration spectrum taking into account the impedance mismatch in the random vibration analysis and testing.

Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch



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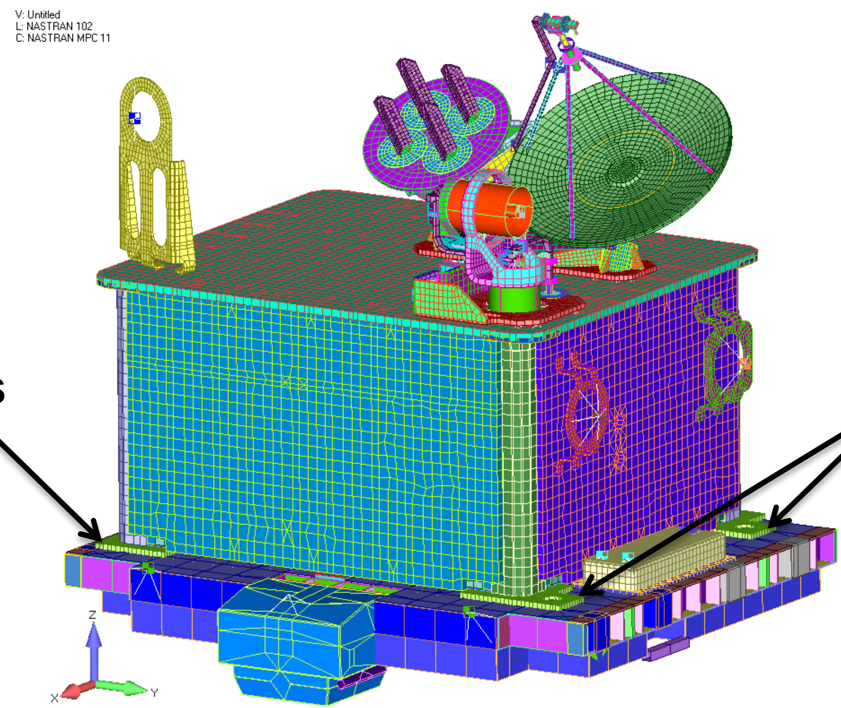
# Implementation of Force-Limiting Analysis in NASTRAN

# Implementation of Force-Limited Analysis for CoNNeCT

- Strength assessment of CoNNeCT Payload originally indicated negative design margins of safety in the interface fasteners.
- Several methods were used to reduce conservatism in the strength analysis including force-limiting analysis. Semi-empirical force-limits were derived and applied to the CoNNeCT Payload in the base shake random vibration analysis.
- Positive design margins of safety were obtained for the interface fasteners.

**Interface Fasteners**




**Interface Fasteners**

**CoNNeCT Flight Configuration FEM**

Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch

# Implementation of Force-Limiting Analysis in NASTRAN

The same force limits are applied in testing and in the NASTRAN random vibration base shake analysis. The main difference is the implementation of the notched input acceleration PSD in the base shake analysis; NASTRAN cannot automatically notch the input acceleration PSD as does the test controller.

The following steps are used to create a notched new input acceleration PSD for a NASTRAN force limited base shake random vibration analysis:

**Step 1.** Apply the input acceleration PSD (un-notched) to the model and recover the force PSD (FPSD) at the node where the input spectrum is applied. For CoNNeCT the input acceleration PSD is applied at the center node of the rigid element that connects to all the model interface points.

**Step 2.** Create a force limited PSD (FL_FPSD) based on the semi-empirical equations (Equations 1a and 1b) using the C value, input acceleration PSD, fundamental resonant frequency, and the total weight of the payload. The frequency of the largest peak from Step 1 is $f_o$ and is used in the semi-empirical equation.

$$S_{FF} = C^2 M_o^2 S_{AA} \quad , \quad f < f_o \qquad \textbf{(Eq. 1a)}$$

$$S_{FF} = C^2 M_o^2 S_{AA} (f_o/f)^2 \quad , \quad f \geq f_o \qquad \textbf{(Eq. 1b)}$$



Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch

# Implementation of Force-Limiting Analysis in NASTRAN (continued)

**Step 3.** Create the notched new acceleration input PSD (Equations 2a and 2b). Whenever the force PSD recovered in Step 1 exceeds the force limited PSD from Step 2, the input acceleration PSD will be notched, creating a new input acceleration PSD. The depth of the notch is calculated based on the ratio of the force limited PSD (FL_FPSD) to the recovered force PSD (FPSD). If the ratio (FL_FPSD divided by FPSD) is greater than 1.0 (if the recovered force is less than the force limited PSD), the new input acceleration PSD equals the original input acceleration PSD.

$$New\_Accel\_PSD = \left(\frac{FL\_FPSD}{FPSD}\right) * Original\_Accel\_PSD \qquad \left(\frac{FL\_FPSD}{FPSD}\right) < 1 \qquad \textbf{(Eqn. 2a)}$$

$$New\_Accel\_PSD = Original\_Accel\_PSD \qquad \left(\frac{FL\_FPSD}{FPSD}\right) \geq 1 \qquad \textbf{(Eqn. 2b)}$$

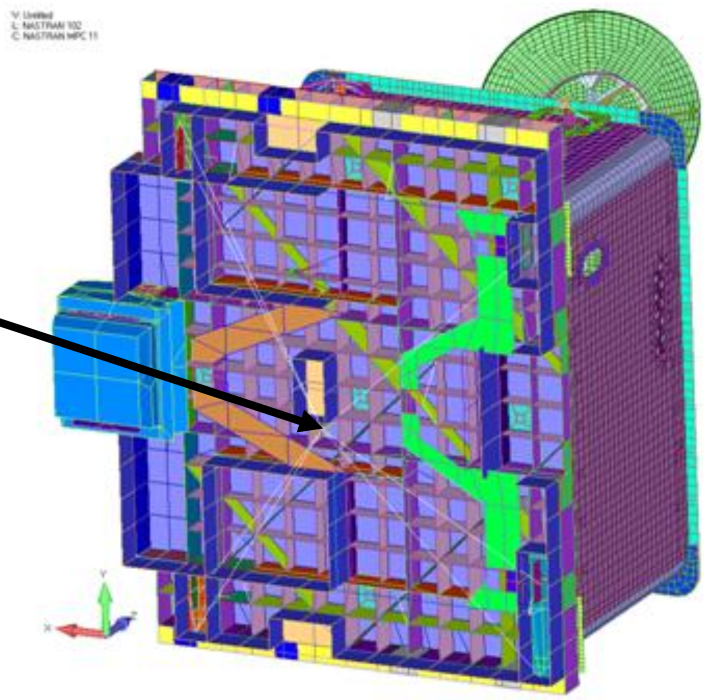
**Equation 2 – Notched New Input Acceleration PSD**

**Step 4.** Apply the notched new input acceleration PSD to the finite element model in a random base shake analysis and recover the desired response data.

Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch

# Implementation of Force-Limiting Analysis in NASTRAN (continued)

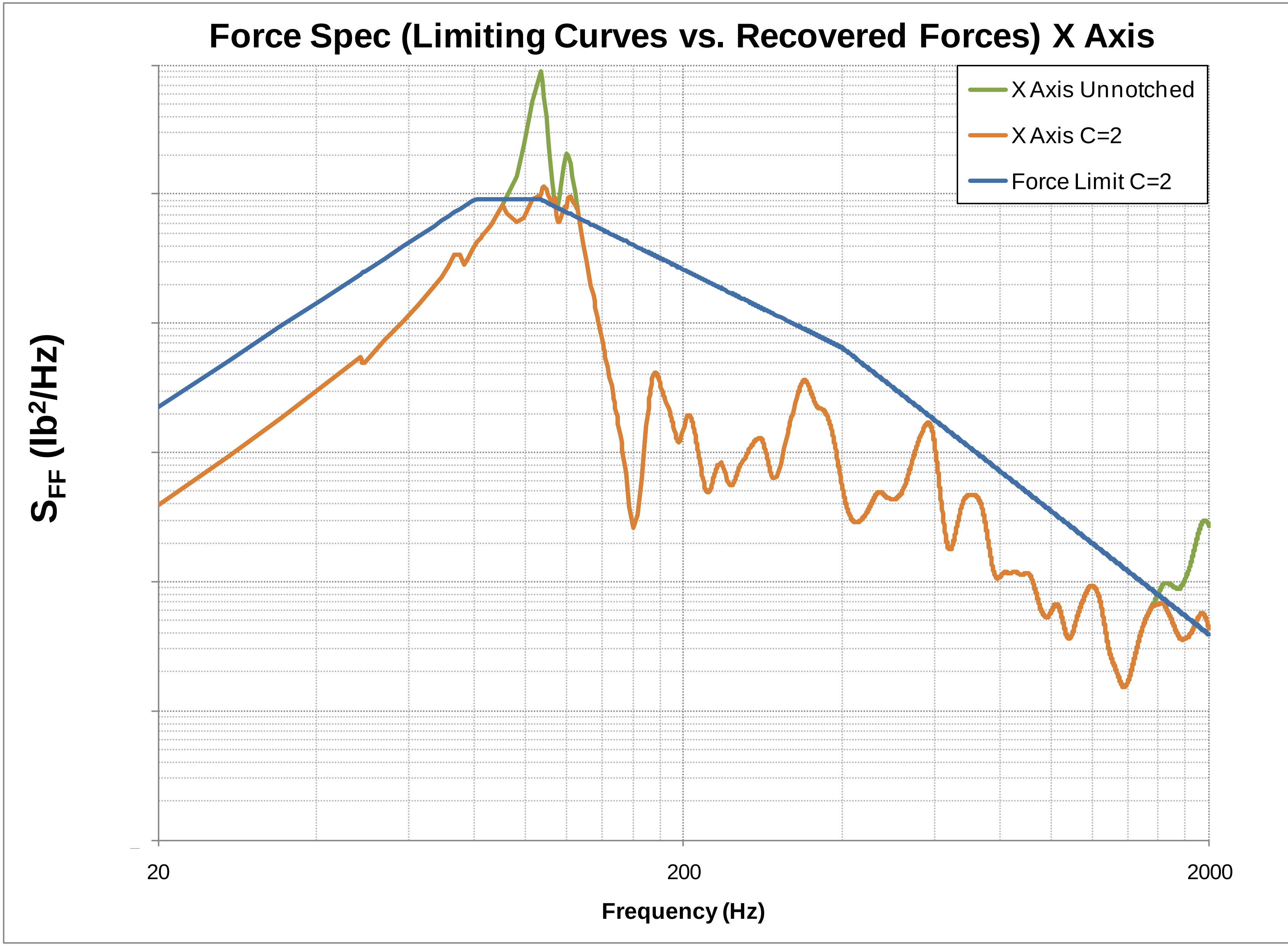
**Notched input acceleration PSD is applied at the center node at the base of the payload.**



- The boundary condition for the random base shake analysis is enforced acceleration.
- At the base of the FEM is a rigid element (RBE2) connected from the center node out to all the attach points of the model.
- Notched input acceleration PSD is applied at the center (independent) node of the rigid element.

Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch

# Example Force-Limited Spectrum




Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch



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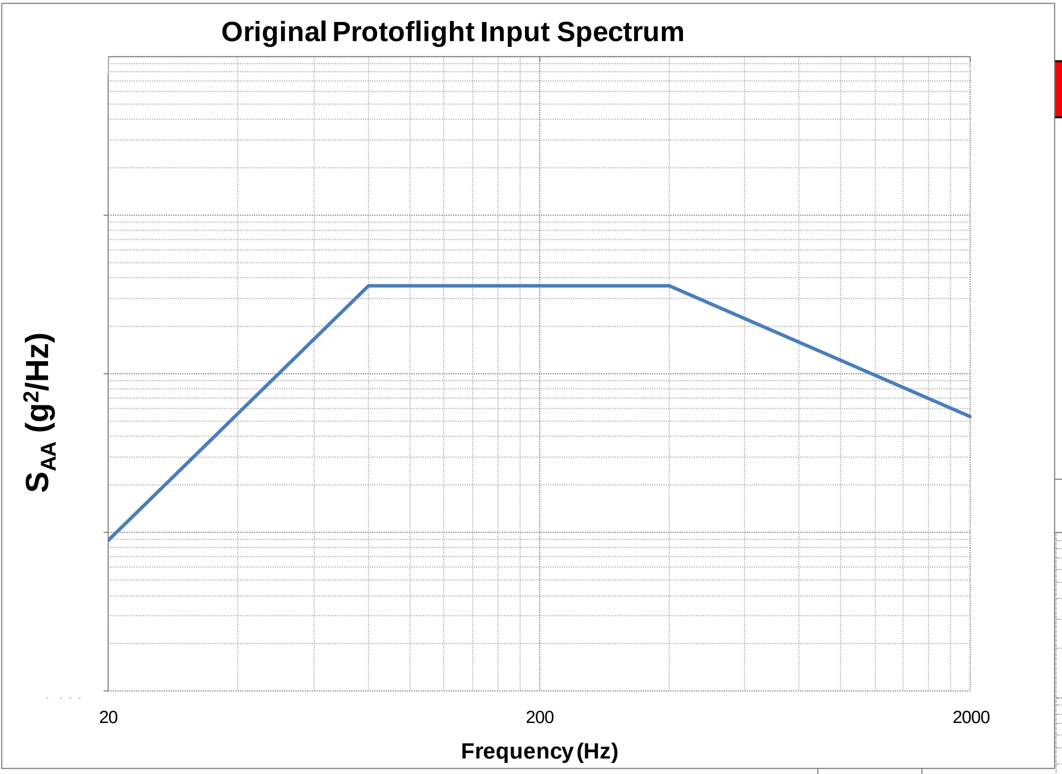
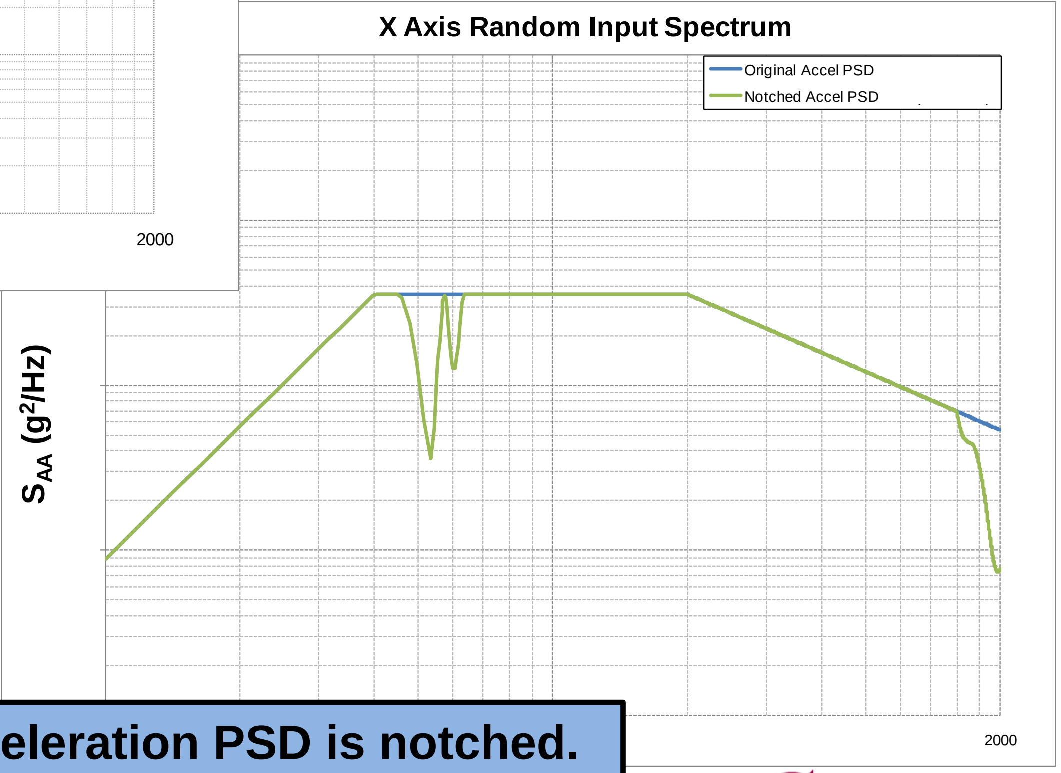
# Example Results of Semi-Empirical Force-Limiting




Applying Semi-Empirical Force-Limiting Analysis using C=2




**The input acceleration PSD is notched.**


Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch

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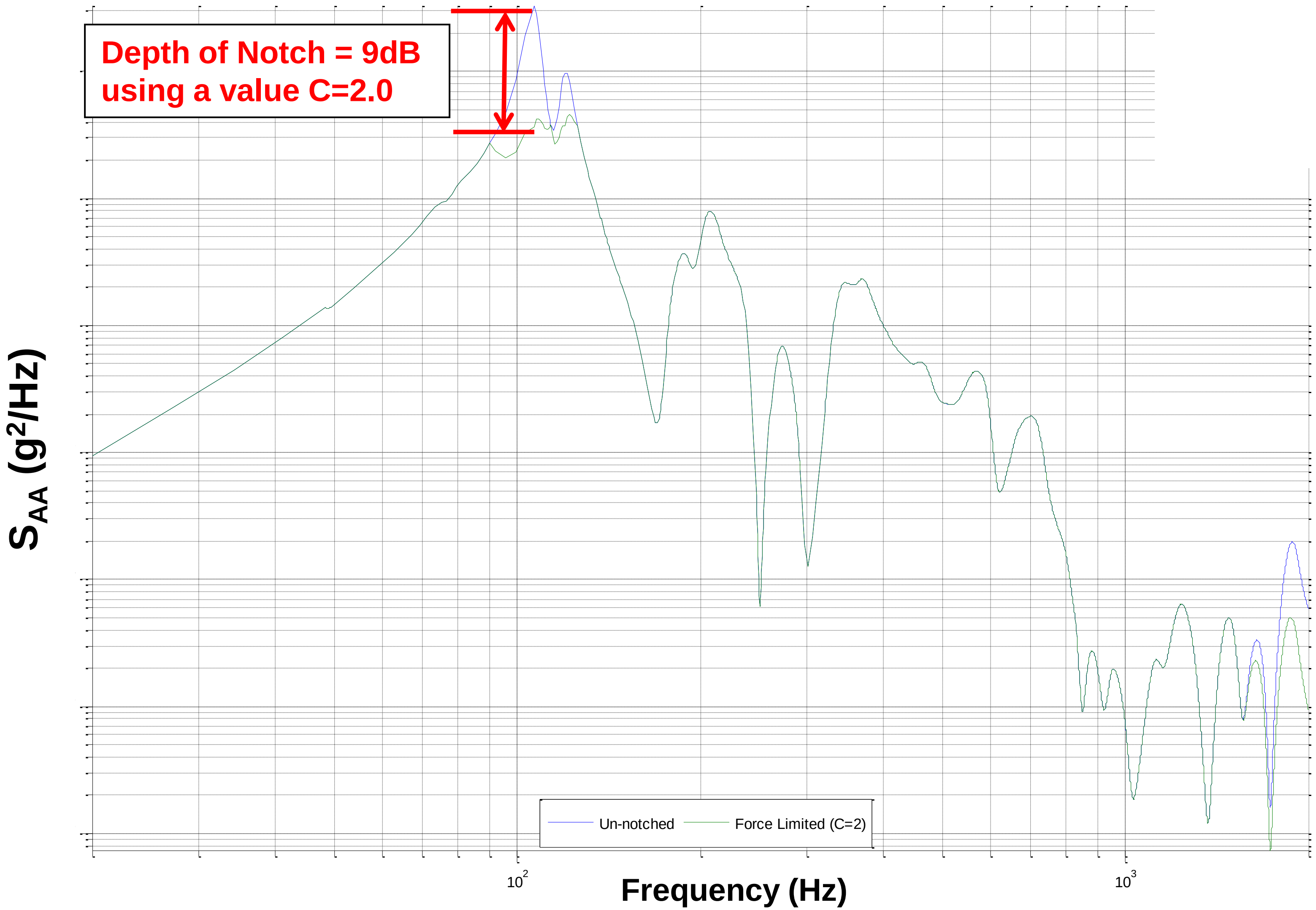
# Example Results of Semi-Empirical Force-Limiting




