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

Lucas D. Staab, Mark E. McNelis, James C. Akers, Vicente J. Suarez, and Trevor M. Jones
Glenn Research Center, Cleveland, Ohio

September 2012

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Contents

Abstract 1
1.0 Introduction 1
2.0 Analysis Approach 1
2.1 Force-Limiting Background and Theory 1
2.2 CoNNeCT Finite Element Models 5
3.0 Implementation of Force-Limiting for CoNNeCT Flight System 6
4.0 CoNNeCT System Vibration Testing 9
5.0 Force Limits Evaluation 17
6.0 Component Qualification Assessment Due to Z Axis Force Limits 20
7.0 Lessons Learned and Recommendations 21
8.0 Conclusion 22
Appendix A.—Historical Force-Limiting *C* Values 25
Appendix B.—CoNNeCT Force Limits Calculations 27
References 30

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Abstract

The semi-empirical force-limiting 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 as, the Communications, Navigation, and Networking re-Configurable Testbed (CoNNeCT), project utilized force-limiting testing and analysis following the semi-empirical approach. This paper presents the steps in performing a force-limiting analysis and then compares the results to test data recovered during the CoNNeCT force-limiting random vibration qualification test that took place at NASA Glenn Research Center (GRC) in the Structural Dynamics Laboratory (SDL) December 19, 2010 to January 7, 2011. A compilation of lessons learned and considerations for future force-limiting tests is also included.

1.0 Introduction

The Space Communications and Navigation Testbed (SCAN Testbed), known at NASA as, the Communications, Navigation, and Networking re-Configurable Testbed (CoNNeCT) project will provide an on-orbit, adaptable, SDR/STRS-based facility to conduct experiments to advance the Software Defined Radio (SDR) Space Telecommunications Radio Systems (STRS) Standards. The CoNNeCT flight system will be launched aboard the Japanese H-2 Transfer Vehicle (Figure 1) Multi-Purpose Exposed Pallet (EPMP) (Figure 2) to the ISS.

Initial base shake random vibration analysis of the CoNNeCT flight payload indicated negative margins. To reduce conservatism in the analysis, a force-limiting analysis approach was used. This document will outline the steps taken for the CoNNeCT force-limiting analysis application and compare the results to those from the CoNNeCT system force-limited random vibration qualification test. Figure 3 illustrates the CoNNeCT flight mounting structure. The load and source impedances are important factors that need to be taken into account during force-limiting testing or analysis.

2.0 Analysis Approach

2.1 Force-Limiting Background and Theory

Force-limiting is a test and analysis method that gives a more realistic representation of a payload flight response to random vibration excitation. Force-limiting was initially developed and implemented for payload testing by Terry Scharton at the NASA Jet Propulsion Laboratory (JPL) to limit the structural impedance mismatch (high force) that occurs during shaker sine and random vibration testing. The NASA Headquarters chief engineer sponsored Scharton to collaborate with other NASA centers to transfer the knowledge of force-limiting as an acceptable practice for testing NASA payloads. NASA-HDBK-7004B was the result of this collaboration. Subsequent to using force-limiting for payload testing, Daniel S. Kaufman (NASA Goddard Space Flight Center (GSFC) and NESC deputy technical fellow for Loads and Dynamics) developed and implemented force-limiting analysis for the Mars Observer Laser Altimeter

(MOLA) http://analyst.gsfc.nasa.gov/ryan/MOLA/ randlim.html). Although this document deals only with random vibration force-limiting testing and analysis, NASA-HDBK-7004B gives details for sine vibration force-limiting.

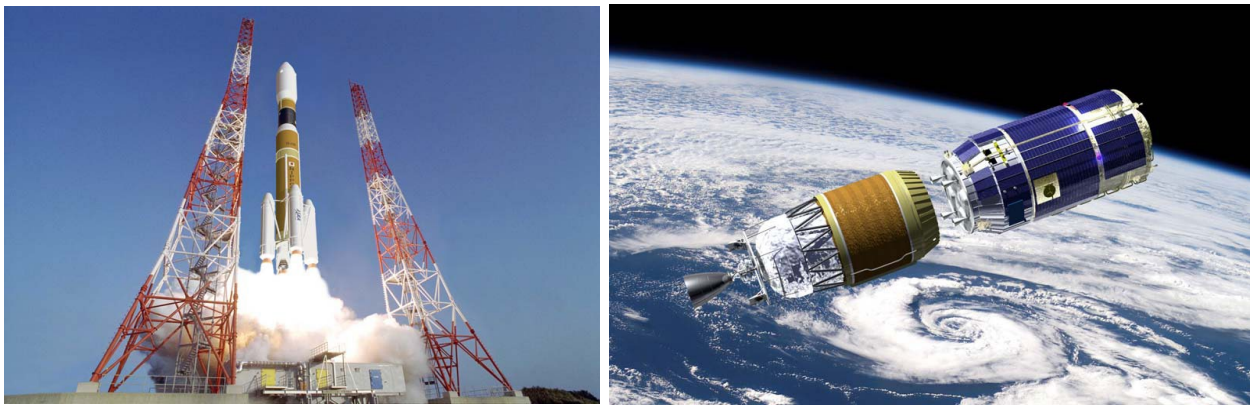

Figure 1.—JAXA Tanegashima Space Center and H-IIB Launch Vehicle (left) and upper stage and H2 Transfer Vehicle (right).

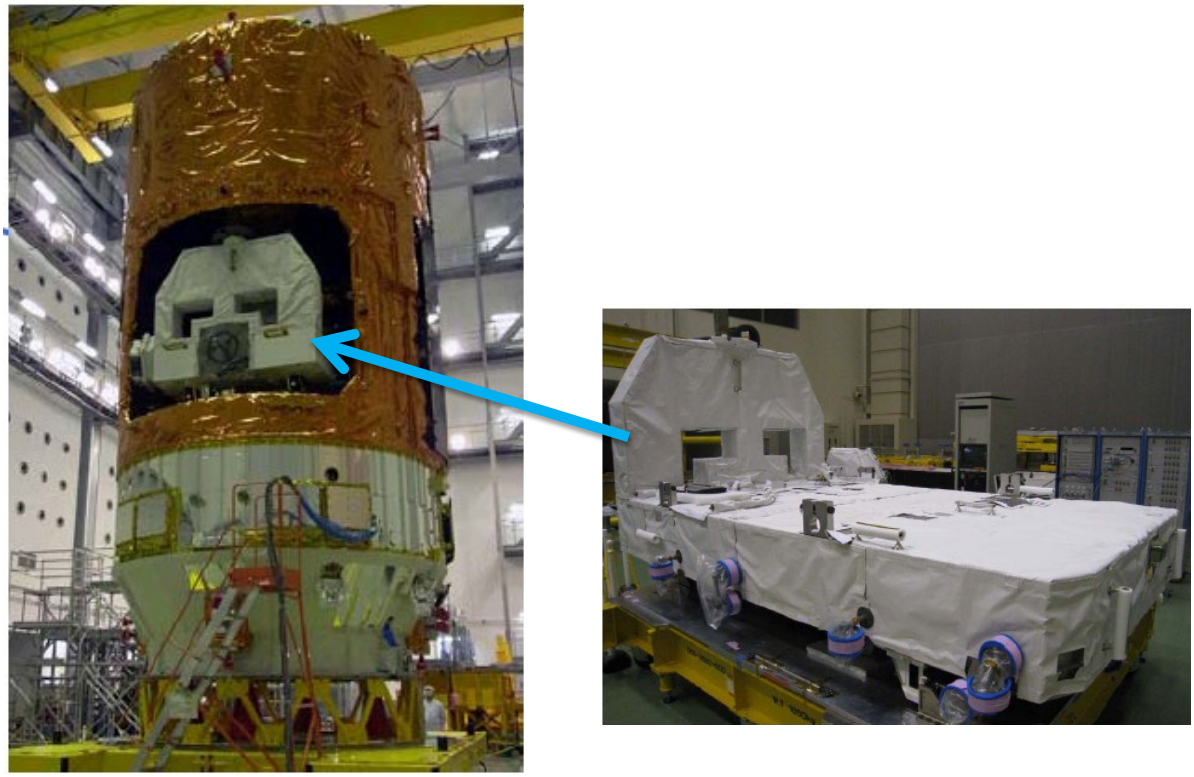

Figure 2.—HTV Configuration (left) and Multi-Purpose Exposed Pallet (right).

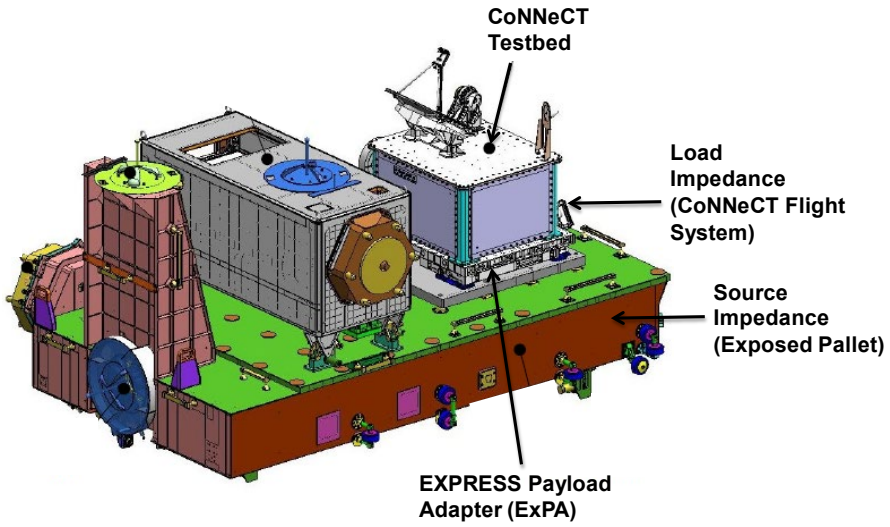

Figure 3.—CoNNeCT Flight Mounting Structure.

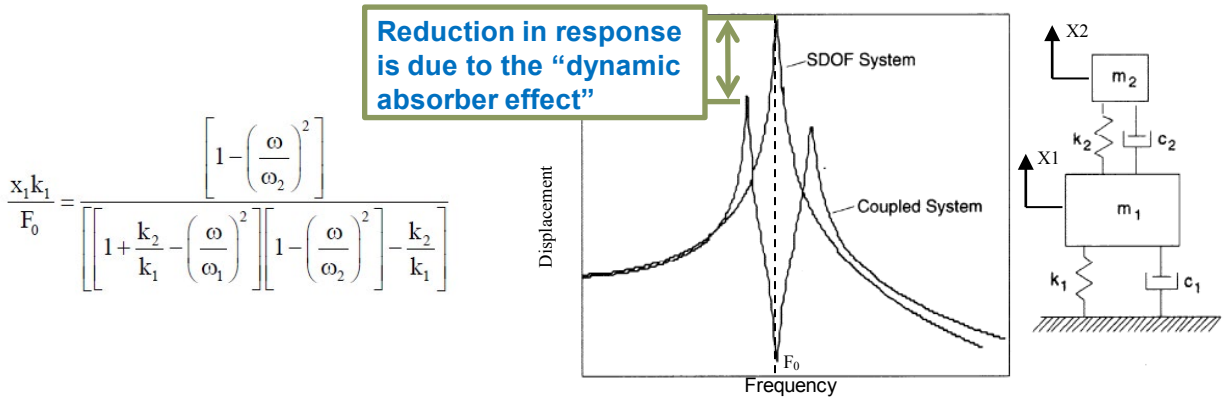

Figure 4.—Dynamic Absorber Effect.

The actual interface structural impedance between the payload and the launch vehicle is often not represented during a traditional base shake random vibration test or analysis because the interface is too stiff resulting in overdriving the payload. Hence this impedance mismatch results in a conservative estimate of the flight response analytically and during testing could result in damage to the hardware. Force-limiting can be implemented because of the dynamic absorber effect. In a coupled system, payload (m_2 in Figure 4) and launch vehicle (m_1 in Figure 4), the payload will respond much less to a flight like environment than when tested in a traditional base shake vibration test. The payload will behave much more like the SDOF system shown in Figure 4 during traditional base shake vibration testing.

Representing the launch vehicle and payload as each being a single degree of freedom (SDOF) oscillator, as shown in Figure 4, it can be seen the amount of dynamic interaction is dependent on the natural frequency of each SDOF oscillator and the stiffness ratio between the two SDOF oscillators. The separation of the two peaks in Figure 4 is dependent on the relative mass ratios of the system components (Ref. 1). The implementation of force-limiting can account for most of this reduction in response and provides a much more representative flight response.

