Challenges in Random Vibration Qualification Testing of Structures Behaving Nonlinearly

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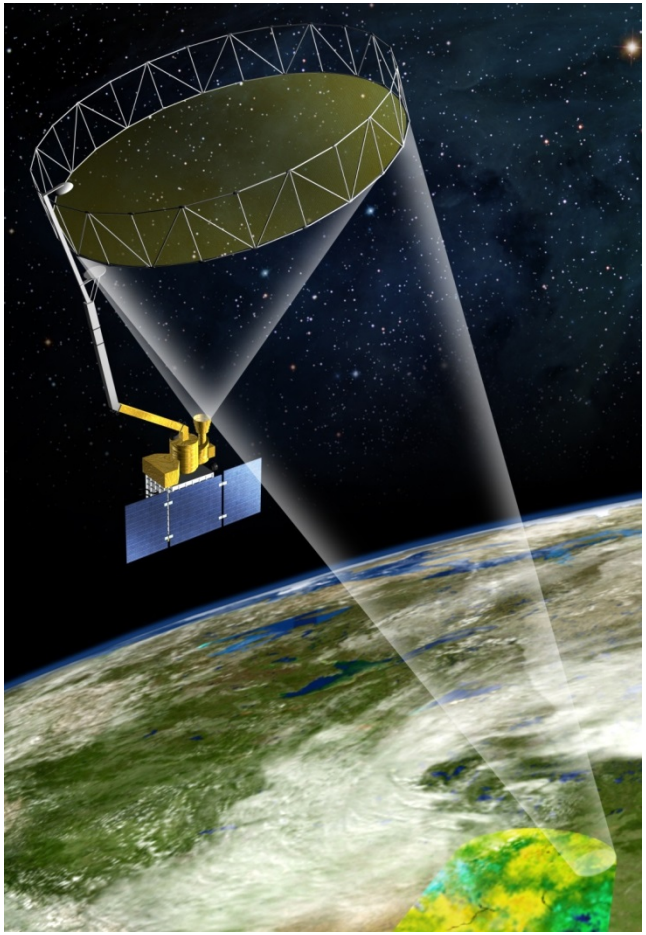

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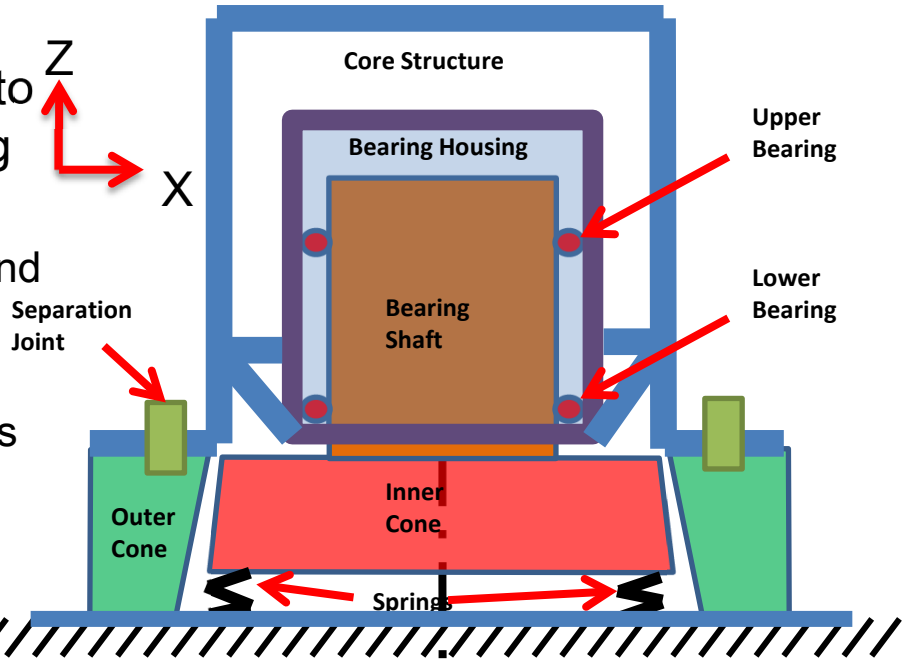
Outline