**The depth of notch is controlled by the "C" value.**


Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch

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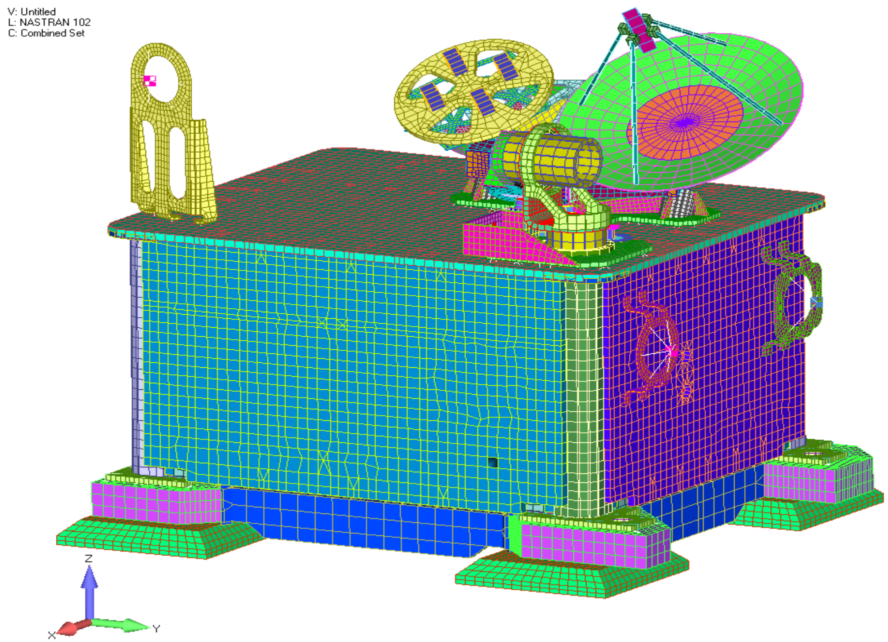
# Impedance Analysis and Force-Limited Test Results

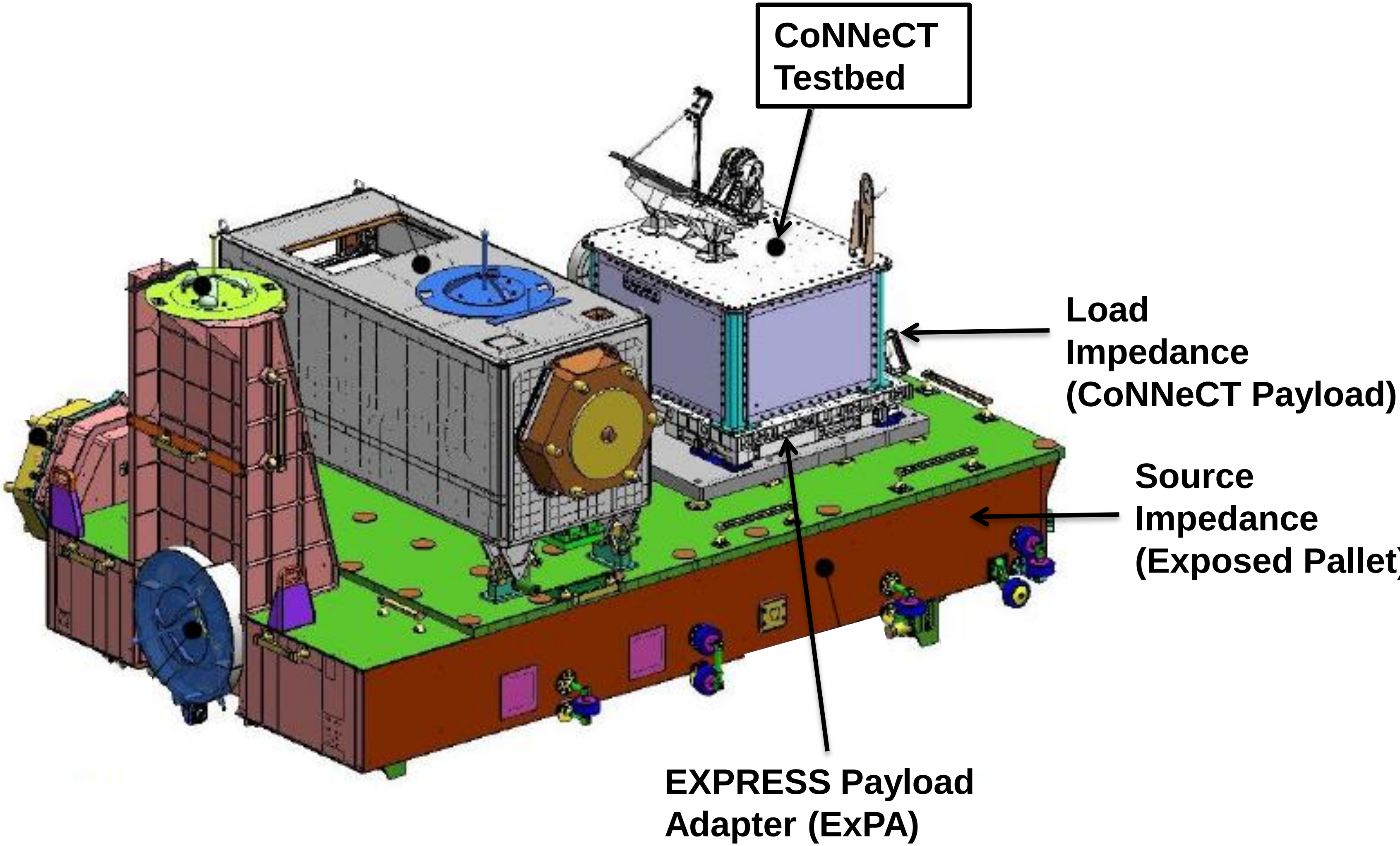
# CoNNeCT Force-Limited Protoflight Testing