The semi-empirical approach is one method of implementing force-limiting for vibration testing and analysis. Equations (1a) and (1b) from the NASA-HDBK-7004B outline the semi-empirical approach for force-limiting:

$$S_{FF} = C^2 M_0^2 S_{AA} \qquad f < f_0 \tag{1a}$$

$$S_{FF} = C^2 M_0^2 S_{AA} (f_o / f)^n \qquad f \geq f_0 \tag{1b}$$

- f_0 is the fundamental frequency of the payload in test setup (m_2 in Figure 4)
- S_{FF} is the force spectral density
- S_{AA} is the acceleration spectral density
- C is a nondimensional dynamic amplification factor, defines the depth of notch.
- M_0 is the total mass of the payload
- The exponent of the rolloff factor $(f_0/f)^n$ is included in the equations to reflect the decrease in the payload residual mass with frequency. A value of $n = 2$ is generally initially used but, must be verified by analysis or a low level vibration test run.

The semi-empirical approach creates a notch in the input spectrum that takes into account the impedance mismatch in the test or random vibration analysis. The implementation of force-limiting for testing and for analysis uses the same methodology.

The nondimensional dynamic amplification factor, *C*, is an important parameter used in force-limiting. The *C* value controls the depth of notch and limits the amount of force and acceleration response at the fundamental resonance of the payload. The lower the *C* value used, the deeper the notch and the less resonance response. The higher the *C* value used, the smaller the notch depth and the more resonance response. Figure 5 illustrates the effect of different *C* values and the depth of notching.

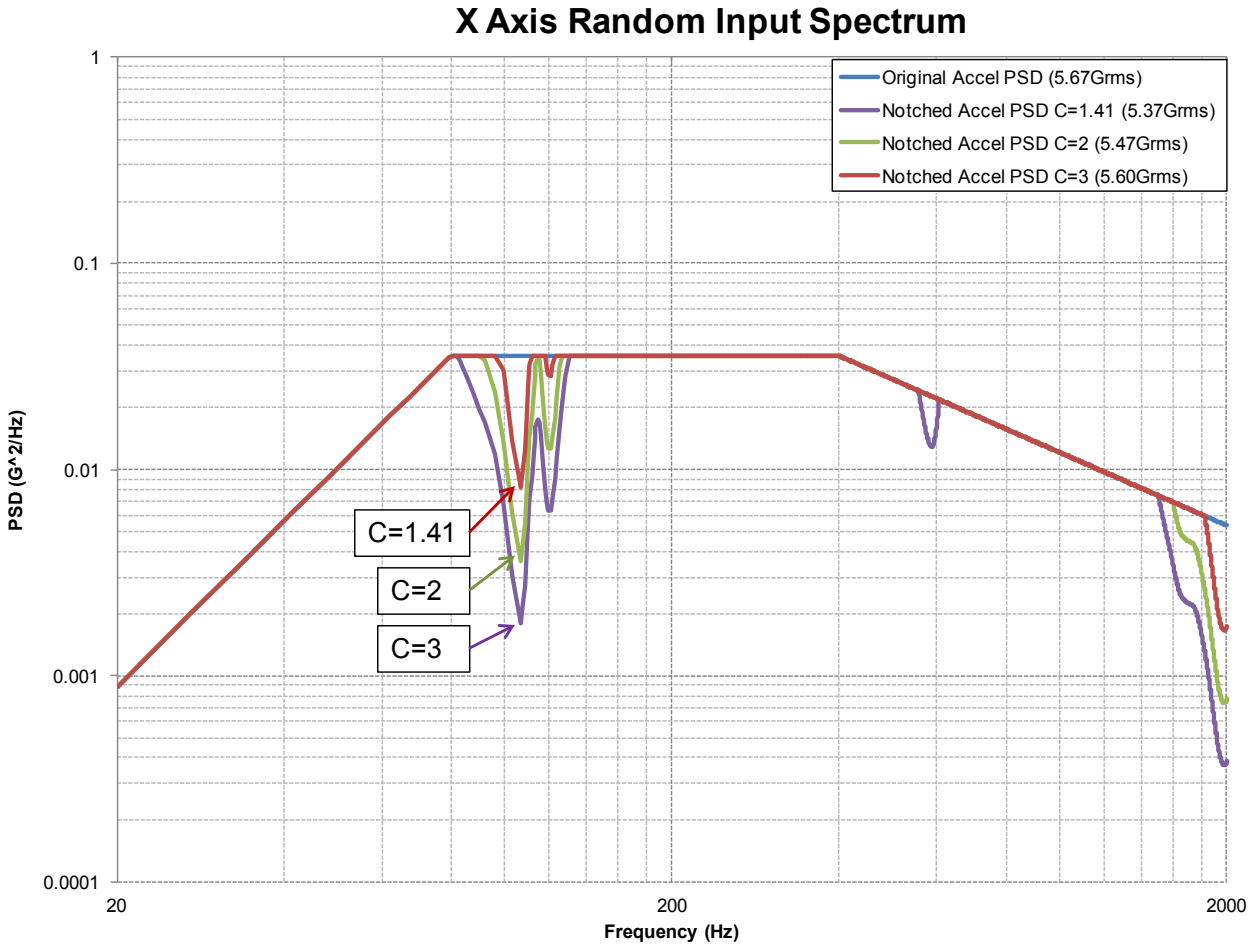

Figure 5.—Example Plot of Influence of *C* Value

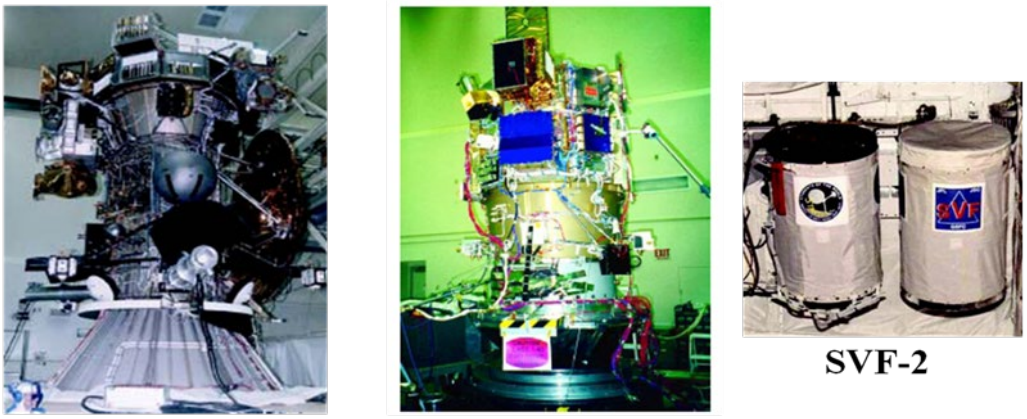

Figure 6.—Notable NASA Payloads Tested Using Force-Limiting

Force-limiting has been utilized by JPL, GSFC, NASA Langley Research Center (LaRC) and GRC to qualify flight payloads. Some notable spacecraft tested using force-limiting (Figure 6) are Cassini (M_0 = 8,380 lb, C = 0.7) (Ref. 2), Deep Space-1 (M_0 = 1,070 lb, C = 2.0) (Ref. 3), and SVF-2 (M_0 = 230 lb, C = 2.0) (Ref. 4). Scharton also validated the semi-empirical force-limiting method with in-flight force measurements for SVF-2 and the Cosmic Ray Isotope Spectrometer (CRIS). During the SVF-2 (M_0 = 230 lb) flight, the C value measured was 1.38; the in-flight C value measured for CRIS (M_0 = 65 lb) was 1.30 (Ref. 2).

2.2 CoNNeCT Finite Element Models

For the CoNNeCT project, both force-limiting testing and analysis were implemented. The CoNNeCT flight system is mounted to an EXPRESS Payload Adapter (ExPA), which was not available for the system level vibration testing. Also not available for the system level vibration testing was the Antenna Pointing System (APS) and its associated control electronics (Gimbal Control Electronics, GCE), which sits on the starboard radiator panel (top panel during testing) of the CoNNeCT flight system. Mass simulators of the APS and the GCE were therefore used for the system level test. This use of mass simulators during the system level vibration testing led to the development of two Finite Element Models (FEMs); Figure 7 shows the CoNNeCT Flight Configuration and shows the CoNNeCT Test Configuration. The CoNNeCT Test Configuration FEM was identical to the CoNNeCT Flight Configuration FEM except for the incorporation of the APS and GCE mass simulators in the CoNNeCT flight system FEM and the ExPA FEM being replaced by the test fixture FEM. The JAXA requirements specified the vibration input under the ExPA. Therefore, the vibration input was applied under the test fixture for analysis and testing. The CoNNeCT flight system FEM was updated several times before, during, and after system level vibration testing. The updates before testing were part of design maturation and changes. The updates during and after testing were based on low level test data to provide more accurate response limit predictions for the system components during the test. Each time the FEM was updated, a new set of analyses, force limit curves, and component evaluation was completed. The test fixture was correlated during the fixture certification survey prior to the start of vibration testing.

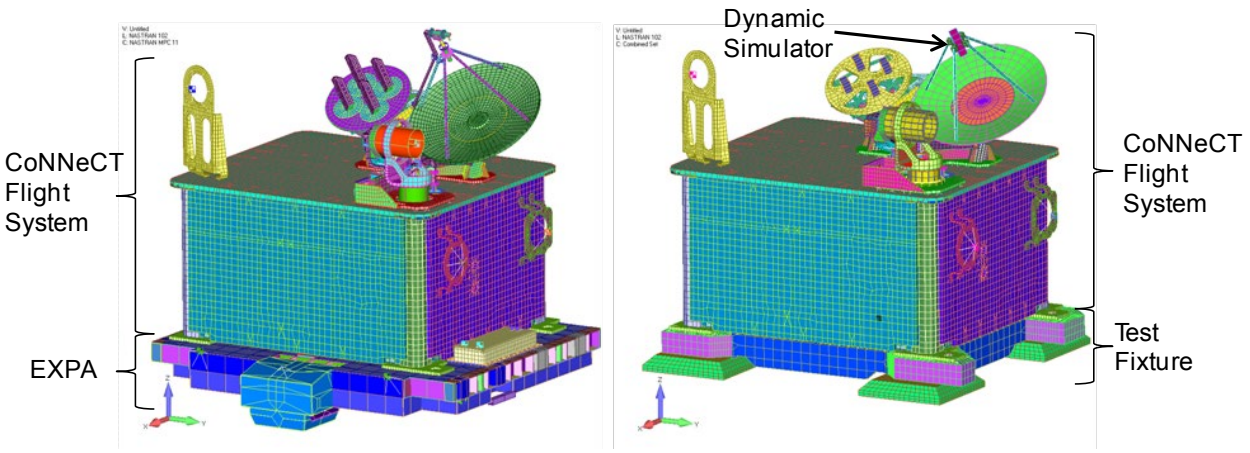

Figure 7.—CoNNeCT Flight Configuration (left); Test Configuration (right)

Analysis presented in this report is based on the Version 11 Revision 2 (released January 6, 2011) FEM of the CoNNeCT flight system. This FEM was updated based on the results of the system level vibration test. The CoNNeCT flight system weight was measured in the lab prior to testing and the FEM weight was adjusted to match the measured results. The total weight of the flight configuration FEM (CoNNeCT flight system and ExPA mounting platform) is 795.35 lb; of which 527.86 lb is the CoNNeCT flight system. The CoNNeCT Test Configuration FEM (CoNNeCT flight system and test fixture) total weight is 741.40 lb; of which 519.72 is the CoNNeCT flight system. The primary difference in the weight of the CoNNeCT flight system is due to the APS mass simulator used in the test configuration. The CoNNeCT Flight Configuration FEM has a total of 314,574 degrees of freedom and the test configuration has a total of 342,708 degrees of freedom.

The boundary condition for the random vibration analysis is enforced acceleration at the rigid interface between the ExPA/launch vehicle (flight configuration) or the test fixture/shaker table (test configuration). At the base of each of the FEMs is a rigid element (RBE2) connected from the center out to all the attach points of the models. In the flight configuration, the rigid element attached to the seven locations where the ExPA interfaced with the carrier (Figure 9). For the test configuration, the rigid element was attached at the 36 locations where the test fixture bases bolted to the shaker table (Figure 9). Enforced acceleration excitation was applied at the rigid interface with the input flight (4.0 grms) and protoflight (5.66 grms) acceleration spectrums provided by JAXA (Figure 8). In both models, the acceleration was applied to the center (independent) node of the rigid element.

3.0 Implementation of Force-Limiting for CoNNeCT Flight System

The semi-empirical force-limiting approach was used for force-limiting analysis as GRC was not provided with the JAXA launch vehicle interface (source) impedance.

When using the semi-empirical method, the mass (M_0) is determined from the most recent CoNNeCT flight system FEM, which includes the ExPA or test fixture depending on the configuration being analyzed. The CoNNeCT flight system weight/mass was updated based on the weight measurements taken during CoNNeCT system level vibration testing. S_{AA}, the acceleration spectral density, is based on the JAXA provided input acceleration spectrum. The fundamental resonant frequency, f_0, is obtained from a modal analysis of the payload FEM or from a low-level random vibration test. The C value, the dynamic amplification factor, is chosen based on the configuration of the flight system (load) impedance and launch vehicle interface (source) impedance.