- Cone Clutch Assembly (CCA) developmental random vibration test configuration
- Random vibration test input and force limiting specification
- Z-axis test anomaly
- Possible cause of failure
- Analysis correlation
- Summary

Cone Clutch Assembly (CCA) Random Vibration Test Configuration

- A Cone Clutch Assembly (CCA) is designed to prevent the launch load to directly pass through a rotary bearing Assembly
  - The CCA is consists of Inner Cone and Outer Cone
  - The Inner Cone is attached to the Bearing Shaft while the Outer Cone is attached to the Spacecraft
  - Bearing Housing is supported by the Core Structure
  - Core Structure is connected to the Outer Cone through a set of Separation Joints
  - During launch, the CCA is disengaged



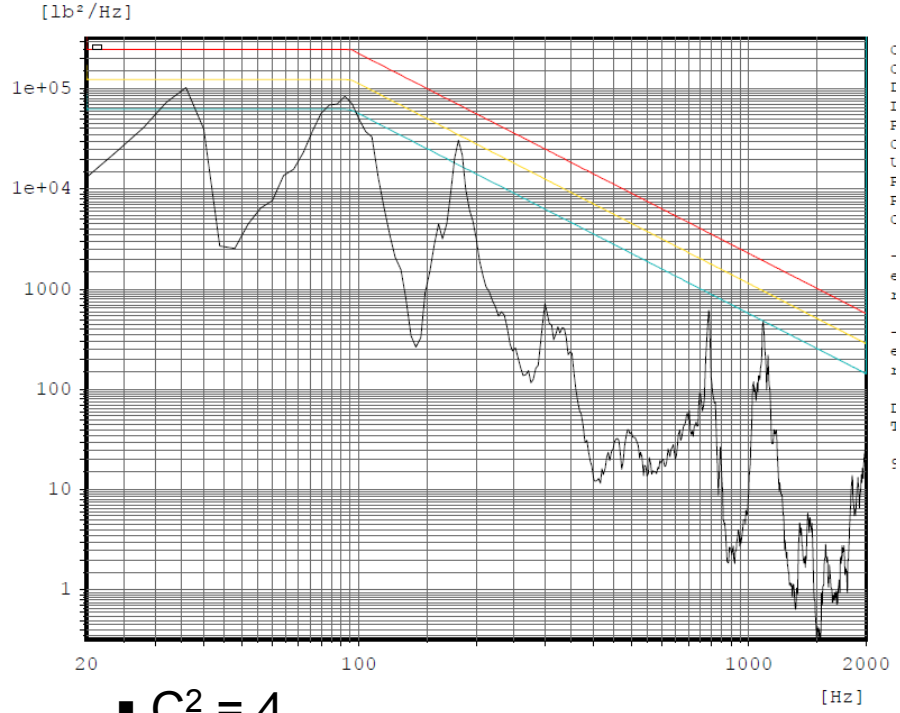
- Random vibration test were performed on the developmental CCA and the Brass Board Bearing Assembly

Random Vibration Test Sequence

- Random vibration tests in X and Z axes were performed in the following sequence:
  1. Low Level Survey
  2. -18 dB w/ and w/o Force Limiting
  3. Higher levels leading to proto-flight level with Force Limiting
- The X-axis was performed first
  - Visual inspection and response data indicated no anomaly
- However, during the Z-axis -18dB w/o FL run, an unexpected large structural responses were detected, shaker control peak limiter (5σ 0-dB level, a safety measure) was triggered that resulted in the shut-down of the system after 6 seconds
- Subsequent tests with Force Limiting performed as expected
- In this presentation the unusual CCA/Bearing structural behavior observed during the test are discussed