- The CoNNeCT payload was force-limited protoflight vibration tested in each orthogonal axis in December 2010 at NASA GRC.
- The CoNNeCT force limits were derived using the semi-empirical method, with an estimated value of C=2. This value was validated by a **load impedance** analysis of the test data. The JAXA launch vehicle **source impedance** is unknown, as NASA GRC did not have access to the launch vehicle coupled system model or detailed information on the Exposed Pallet mounting structure.




**CoNNeCT Test Configuration FEM**

# Background
## CoNNECT Testbed
## Mounting Configuration on the Exposed Pallet



# CoNNeCT Impedance Analysis

**Load Impedance:**
Sffn (f) = K (f) Saau (f)

**Semi-empirical method:**
$K(f) = C^2 M^2$ for $f < f_0$
$K(f) = C^2 M^2 (f_0/f)^n$ for $f > f_0$

- Dan Kaufman (NASA GSFC/NESC Deputy Loads & Dynamics) evaluated the **load impedance*** based on CoNNeCT force-limited protoflight test data. Three independent methods were used for calculating load impedance to cross-check the C value used in the semi-empirical method:

**(1) Accelerance method:**
$K(f) = [AI(f)\, AI_E(f)]^{-1}$
AI (f): Load accelerance [g/Lb]
$AI_E$ (f): Load accelerance envelope [g/Lb]

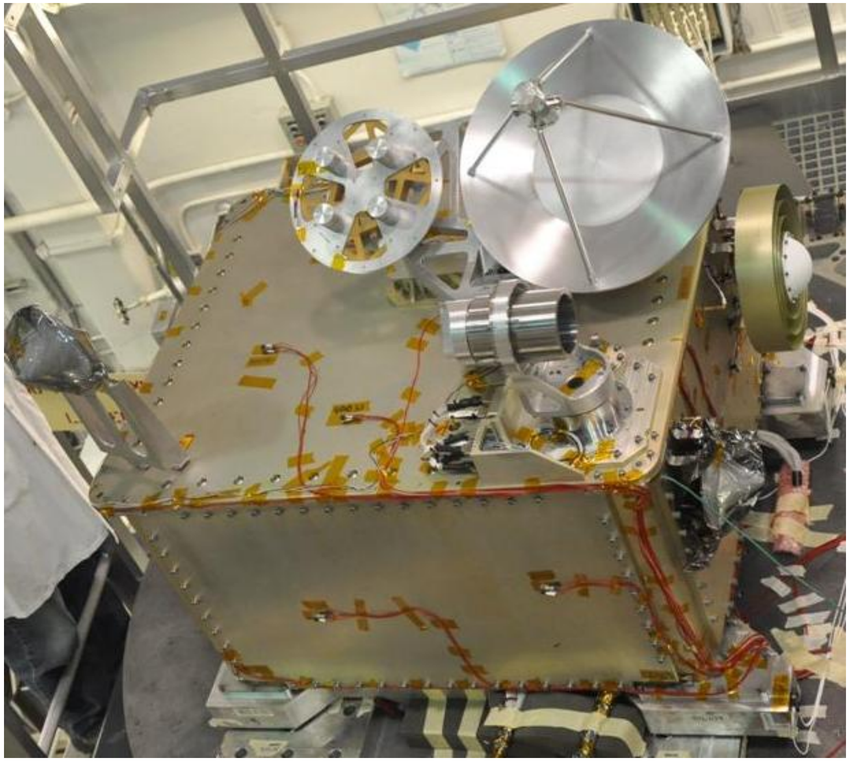
**(2) Bias Impedance method:**
$W_b(f) = W_{min}(f) + 0.1\,[W_{max}(f) – W_{min}(f)]$
$K(f) = [W_b(f)]^2$
$W_b$ (f): Biased acceleration impedance [Lb/g]
Wmin (f): Minimum acceleration impedance [Lb/g]
Wmax (f): Maximum acceleration impedance [Lb/g]

**(3) Q method:**
$K(f) = Meff(f)^2\, Q(f) + Mres(f)^2$
Q (f): Amplification factor
Meff(f) : Effective mass of mode f (or weight) [Lb]
Mres(f): Residual Mass mode f [Lb]

***Reference:** "Force Limiting Testing for the Small Explorer Satellite Program at NASA Goddard Space Flight Center," Daniel S. Kaufman, Journal of the IEST, Volume 43, Number 1, pp. 24-30, Winter 2000.