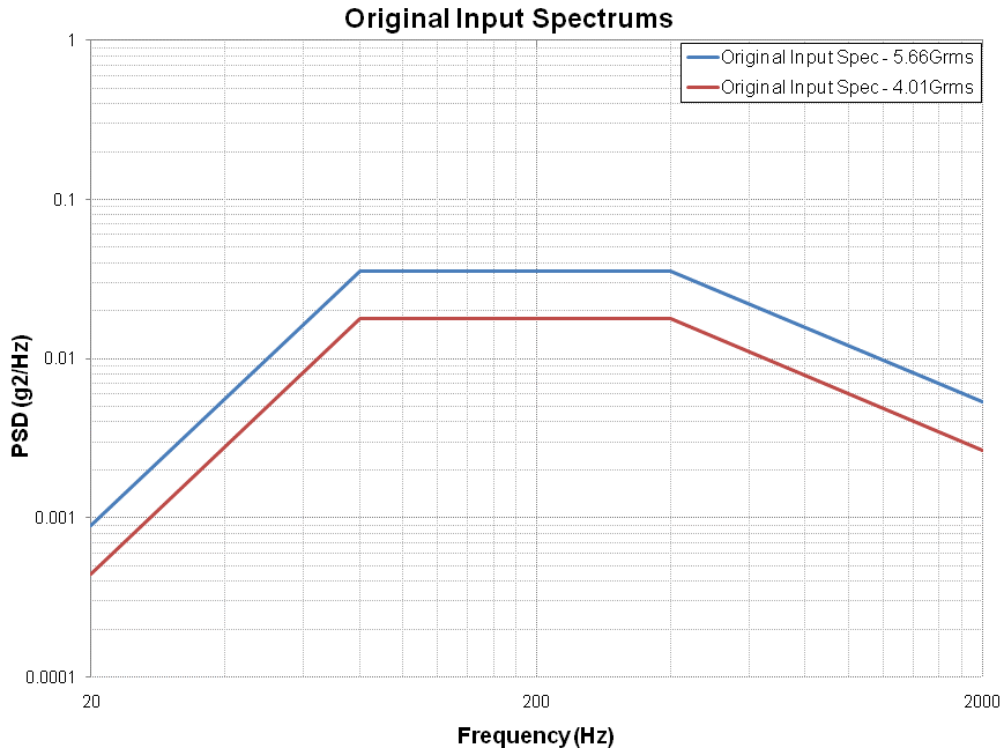

Figure 8.—Unnotched Protoflight and Flight Input Acceleration Spectrums

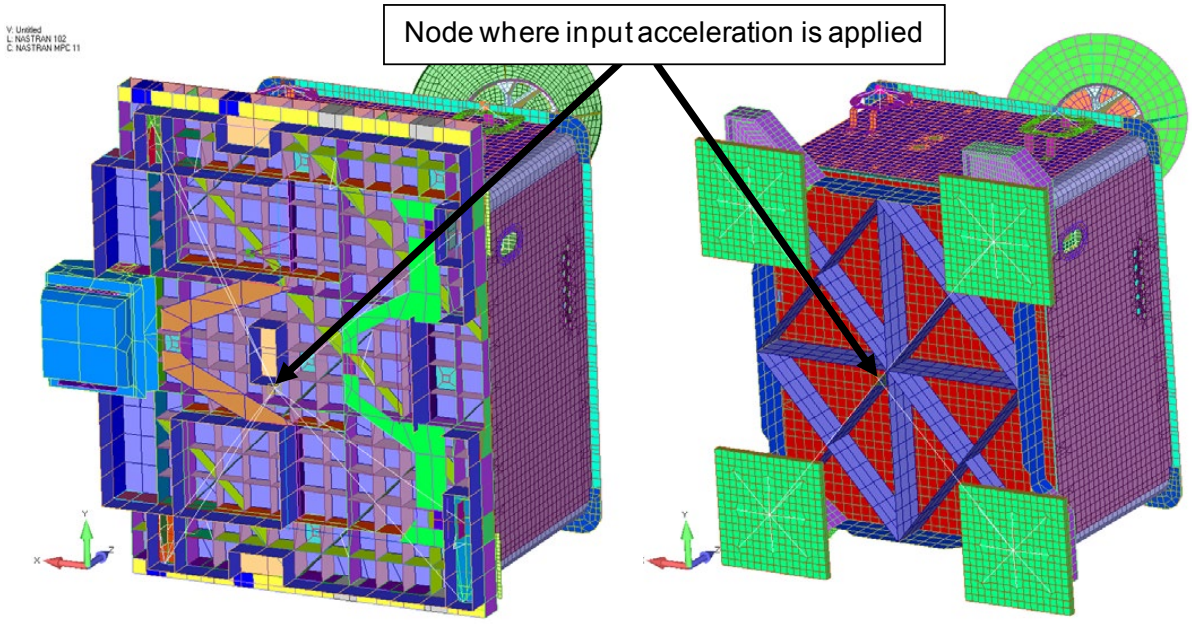

Figure 9.—CoNNeCT Flight Configuration (left) and Test Configuration (right) Input Acceleration Locations

A listing of C values used on payloads weighing between 1 and 8,380 lb is listed in Appendix A. Note these C values range from 0.7 to 2.2. For the CoNNeCT flight system, a value of $C = 2.0$ was chosen in lieu of not having the JAXA HTV launch vehicle impedance data and being conservative compared to the provided values listed in Appendix A. The selection of $C = 2.0$ for the CoNNeCT flight system was also reviewed by NASA force-limiting experts Terry Scharton (retired JPL) and Daniel S. Kaufman (GSFC) and has their concurrence. Load impedance analysis of the test data was performed by Daniel S. Kaufman, which verified the selection of $C = 2$ (Section 5.0). A better method for choosing a C value would be to use the coupled system FEM, which includes both the load (CoNNeCT flight system) and source (launch vehicle) impedances. For CoNNeCT, the source impedance data was not available for analysis or testing.

In force-limiting vibration testing, the shaker controller adjusts the shaker's vibration level such that it meets the controlled average acceleration Power Spectral Density (PSD) at the base of the test article while the controlled average force PSD at the base of the test article is limited to a user defined force-limiting curve. Hence during testing, the shaker controller automatically takes care of notching the input acceleration PSD based on the user defined force-limiting curve.

In force-limiting analysis, the same methodology is used as in force-limiting testing. The same force limits that are applied in testing are also applied in the random vibration base shake analysis. Because MSC NASTRAN SOL 103 cannot duplicate the notching function of the shaker controller, the following steps are used in a NASTRAN force-limited base shake random vibration analysis:

Step 1. Apply the input acceleration PSD (unnotched, Figure 7) 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 (Figure 8).

Step 2. Create a force-limited PSD (FL_FPSD) based on the semi-empirical equations (Eqs. (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_0 and is used in the semi-empirical equation.

Step 3. Create the notched new acceleration input PSD (Eq. (2)). 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.

$$\text{New\_Accel\_PSD} = \left(\frac{\text{FL\_FPSD}}{\text{FPSD}}\right) * \text{Original\_Accel\_PSD}\ , \quad \left(\frac{\text{FL\_FPSD}}{\text{FPSD}}\right) < 1 \tag{2a}$$

$$\text{New\_Accel\_PSD} = \text{Original\_Accel\_PSD}\ , \quad \left(\frac{\text{FL\_FPSD}}{\text{FPSD}}\right) \geq 1 \tag{2b}$$

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. Another option that would avoid repeating the entire FEA with the new notched input acceleration PSD would be to recover frequency response functions (FRFs) of all desired response data in Step 1. Multiplying the new notched input acceleration PSD by the FRF2 results in a response PSD.

Figure 10 shows three force-limiting curves using three commonly selected C values, $C = 1.41$, $C = 2$, and $C = 3$ compared with the unlimited force PSD recovered at the base of a CoNNeCT FEM from a random vibration base shake analysis. The figure illustrates as the C value decreases, the interface force will also be reduced.

Figure 11 shows the unnotched, and notched input acceleration PSD created from the force limits shown in Figure 10 for $C = 2.0$. A value of $C = 2.0$ is shown as it relevant to the CoNNeCT project testing and analysis. Figure 5 shows the three notched acceleration spectrums corresponding to the force limits used in Figure 10 for $C = 1.41$, $C = 2.0$, and $C = 3.0$.

Figure 12 shows the force PSD (X Axis $C = 2$) recovered when the notched new input acceleration PSD, using $C = 2.0$, is applied to the CoNNeCT FEM. Also shown are the force PSD from the unnotched input spectrum (X Axis Unnotched), and the semi-empirical force-limiting curve (Force Limit $C = 2$). Note how the new force PSD (X-Axis $C = 2$) has been limited compared to the semi-empirical force limit (Force Limit $C = 2$).

4.0 CoNNeCT System Vibration Testing

The methodology for implementing force-limiting for testing and analysis is the same. For a traditional base shake analysis or test, the high interface impedance at the test article to shaker interface results in a conservative (high) test article response. By implementing force-limiting, the impedance mismatch is accounted for, and a more realistic flight response is obtained.