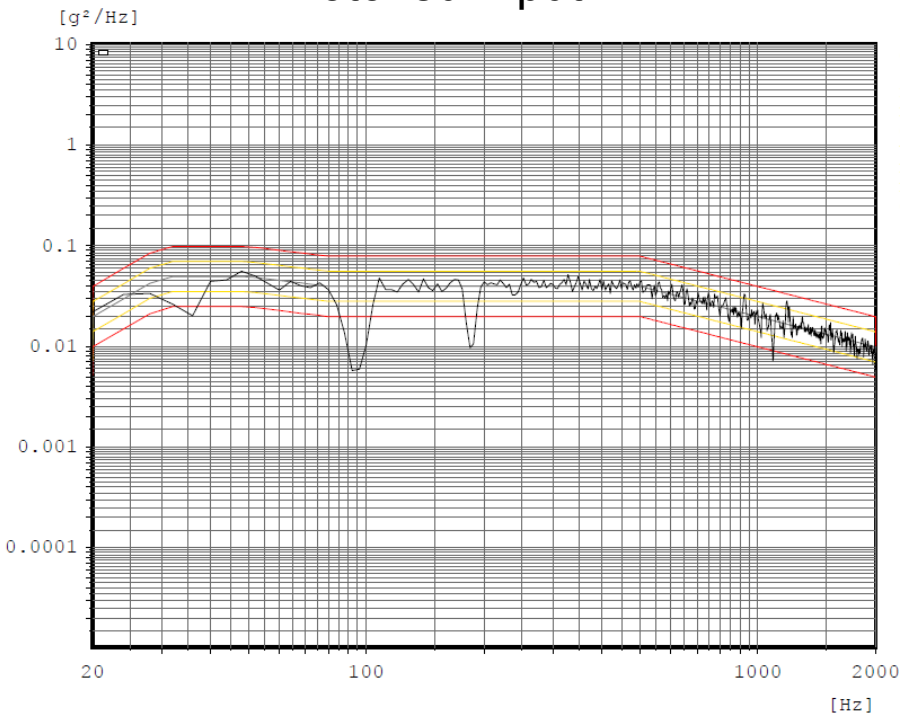
X-axis: Shaker Interface Force and Notched Input