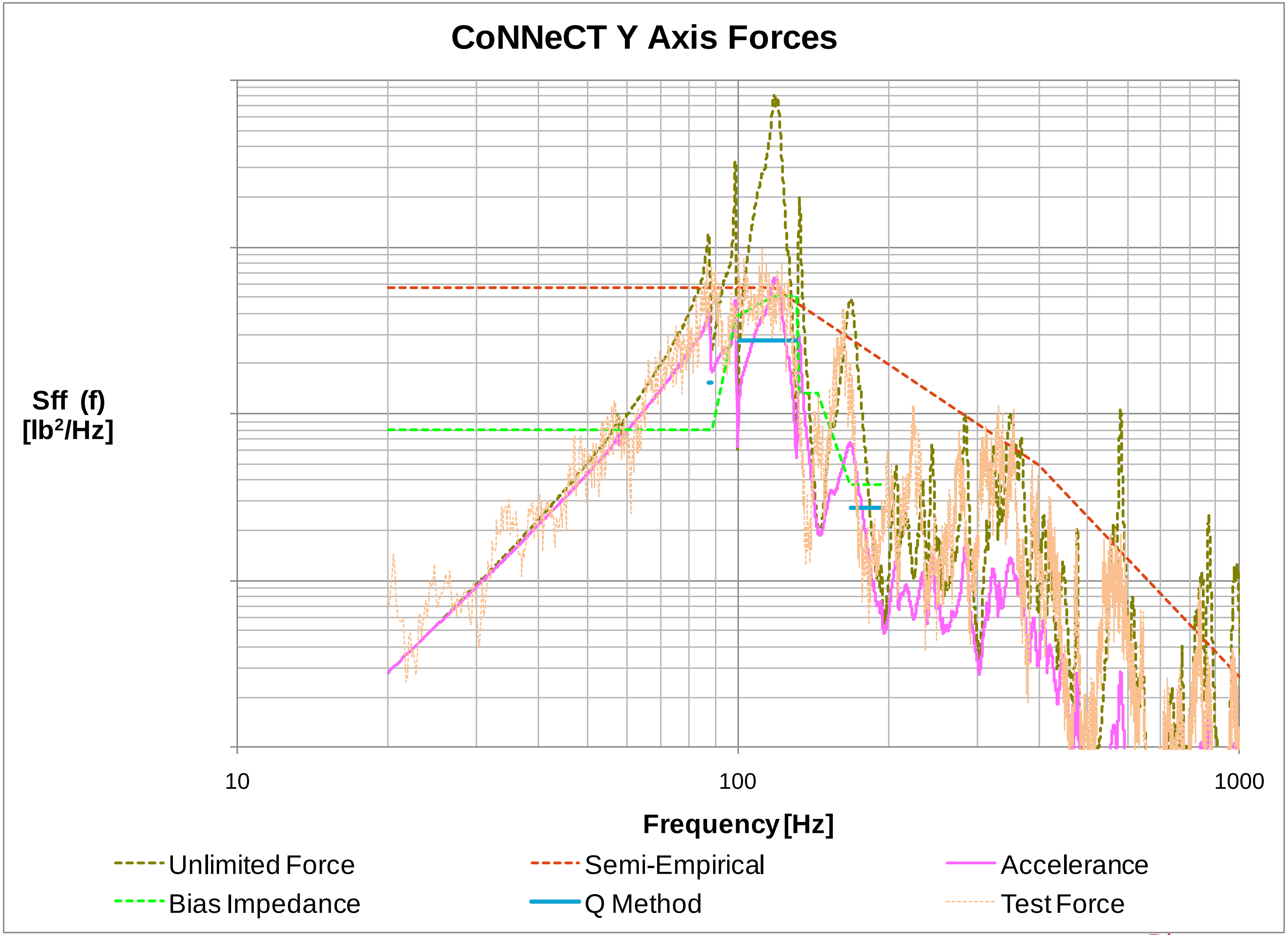
# CoNNeCT Impedance Analysis (continued)

- Based on the load impedance analysis, the test force limits using C=2 are considered appropriate.
- ***An improved methodology would involve knowledge of the source impedance and / or the coupled system or using load and source methods, which are unavailable at this time.***



Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch

# CoNNeCT Test Impedance Analysis

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NASA GRC/DEV/Structural Systems Dynamics Branch



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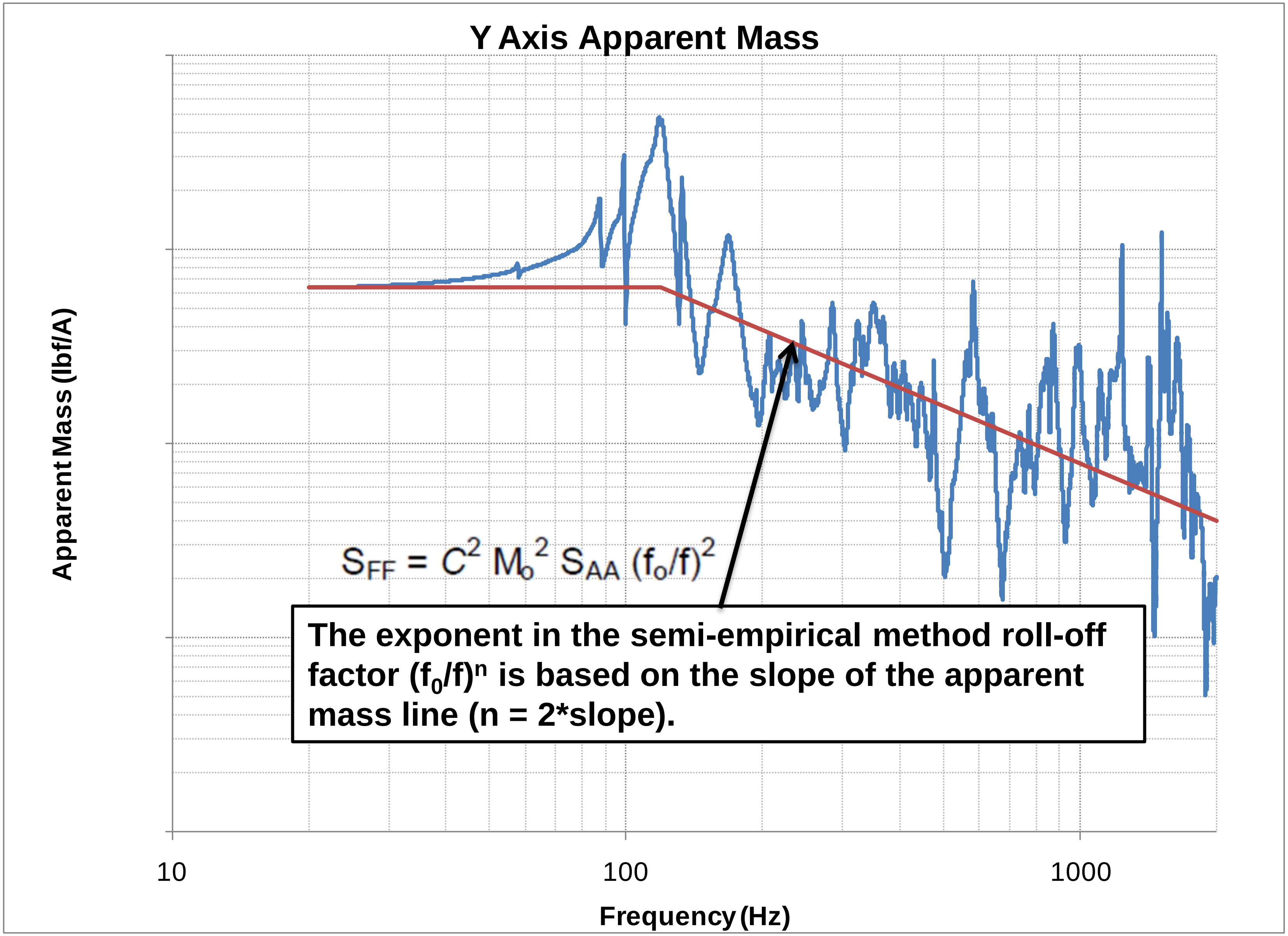
# CoNNeCT Test Apparent Mass