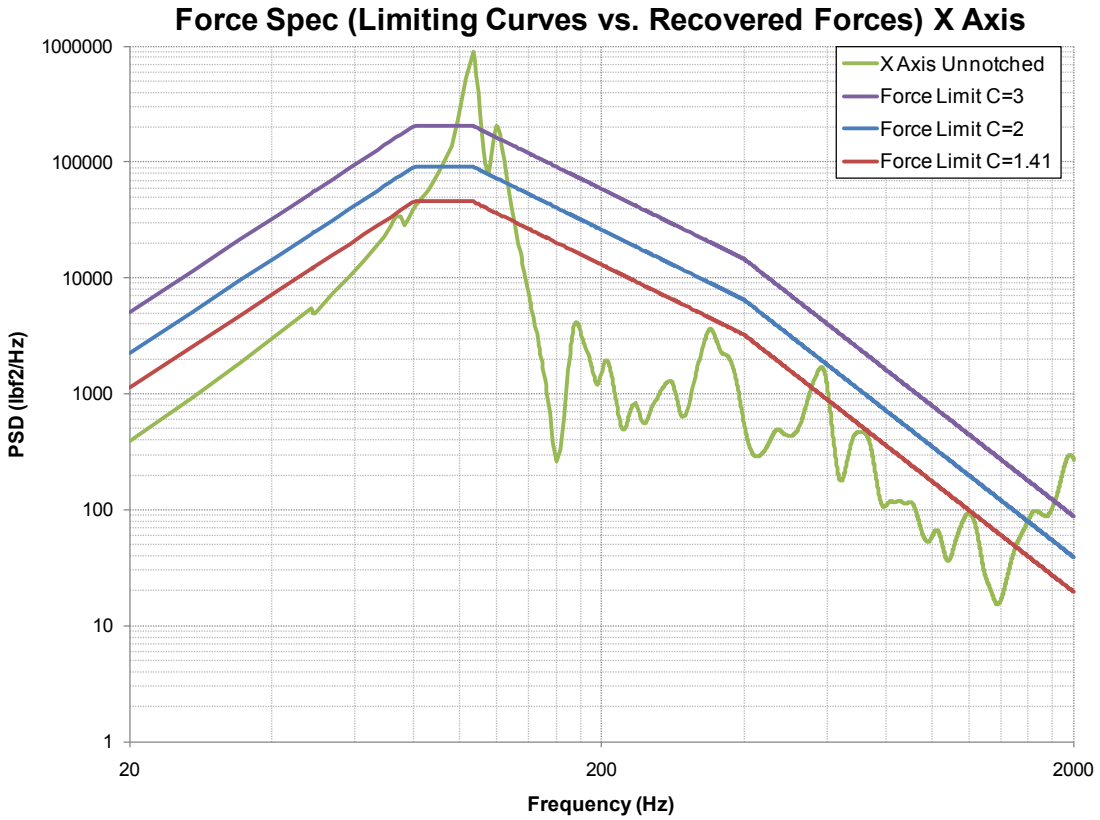

Figure 10.—Example Force Limit Spectra

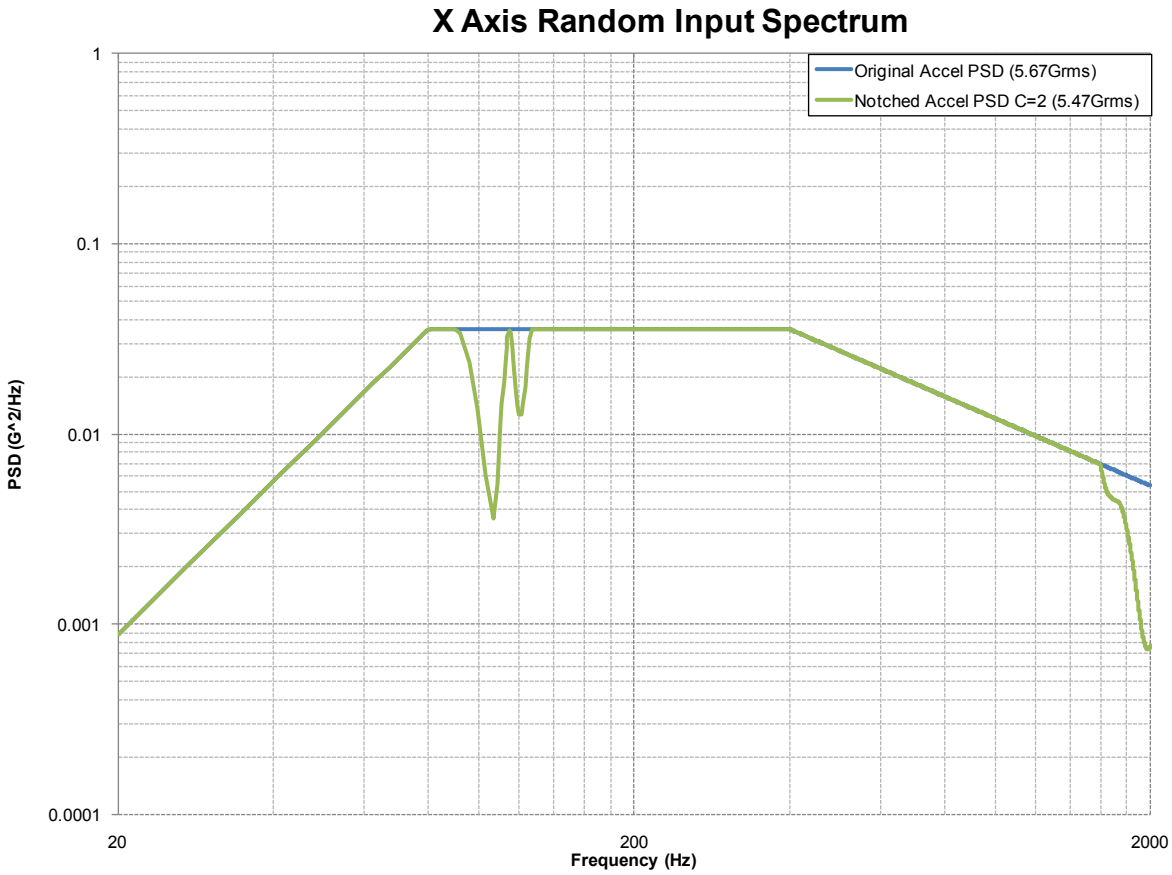

Figure 11.—Example Notched Input Acceleration Spectrum

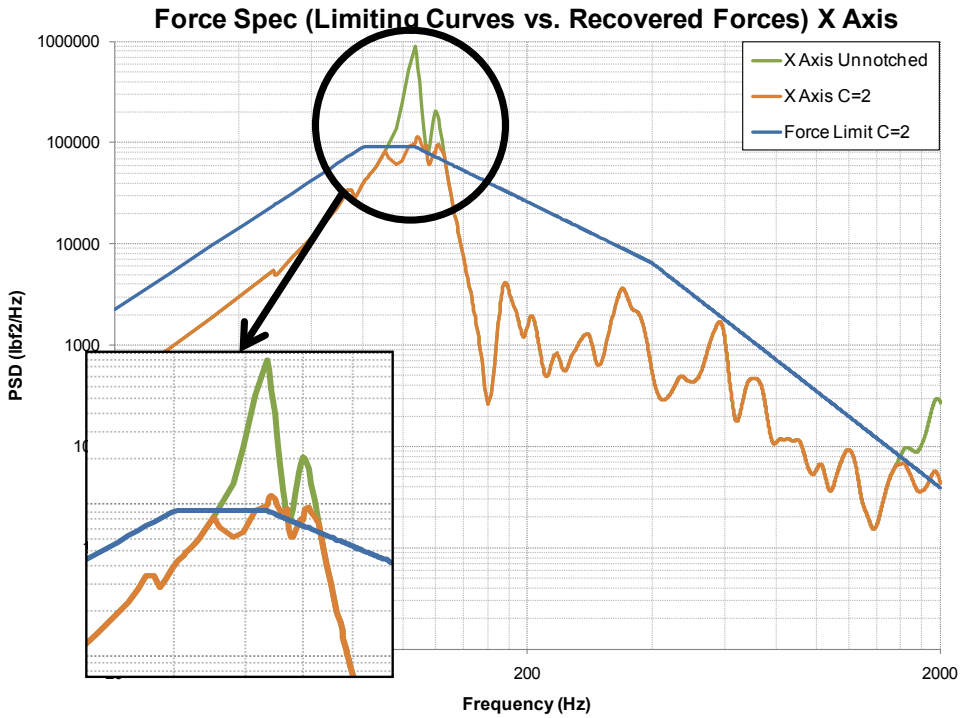

Figure 12.—Example Limited Force PSD

The semi-empirical approach was used for the CoNNeCT system level vibration testing that took place in the Structural Dynamics Laboratory (SDL) at GRC on December 19, 2010 to January 7, 2011. Figure 13 shows the Y axis test setup and Figure 14 shows the Z axis test setup with a callout to the load cell locations. $C = 2.0$ was used during testing. The force-limiting analysis spectrum is based on the same methodology used during the CoNNeCT system vibration testing. Therefore, the interface forces applied in the CoNNeCT flight analysis model are representative of the forces seen by the CoNNeCT system vibration test article during protoflight testing. The force-limiting curves that were imposed in both instances produce very similar interface forces between the CoNNeCT flight system and its mounting structure (EXPA in flight configuration and test fixture in test configuration).

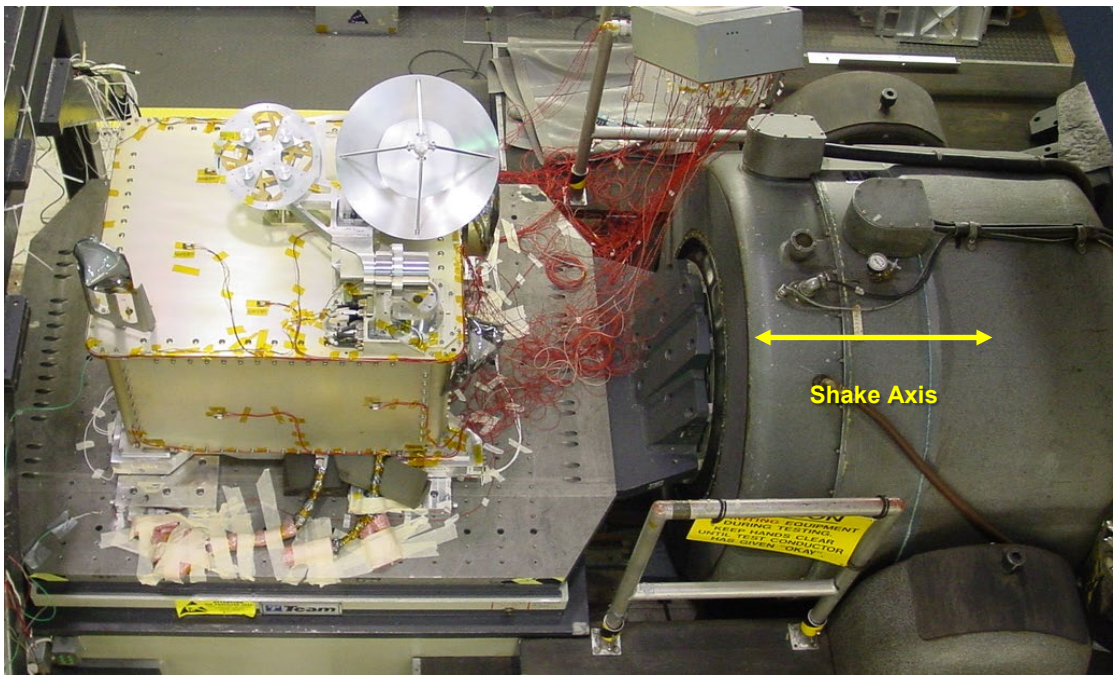

Figure 13.—CoNNeCT System Vibration Testing Y Axis Base Shake

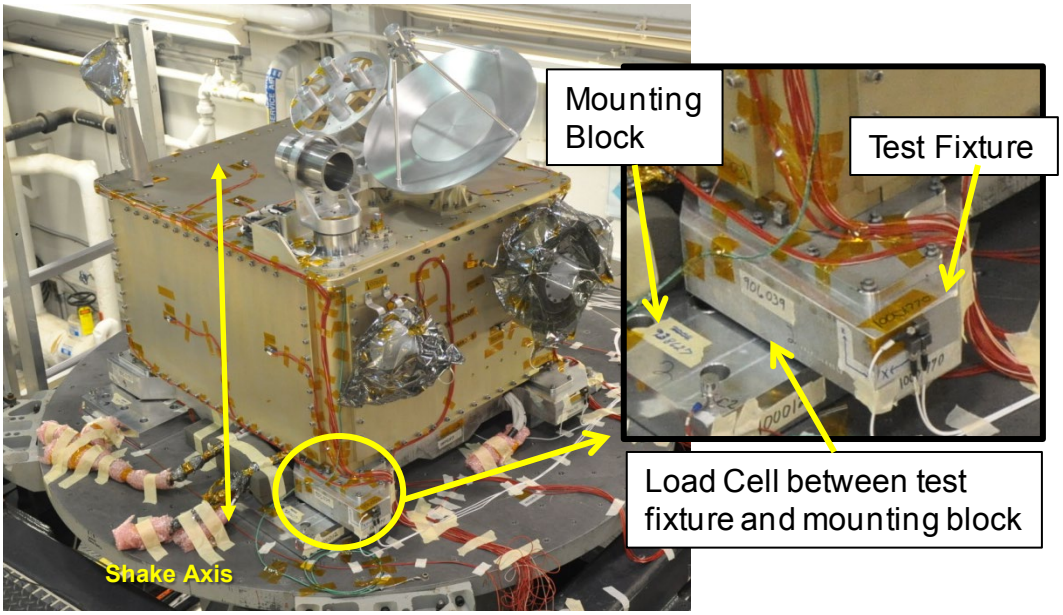

Figure 14.—CoNNeCT System Vibration Testing Z Axis Base Shake

Equations (1a) and (1b) define the semi-empirical force-limiting method. The roll-off factor, n, was initially picked to be 2. To determine the roll-off factor, n, from a low-level test, the asymptotic apparent mass is used. The apparent mass is defined to be the frequency response function (FRF) of the reaction force (sum of the load cell measurements) divided by the applied base acceleration (acceleration of the shaker slip table/expander head at the center of the test articles footprint) and therefore has a real and imaginary component (Ref. 5). This is an accurate estimate of the true apparent mass for frequencies below which the shaker slip table or expander head do not flex. One method used to calculate the asymptotic apparent mass, which is a real quantity, is to take the geometric average of the magnitude of the apparent mass (i.e., FRF of base acceleration to reaction force) over frequency, such that there is an equal area of the magnitude of the apparent mass curve above and below the asymptotic apparent mass line when plotted with log-log scaling. The roll-off factor, n, is then twice the slope of the roll off of the asymptotic apparent mass line when plotted on a log-log scale. The roll-off factor, n, is twice the slope of the asymptotic apparent mass line (scalar function) because it is being used to define the input force PSD (power function) (Refs. 6, 7, and 8). Figure 15 to Figure 17 presents the test-based apparent mass and asymptotic apparent mass of the CoNNeCT flight system during the system level vibration test. It can be seen the slope of the roll off of each asymptotic apparent mass line is approximately unity. Thus, the roll-off factor of $n = 2$ is used during the force limited system level test. The knee in the asymptotic apparent mass curve is at the same frequency, f_0 that is used in the force limited semi-empirical equations.