X shake PF Level
Fx and Force Limit



- $C^2 = 4$
- RMS Fx is 2066 lbs
- A notch of ~ 8 dB at 95 Hz

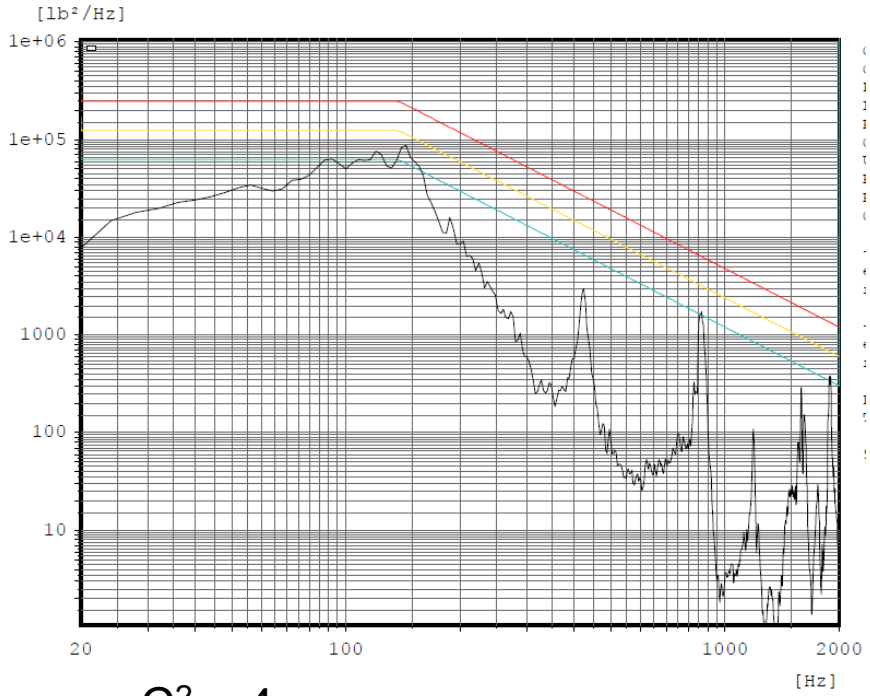
X shake PF Level
Notched Input



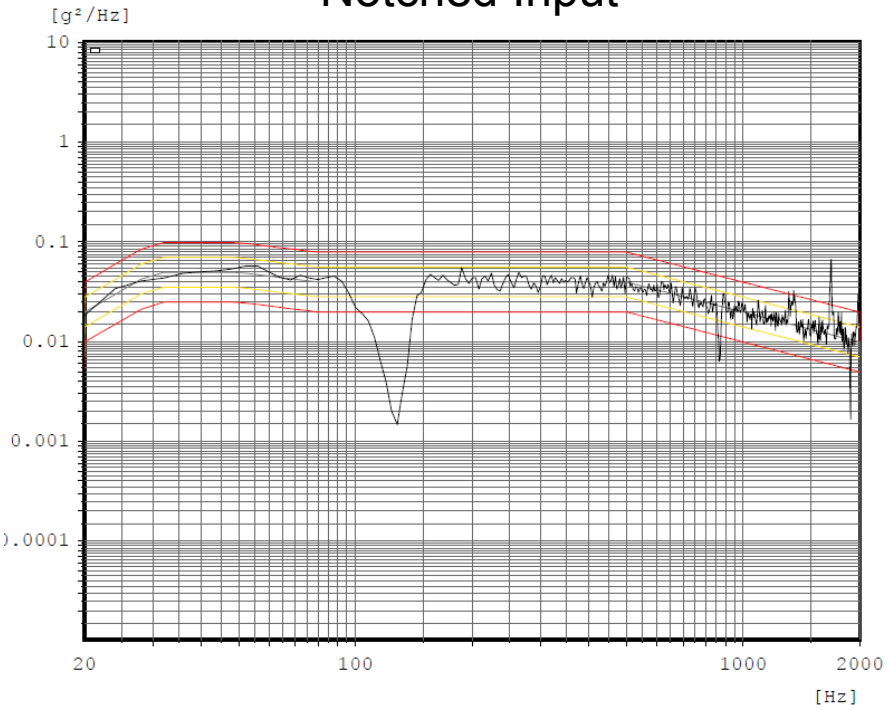
X-axis test completed with no obvious structural issues