**The exponent in the semi-empirical method roll-off factor $(f_0/f)^n$ is based on the slope of the apparent mass line (n = 2*slope).**


Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch

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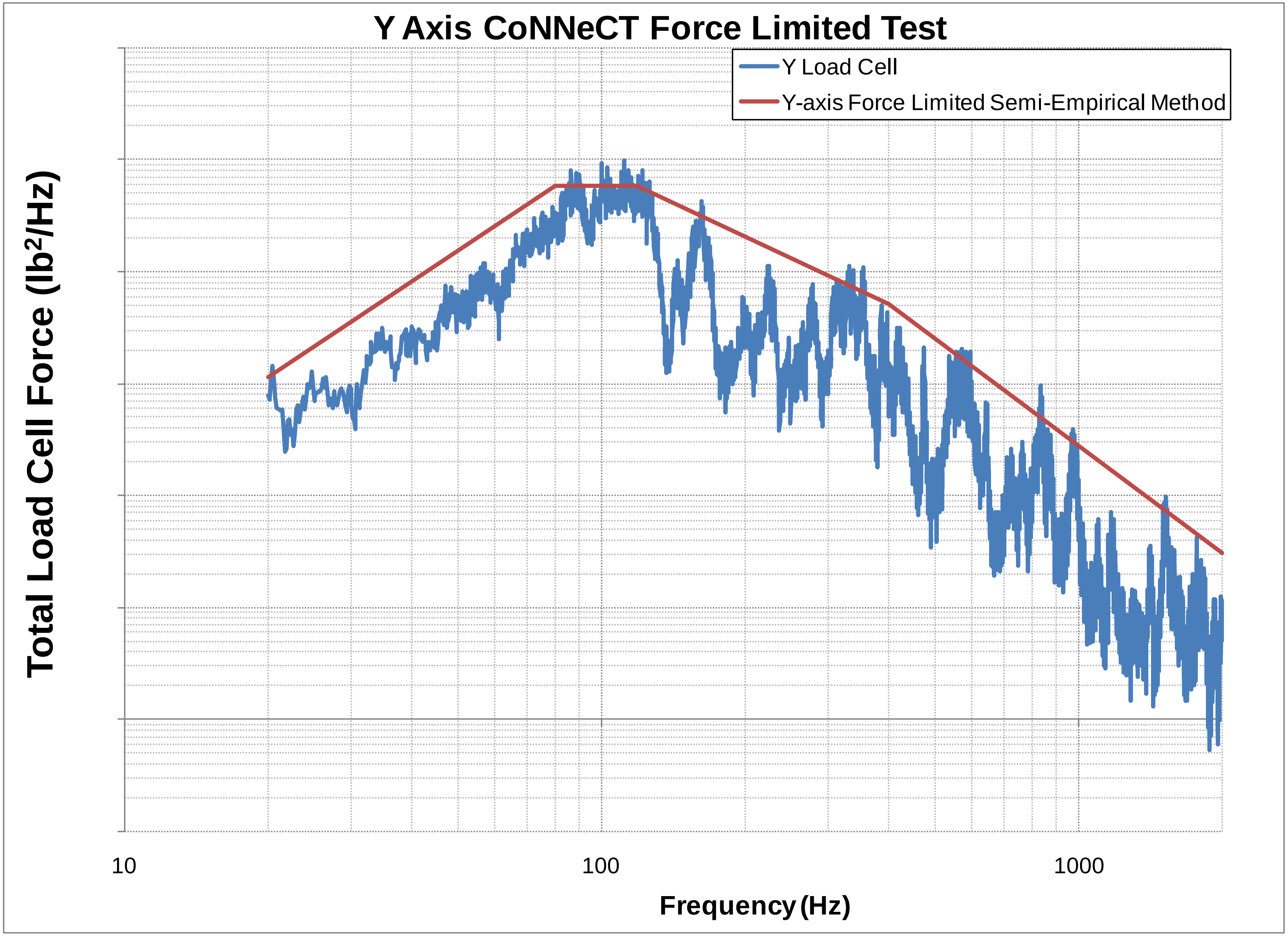
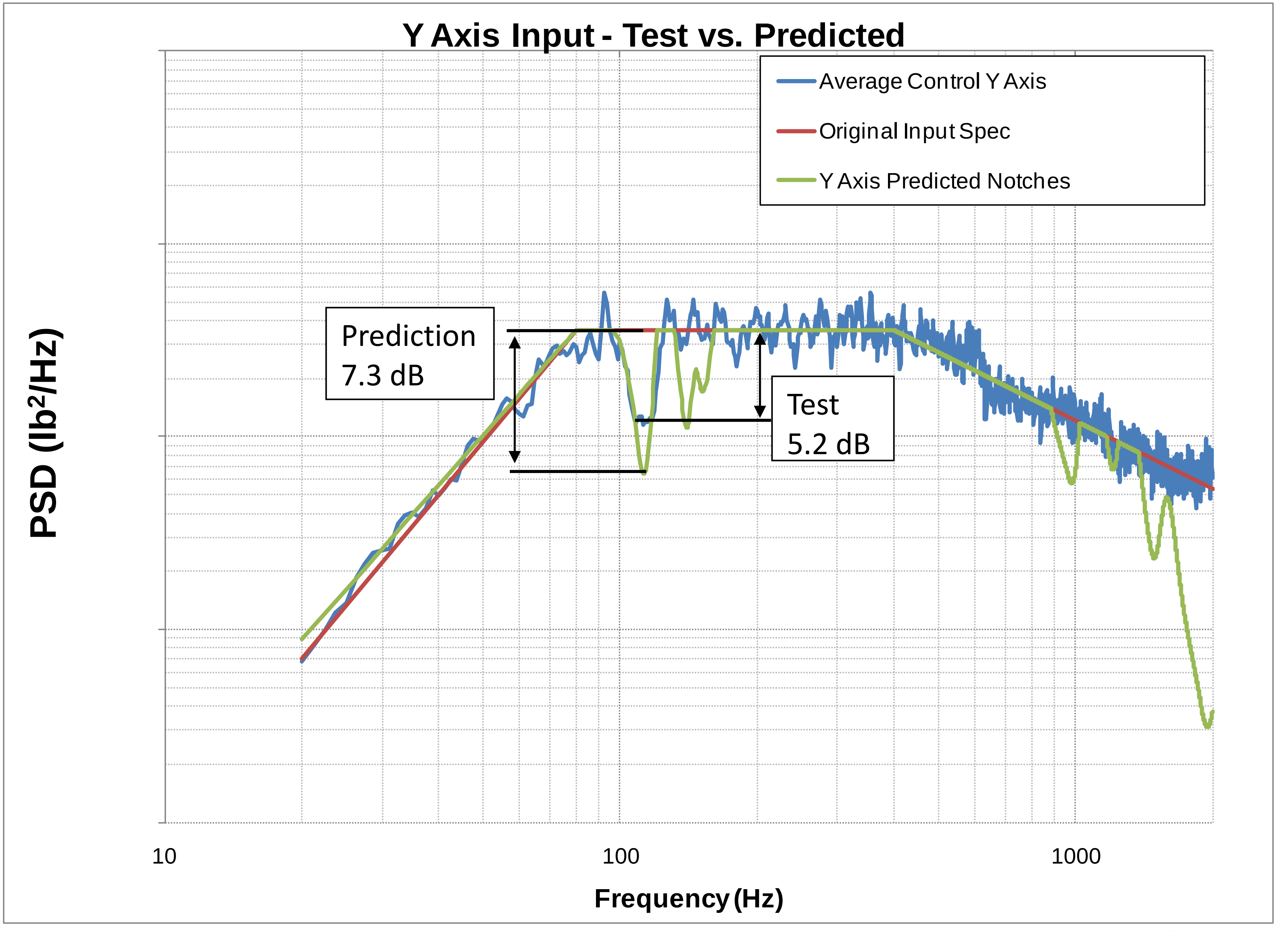
# CoNNeCT Test Force Limits