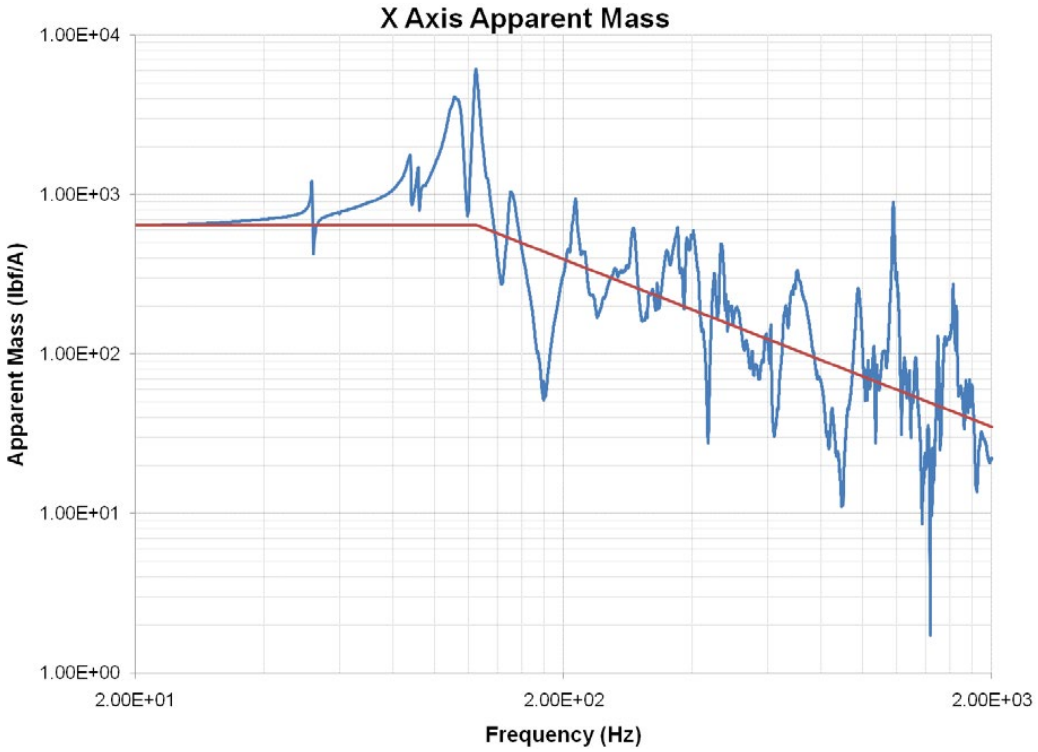

Figure 15.—X Axis Apparent Mass (blue) and Asymptotic Apparent Mass (red)

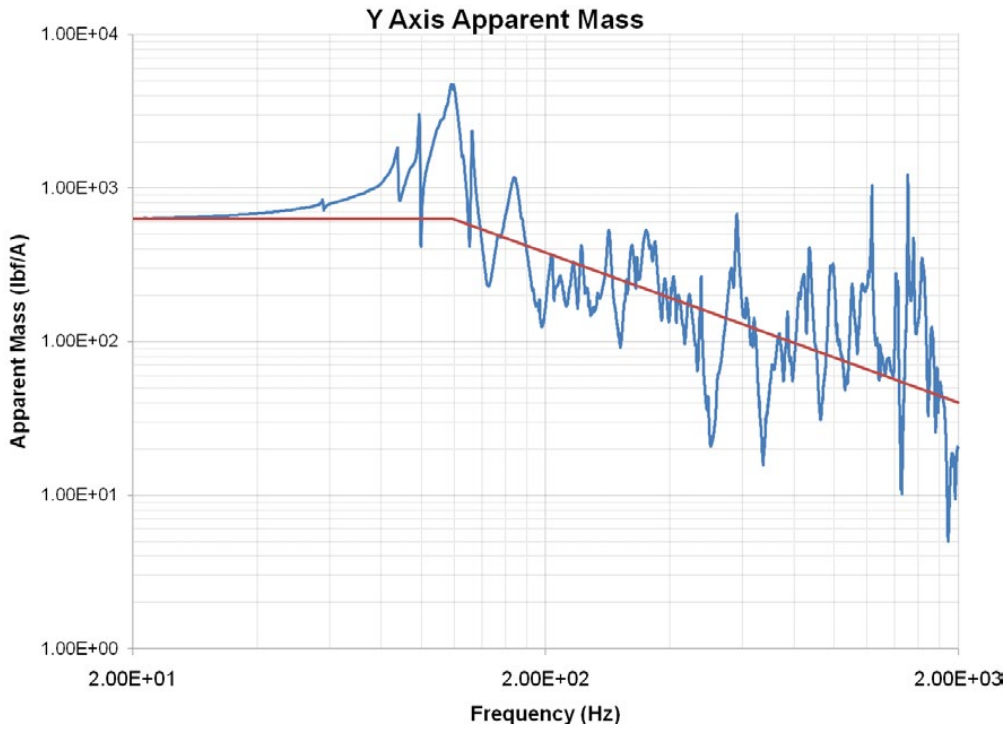

Figure 16.—Y Axis Apparent Mass (blue) and Asymptotic Apparent Mass (red)

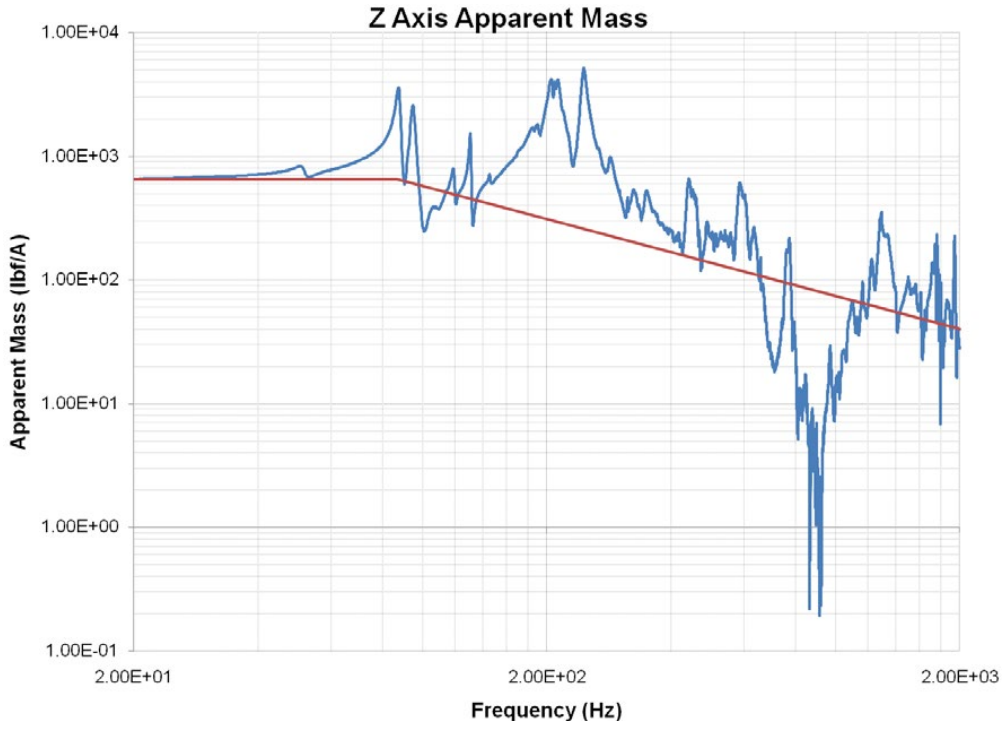

Figure 17.—Z Axis Apparent Mass (blue) and Asymptotic Apparent Mass (red)

The semi-empirical force limits for the CoNNeCT system test were calculated using M_0 = 635 lb (this was the total weight above the load cells), C = 2.0, n = 2, and f_0 found from a low level random vibration test run. For the CoNNeCT flight system, the X-Axis fundamental frequency is f_0 = 125 Hz; the Y-Axis fundamental frequency is f_0 = 119 Hz; and the Z-Axis fundamental frequency is f_0 = 87 Hz. Appendix B

provides the actual calculations of the test force limits for each axis. Figure 18 to Figure 20 present the total load cell force recovered during the CoNNeCT system vibration test with the force-limiting spectrum superimposed for each axis tested. Each figure shows how the load cell response was limited by the semi-empirical force limit spectrum during the test within the test control tolerances.

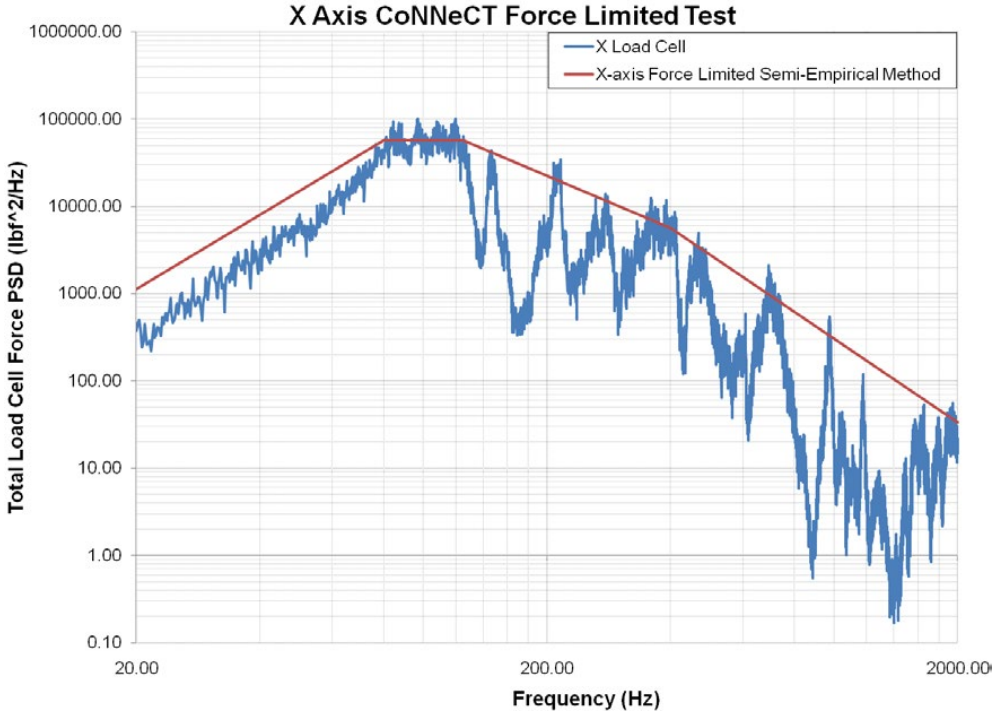

Figure 18.—X Axis Total Load Cell Force

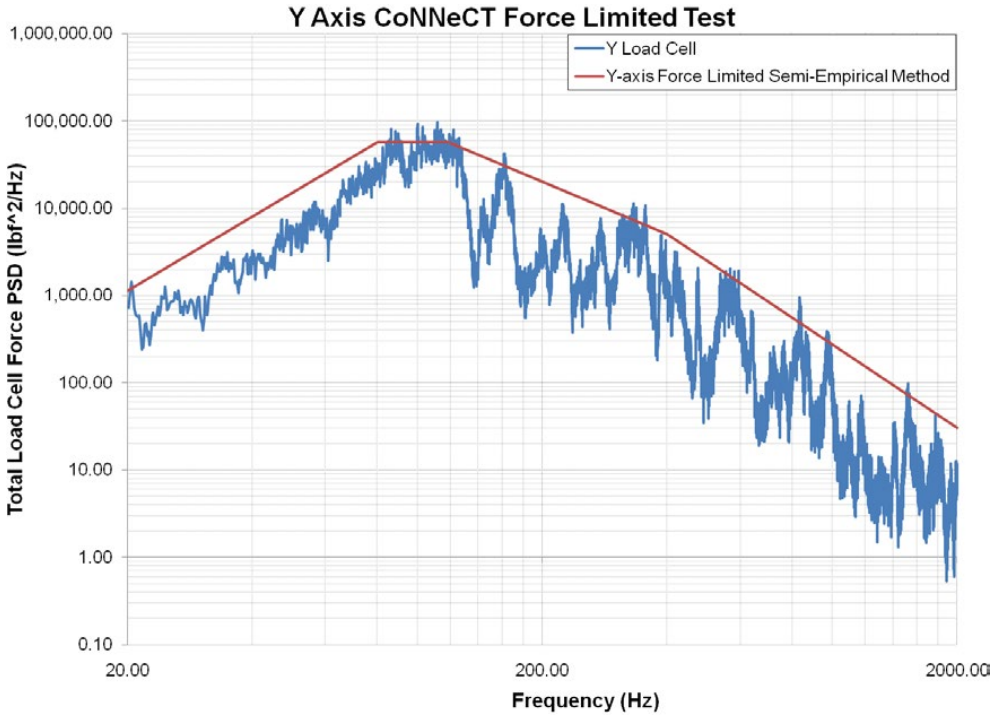

Figure 19.—Y Axis Total Load Cell Force

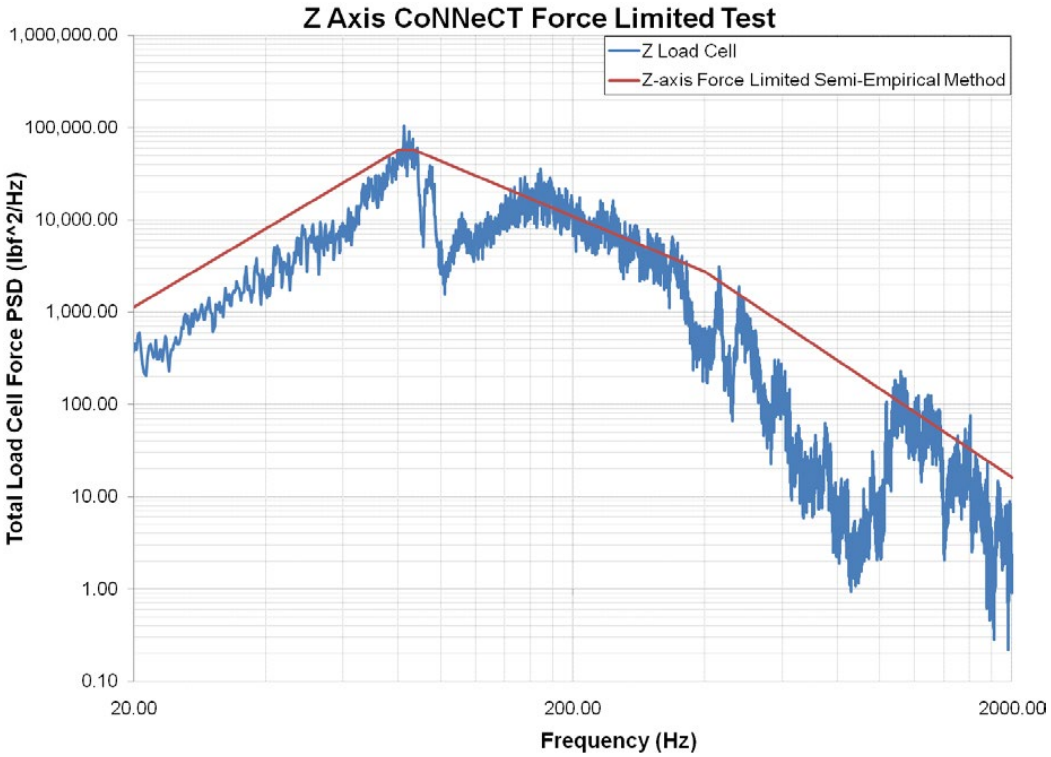

Figure 20.—Z Axis Total Load Cell Force

When force limits are applied during a vibration test, the shaker controller automatically notches the input acceleration spectrum. In force-limiting analysis, the input spectrum must be notched manually using the procedure described in Section 4.0 of this document. The CoNNeCT analysis model was updated (Version 11 Revision 2) based on the results of the system vibration test, and new notched input spectrums were created. Figure 21 to Figure 23 present the predicted notched input spectrum overlaid with the average control response from the CoNNeCT system vibration test. For each axis, the two spectrums (analysis vs. test) follow similar trends in the lower frequency range (< 300 Hz). The 16 dB notch in the Z Axis test may have been excessive; Sections 6.0 and 7.0 address this issue. Also, the high frequency notches (due to the test fixture interactions) that appear in the analysis predictions were not representative of the test. The differences between the test and analysis curves in Figure 21 to Figure 23 are due to differences in the as built hardware and the FEM.

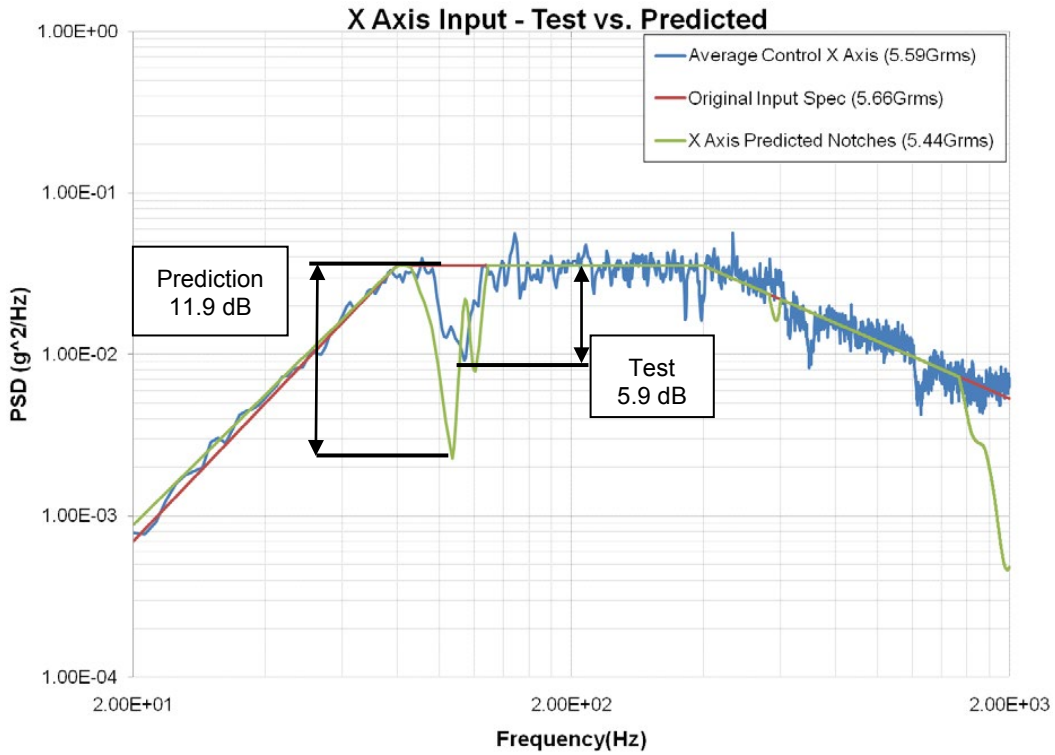

Figure 21.—X Axis Input Acceleration Spectra (Test vs. Analytical Prediction)

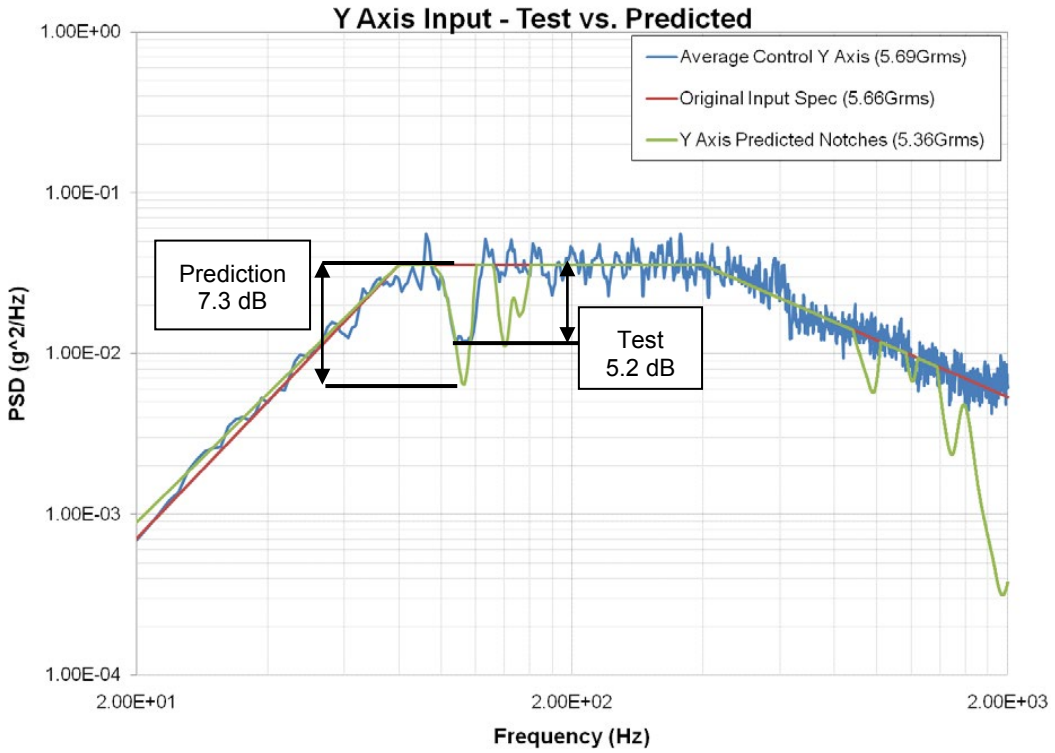

Figure 22.—Y Axis Input Acceleration Spectra (Test vs. Analytical Prediction)

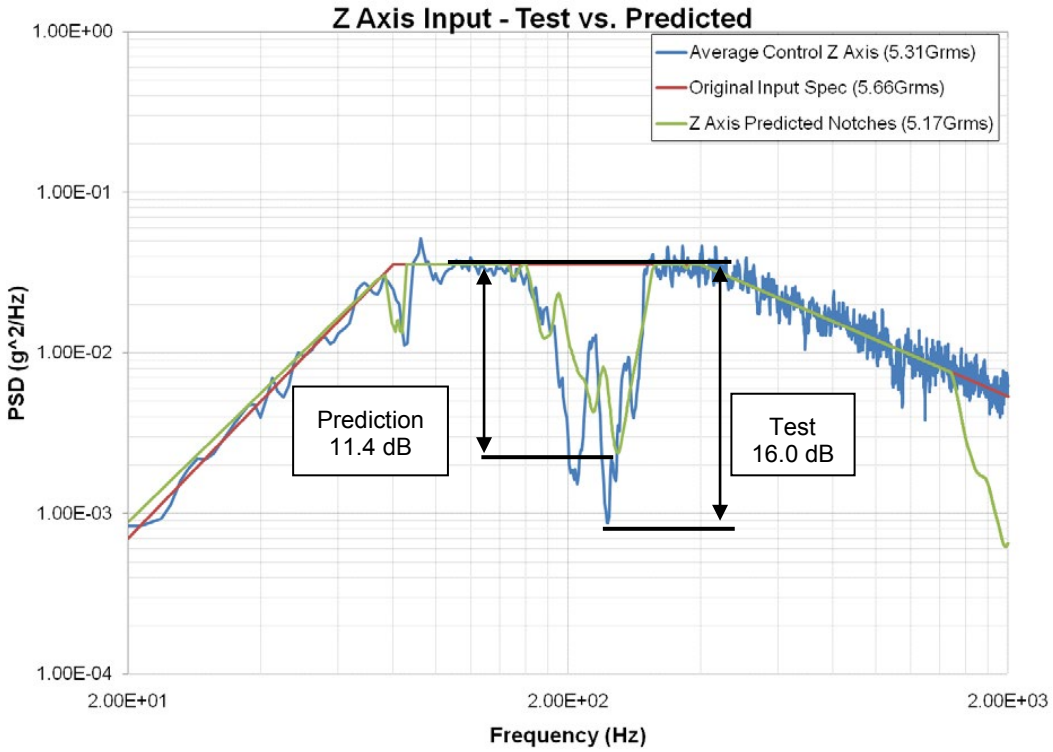

Figure 23.—Z Axis Input Acceleration Spectra (Test vs. Analytical Prediction)

5.0 Force Limits Evaluation

Due to the unavailability of the CoNNeCT launch vehicle mounting structure (source impedance) following the system vibration test, Daniel S. Kaufman (GSFC) provided a report to GRC evaluating the selection of $C = 2.0$ and an overall assessment of the test force limits. The report summarizes three load impedance methods used to independently evaluate the semi-empirical force-limiting method and provides added confidence in the force limits imposed during system level vibration testing (Ref. 9).

1. Bias Impedance
2. Accelerance
3. Q Method

These methods are not meant to give exact force limits but, rather to provide bounds on the force limits. In general force limit calculations consist of finding a force spectrum based on a given acceleration spectrum. Each of the methods described above along with the semi-empirical method entails the calculation of an impedance function. The basis of the force-limiting methodology is that the applied force limits are representative of the flight forces.

The following briefly describes each of the force limit methods that were used in Kaufman's report (Ref. 9).

***Unnotched force*:**

$$S_{ffu}(f) = [W_L(f)]^2 S_{aau}(f)$$

where

$S_{ffu}(f)$ unnotched force spectral density [lbf^2/Hz]
$W_L(f)$ is the driving point apparent mass or acceleration impedance of the article [lb/g]
$S_{aau}(f)$ unnotched acceleration spectral density [g^2/Hz]

***Load Impedance Force Limits or forces to notch*:** the unnotched acceleration is multiplied by an attenuation function with respect to the load impedance.

$$S_{ffn}(f) = K(f)\, S_{aau}(f)$$

where

$S_{ffn}(f)$ Notched force spectral density [lbf^2/Hz]
$K(f)$ Force limit factor [lbf^2/g^2]

***Semi-empirical method*: (SE)**

$$K(f) = C^2 M^2 \qquad \text{for } f < f_0$$

$$K(f) = C^2 M^2 (f/f1)^{-n} \qquad \text{for } f > f_0$$

where

M Test item static mass [lb]
C Factor for semi-empirical approach (CoNNeCT used a value of 2.0)
f_0 Test item first major mode with the largest effective mass [Hz]
n Roll-off factor (n=2 is a starting reference, but it has to be evaluated and adjusted based on additional considerations such as measured test article apparent mass characteristics)

***Bias Impedance method*:**

$$W_b(f) = \mathrm{W}_{\min}(f) + 0.1\,[\mathrm{W}_{\max}(f) - \mathrm{W}_{\min}(f)]$$

$$K(f) = [W_b(f)]^2$$

where

$W_b(f)$ Biased acceleration impedance [lb/g]
$W_{\min}(f)$ Minimum acceleration impedance [lb/g]
$W_{\max}(f)$ Maximum acceleration impedance [lb/g]

***Accelerance method*:**

$$K(f) = [Al(f)\, Al_E(f)]^{-1}$$

where

$Al(f)$ Load accelerance [g/lb]
$Al_E(f)$ Load accelerance envelope [g/lb]

***Q method*:**

$$K(f) = M_{eff}(f)^2\, Q(f) + M_{res}(f)^2$$

where

$Q(f)$ Amplification factor
$M_{eff}(f)$ Effective mass of mode f (or weight) [lb]
$M_{res}(f)$ Residual Mass mode f [lb]

Figure 24 thru Figure 26 compare all four force limit methods to the unnotched test forces $S_{ffu}(f)$ and the measured test forces S_{ffT}. For the X Axis (Figure 24) and Y Axis (Figure 25), Kaufman suggests that the force limits applied during the CoNNeCT system test with a C = 2.0 were adequate because the semi-empirical method with C = 2 enveloped the other three methods. However, for the Z Axis (Figure 26), Kaufman recommended changing f_0 = 87 Hz to f_0 = 200 Hz, due to the presence of a second high effective mass mode. By using f_0 = 87 Hz in the CoNNeCT system test, the resulting notches at ~200 Hz in the Z Axis were too deep compared to the other three impedance methods. However, the C = 2.0 value is still adequate.