# CoNNeCT Test Acceleration Limits




Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch



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# Lessons Learned

# Lessons Learned

Invaluable lessons learned were obtained from the successful completion of the CoNNeCT force-limited protoflight testing:

1. Include as much of the flight interface hardware in the force-limiting test as possible. For the CoNNeCT testing the ExPA interface hardware was not available.

2. The coupled system should be modeled to account for the **source impedance** to more accurately determine the C value used for the semi-empirical method. For CoNNeCT the source impedance information was not accessible.

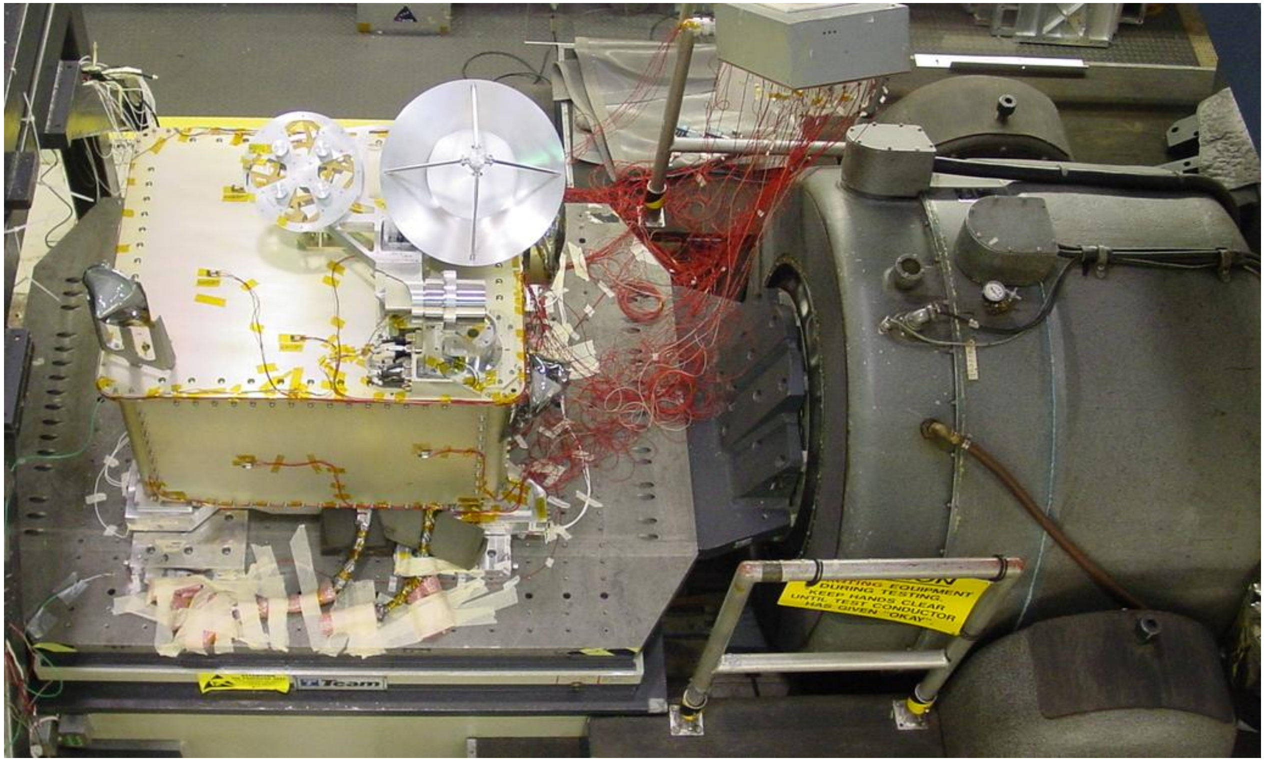
3. **Load impedance** calculations (Bias Impedance, Accelerance, and Q methods) should be performed pre-test and evaluated again after low level testing. These impedance methods should verify the application of the semi-empirical force limits.

Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch

# Conclusions

# Conclusions

- Force-limiting analysis and testing enabled the CoNNeCT project to meet technical and schedule constraints.
  - **Force-Limiting Analysis** was implemented for the strength assessment and provided positive design margins of safety for the CoNNeCT interface fasteners.
  - **Force-Limiting Testing** was successfully implemented to qualify the CoNNeCT payload for flight.






Lucas.D.Staab@nasa.gov
NASA GRC/DEV/Structural Systems Dynamics Branch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# Thank you