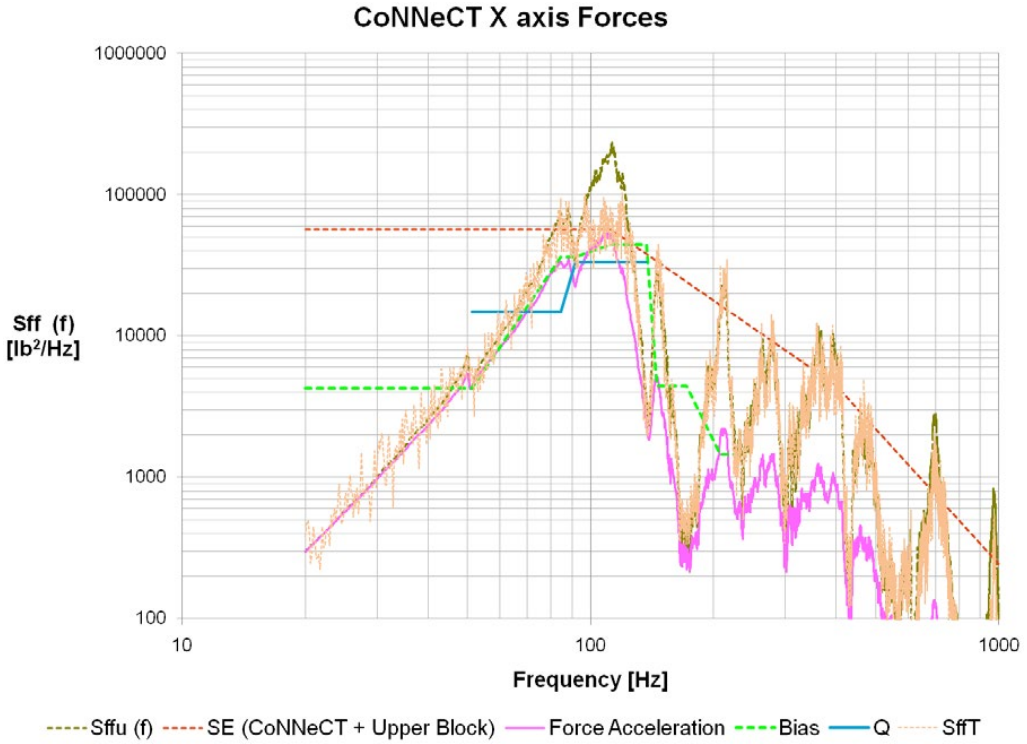

Figure 24.—X Axis Force Limits

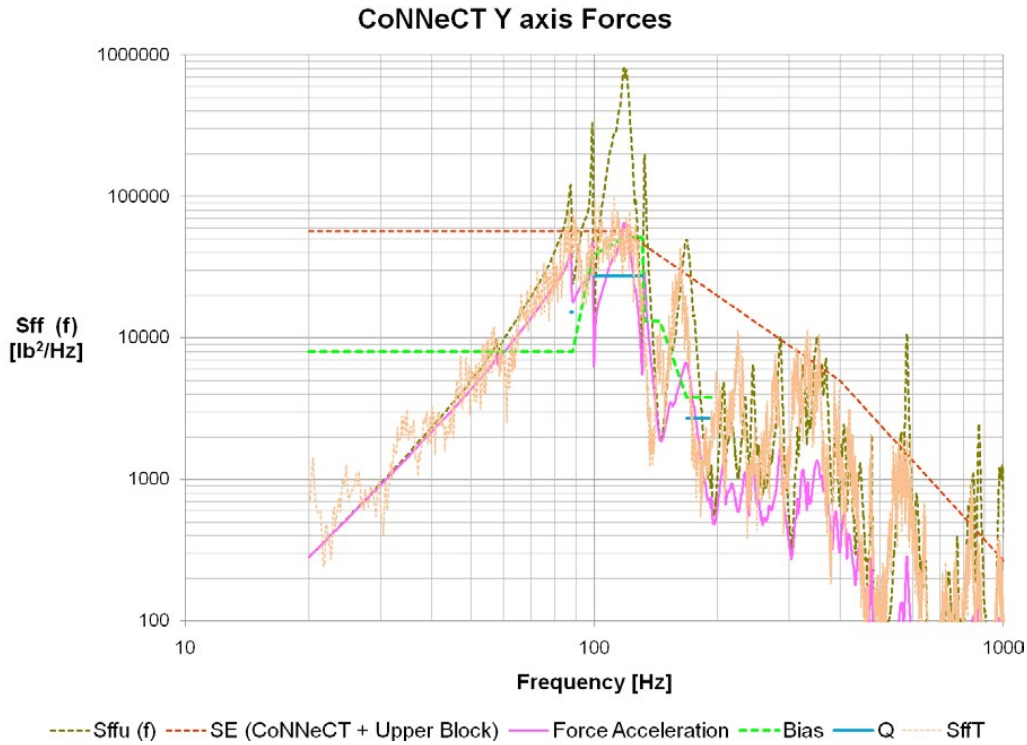

Figure 25.—Y Axis Force Limits

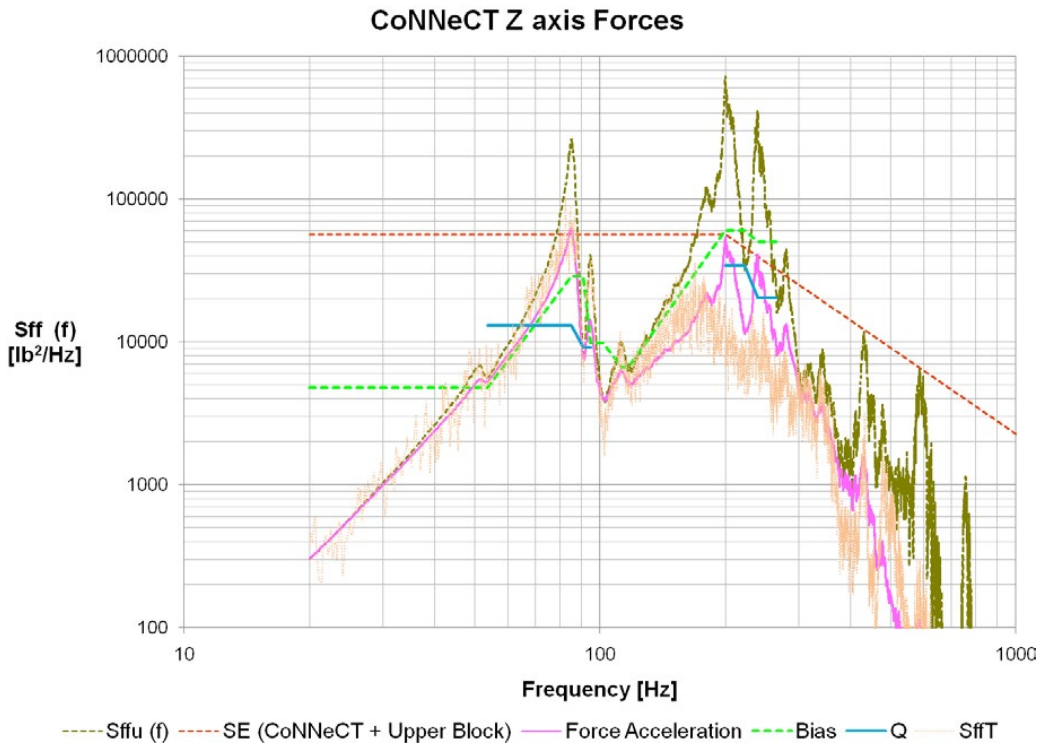

Figure 26.—Z Axis Force Limits

6.0 Component Qualification Assessment Due to Z Axis Force Limits

Kaufman's force-limiting findings for CoNNeCT (Ref. 9) recommended evaluating hardware qualification in the Z-axis due to the force limits (deep notches) at 200 Hz. The purpose of the CoNNeCT system protoflight test is for mission assurance. The Starboard radiator panel is driven by panel bending in the Z-axis test. The Starboard radiator components (top panel, Figure 27) include: the General Dynamics (GD) Software Defined Radio (SDR), JPL SDR, Radio Frequency (RF) Plate, Antenna Pointing System (APS), the Thermostat Control Box (TCB) and the S-and Low Gain Antenna (LGA). The S-Band LGA was not considered in the component qualification assessment because it has no electro-mechanical components and was not instrumented during system testing. The APS was also not considered in the component qualification assessment as it was represented as a dynamic simulator during system testing.

Results of the Starboard component qualification assessment include: (1) The GD SDR and the RF Plate were exposed to protoflight levels. (2) The JPL SDR and the Thermostat Control box also saw protoflight test levels except in the narrow band at 200 Hz, where these components were exposed to at least MEFL (flight) test levels. Based on this assessment, and the fact that the test met NASA-STD-7001 requirements, all the testing objectives and requirements were met.

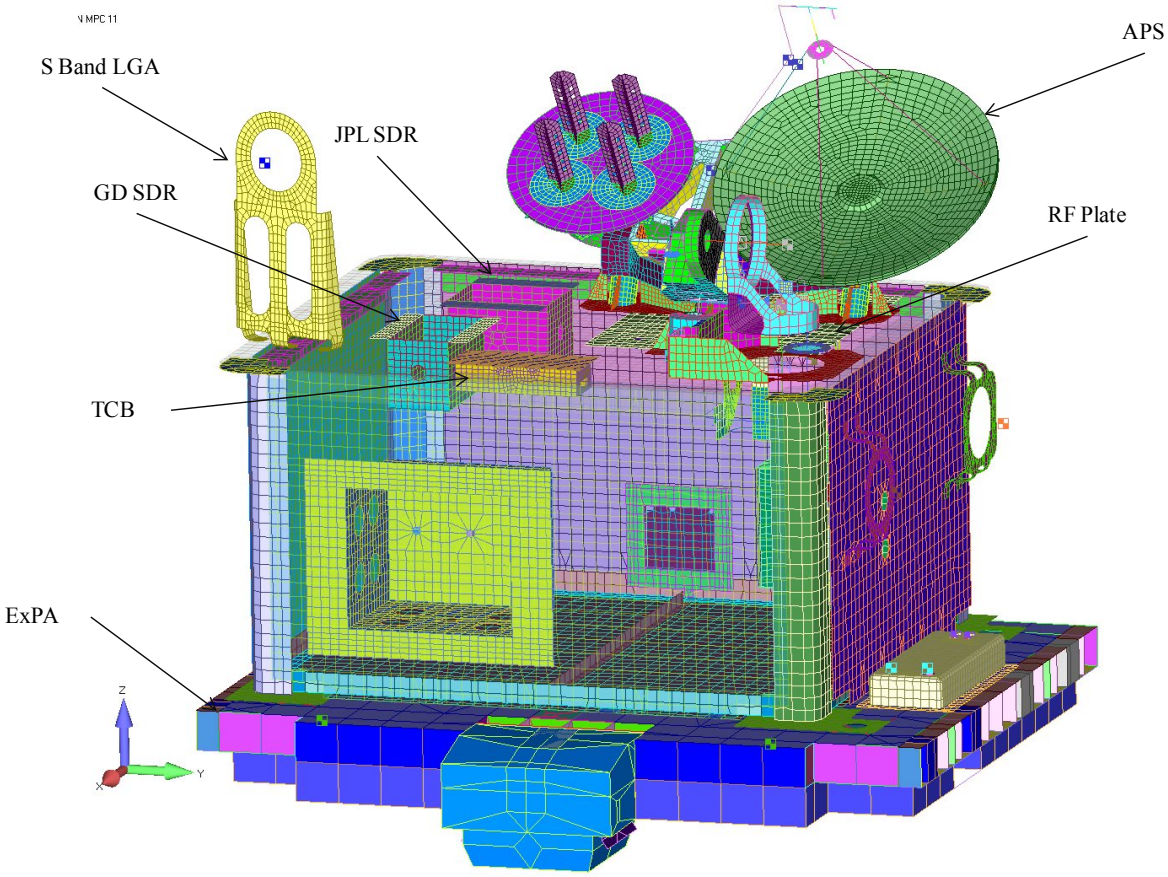

Figure 27.—CoNNeCT Component Layout on Starboard Radiator Panel (Top Panel).

7.0 Lessons Learned and Recommendations

Although the vibration testing that took place on the CoNNeCT flight system was considered a success, several invaluable lessons were taken from the experience.

1) Due to the test boundary conditions, the CoNNeCT system mode at 200 Hz was amplified. The test team chose f_0 = 87 Hz in the Z-Axis for applying the semi-empirical force-limiting approach because the FEM showed 87 Hz to be the fundamental mode. Several factors contributed to this amplification: the head expander on the vertical shaker has elastic modes at 230 Hz (not mass loaded), and the test fixture used during the CoNNeCT testing has a 206 Hz elastic mode (not mass loaded). These modes coupled with a CoNNeCT system mode to produce the response seen during the system vibration test. To better understand the fixture interactions, further evaluation should have been performed to determine the effect on the test hardware. Force limits could potentially have been opened up in the roll off frequency range (>200 Hz).

2) Selection of the C value for the semi-empirical method using historical test data alone is not enough to justify the value selected. Ivan Soucy (Ref. 6) provides several checks that should be performed prior to testing and checked again after the first low-level vibration run during testing. Historical data and similarity checks are one of the steps in choosing a *C* value. Along with that method, Soucy recommends comparison of the semi-empirical force limits to (a) the design limit loads to determine an upper bound, (b) the mechanical impedance correction technique by K.A.

Sweitzer (Ref. 10), (c) the coupled loads interface forces (source impedance) if available and (d) assess the amount of notching.

3) If possible, 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 available.

4) Load impedance calculations (Bias Impedance, Accelerance, and Q methods) (Ref. 9) should be performed pre-test and evaluated again after low-level testing. These impedance methods should cross-check the application of the semi-empirical force limits.

5) The semi-empirical force-limiting method requires the selection of the frequency of the fundamental system mode. However, if there is another high effective mass mode higher in the frequency range, careful consideration must be applied to make sure excessive force limits are not applied. A modal analysis of the test article/test fixture with test verified models (this would require a modal testing effort) would allow much more insight into the behavior of the system. The test team would then be able to scrutinize the test data more thoroughly and with more insight when picking the fundamental system modes. In the case of CoNNeCT, two high effective mass modes did exist. In the flight boundary condition, these two modes were at 77 and 142 Hz, and in the test boundary condition, the two modes were at 87 and 200 Hz.

   The final strength verification for the CoNNeCT flight system will be done analytically. Force-limiting analysis will be utilized and, the frequency used in the semi-empirical method for the Z-Axis will be defined at f_0 = 142 Hz to take into account the second high effective mass mode.

6) Force-limiting is a widely accepted approach for performing random vibration tests. However, applying force-limiting to a random vibration analysis to be used in a strength or loads assessment is not as commonly accepted. Based upon internal reviews, GRC has approved force-limiting analysis as a viable GRC engineering analysis tool to be used on future GRC projects.

8.0 Conclusion

Force-limiting testing and analyses are powerful tools for creating a more realistic flight excitation for space flight hardware. This paper reviews the semi-empirical force-limiting method and presents the steps required for implementing the semi-empirical force-limiting method to a NASTRAN Finite Element Model force-limiting analysis. However, to avoid any confusion with properly selecting a fundamental modal frequency a modal test and FEM correlation effort should be completed. Ultimately, the force-limiting method reduces the risk of over testing and reduces conservatism during analysis by providing more realistic flight interface forces during both random vibration testing and analysis. If all the variables are taken into account properly, the semi-empirical approach is a simple, but effective method for applying force limits. If the semi-empirical force-limiting method is used, other load impedance methods (Bias Impedance, Accelerance and Q Method) should also be implemented to add confidence in the C value selected. More importantly if any information/data is available about the flight mounting structure (source impedance) it should be used in conjunction with the payload model to produce the force limits.

This paper reviewed the force limited testing and analysis of the CoNNeCT flight payload performed using the semi-empirical approach in a force-limited analysis. The force-limiting analysis results are compared with actual test data recovered from the CoNNeCT system protoflight test. The CoNNeCT system protoflight test was deemed successful. Lessons learned are to be applied to future tests at NASA Glenn Research Center.

The most important aspect of force-limiting testing and/or analysis is the understanding of the impedance at the flight interface (both load and source impedance). A coupled FEM that included both

load and source would help to better define a more realistic force limit value. Also, the interface force recovered from the analysis of the coupled FEM could then be used as a more realistic testing input requirement. The semi-empirical method and a *C* value could then be calculated to match or envelop the forces recovered from the coupled system model and used as a test input if desired. However, if nothing is known about the source impedance all of the methods outlined in the lessons learned need to be applied before testing and re-evaluated after low level testing has been completed to help ensure proper force limits are used.

Appendix A.—Historical Force-Limiting *C* Values

Flight Data				
Payload	Organization	Weight, lb	*C* value	Reference no.
CRIS instrument	JPL	65	1.3	11
SVF-2 Canister	JPL	230	1.4	12
Blank Brant Experiment	GSFC	1	1.6	13
Spacecraft Test Programs				
Payload	Organization	Weight, lb	*C* value	Reference no.
Cassini	JPL	8,380	0.7	14
MER	JPL	2143	1	15
GALEX	OSC	640	2	16
Deep Space	JPL	1070	2	17
Cassiope	CSA	1077	1.4	18
MOST	CSA	116	2.2	19

Appendix B.—CoNNeCT Force Limits Calculations

TABLE B.1.—RANDOM VIBRATION SPECIFICATION—X-AXIS FORCE LIMITING CALCULATIONS

(a) CoNNeCT Protoflight Level

FREQ, Hz	ASD, G^2/Hz	dB	OCT	dB/OCT	AREA	Grms
20.00	0.0007	*	*	*	*	*
80.00	0.0356	17.06	2.00	8.53	0.74	0.86
400.00	0.0356	0.00	2.32	0.00	12.13	3.48
2000.00	0.0053	–8.24	2.32	–3.55	32.05	5.66

C = 2.00, n = 2.00, M = 635.00, F_0 = 125.00

(b) Calculation of ASD at F_0 = 125 Hz

FREQ, Hz	ASD, G^2/Hz	dB	OCT	dB/OCT	AREA	Grms	S_{ff}
20.00	0.0007	*	*	*	*	*	1129.03
80.00	0.0356	17.06	2.00	8.53	0.74	0.86	57419.24
125.00	0.0356	0.00	0.64	0.00	1.60	1.27	57419.24
400.00	0.0356	0.00	2.32	0.00	12.13	3.48	5607.35
2000.00	0.0053	–8.27	4.00	–2.07	21.25	4.61	33.39

(c) Force Limited Semi-Empirical Method

FREQ, Hz	S_{ff}, lb^2/Hz	dB	OCT	dB/OCT	AREA	Grms
20.00	1129.0300	*	*	*	*	*
80.00	57419.2400	17.06	2.00	8.53	1192157.79	1091.86
125.00	57419.2400	0.00	0.64	0.00	3776023.59	1943.20
400.00	5607.3477	–10.10	1.68	–6.02	8710489.53	2951.35
2000.00	33.3921	–22.25	2.32	–9.58	9707162.77	3115.63

(d) Force Limited Simplified Method

FREQ, Hz	ASD, G^2/Hz	dB	OCT	dB/OCT	AREA	Grms
20.00	57419.2400	*	*	*	*	*
125.00	57419.2400	0.00	2.64	0.00	6029020.20	2455.41
2000.00	228.0000	–24.01	4.00	–6.00	12790390.65	3576.37

TABLE B.2.—RANDOM VIBRATION SPECIFICATION—Y-AXIS FORCE LIMITING CALCULATIONS

(a) CoNNeCT Protoflight Level

FREQ, Hz	ASD, G^2/Hz	dB	OCT	dB/OCT	AREA	Grms
20.00	0.0007	*	*	*	*	*
80.00	0.0356	17.06	2.00	8.53	0.74	0.86
400.00	0.0356	0.00	2.32	0.00	12.13	3.48
2000.00	0.0053	–8.24	2.32	–3.55	32.05	5.66

$C = 2.00$, $n = 2.00$, $M = 635.00$, $F_0 = 119.00$

(b) Calculation of ASD at F_0

FREQ, Hz	ASD, G^2/Hz	dB	OCT	dB/OCT	AREA	Grms	S_{ff}
20.00	0.0007	*	*	*	*	*	1129.03
80.00	0.0356	17.06	2.00	8.53	0.74	0.86	57419.24
119.00	0.0356	0.00	0.57	0.00	2.13	1.46	57419.24
400.00	0.0356	0.00	1.75	0.00	12.13	3.48	5081.96
2000.00	0.0053	–8.27	2.32	–3.56	31.98	5.65	30.26

(c) Force Limited Semi-Empirical Method

FREQ, Hz	S_{ff}, lb^2/Hz	dB	OCT	dB/OCT	AREA	Grms
20.00	1129.0300	*	*	*	*	*
80.00	57419.2400	17.06	2.00	8.53	1192157.79	1091.86
119.00	57419.2400	0.00	0.57	0.00	3431508.15	1852.43
400.00	5081.9616	–10.53	1.75	–6.02	8231613.07	2869.08
2000.00	30.2634	–22.25	2.32	–9.58	9134902.01	3022.40

(d) Force Limited Simplified Method

FREQ, Hz	ASD, G^2/Hz	dB	OCT	dB/OCT	AREA	Grms
20.00	57419.2400	*	*	*	*	*
119.00	57419.2400	0.00	2.57	0.00	5684504.76	2384.22
2000.00	208.0000	–24.41	4.07	–6.00	12154038.01	3486.26

TABLE B.3.—RANDOM VIBRATION SPECIFICATION—Z-AXIS FORCE LIMITING CALCULATIONS

(a) CoNNeCT Protoflight Level

FREQ, Hz	ASD, G^2/Hz	dB	OCT	dB/OCT	AREA	Grms
20.00	0.0007	*	*	*	*	*
80.00	0.0356	17.06	2.00	8.53	0.74	0.86
400.00	0.0356	0.00	2.32	0.00	12.13	3.48
2000.00	0.0053	–8.24	2.32	–3.55	32.05	5.66

$C = 2.00$, $n = 2.00$, $M = 635.00$, $F_0 = 87.34$

(b) Calculation of ASD at F_0

FREQ, Hz	ASD, G^2/Hz	dB	OCT	dB/OCT	AREA	Grms	S_{ff}
20.00	0.0007	*	*	*	*	*	1129.03
80.00	0.0356	17.06	2.00	8.53	0.74	0.86	57419.24
87.34	0.0356	0.00	0.13	0.00	1.00	1.00	57419.24
400.00	0.0356	0.00	2.20	0.00	12.13	3.48	2737.56
2000.00	0.0053	–8.27	2.32	–3.56	31.98	5.65	16

(c) Force Limited Semi-Empirical Method

FREQ, Hz	S_{ff}, lb^2/Hz	dB	OCT	dB/OCT	AREA	Grms
20.00	1129.0300	*	*	*	*	*
80.00	57419.2400	17.06	2.00	8.53	1192157.79	1091.86
87.34	57419.2400	0.00	0.13	0.00	1613615.01	1270.28
400.00	2737.5612	–13.22	2.20	–6.02	5533586.97	2352.36
2000.00	16.3023	–22.25	2.32	–9.58	6020172.45	2453.60

(d) Force Limited Simplified Method

FREQ, Hz	ASD, G^2/Hz	dB	OCT	dB/OCT	AREA	Grms
20.00	57419.2400	*	*	*	*	*
87.34	57419.2400	0.00	2.13	0.00	3866611.62	1966.37
2000.00	112.0000	–27.10	4.52	–6.00	8692365.96	2948.28

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14. ABSTRACT
The semi-empirical force-limiting 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 as, the Communications, Navigation, and Networking re-Configurable Testbed (CoNNeCT), project utilized force-limiting testing and analysis following the semi-empirical approach. This paper presents the steps in performing a force-limiting analysis and then compares the results to test data recovered during the CoNNeCT force-limiting random vibration qualification test that took place at NASA Glenn Research Center (GRC) in the Structural Dynamics Laboratory (SDL) December 19, 2010 to January 7, 2011. A compilation of lessons learned and considerations for future force-limiting tests is also included.

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Impedance; Vibration tests; Dynamic tests; Random vibration; Dynamic models

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