Z-axis: Shaker Interface Force and Notched Input

Z shake PF Level
Fz and Force Limit



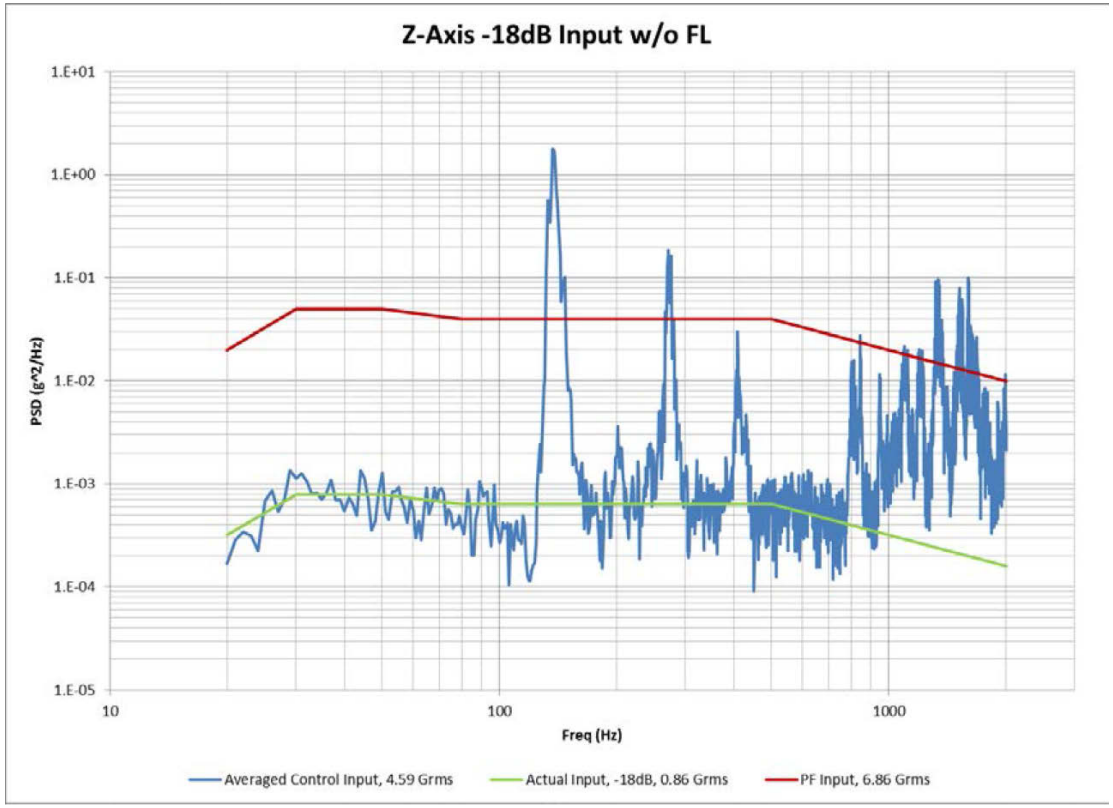
Z shake PF Level
Notched Input



- $C^2 = 4$
- RMS Fz is 2790 lbs
- A notch of ~14 dB at 135 Hz

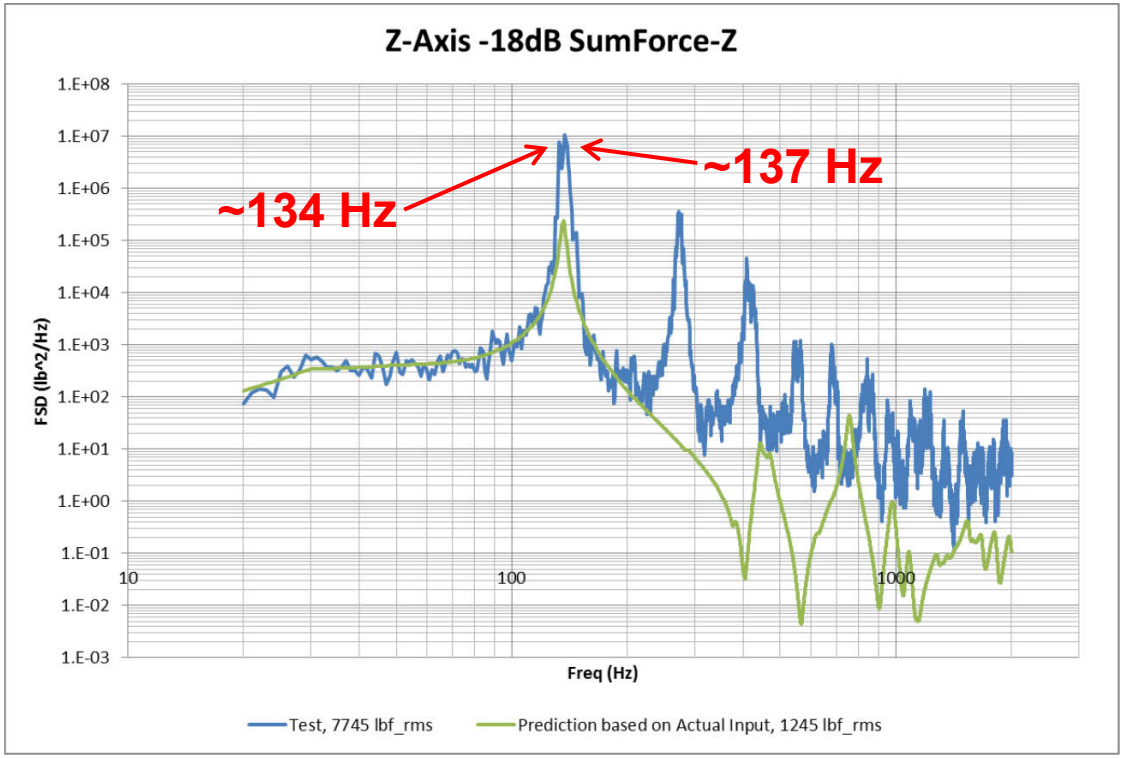
Z-Axis -18dB w/o FL Test Anomaly

- Post-processing of the data has revealed that the shaker control system was not able to control the input due to unexpected structural behavior
  - Input G_rms = 0.86
  - Control G_rms = 4.59



Z-Axis -18dB w/o FL Test Anomaly

- Two closely spaced modes were observed
- As well as evidence of super harmonic excitation
  - Test interface force = 7745 lbf_rms
- Linear random vibration analysis was not able to capture the non-linear behavior, obviously
  - Predicted interface force = 1245 lbf_rms
- Bearings were later determined to be damaged



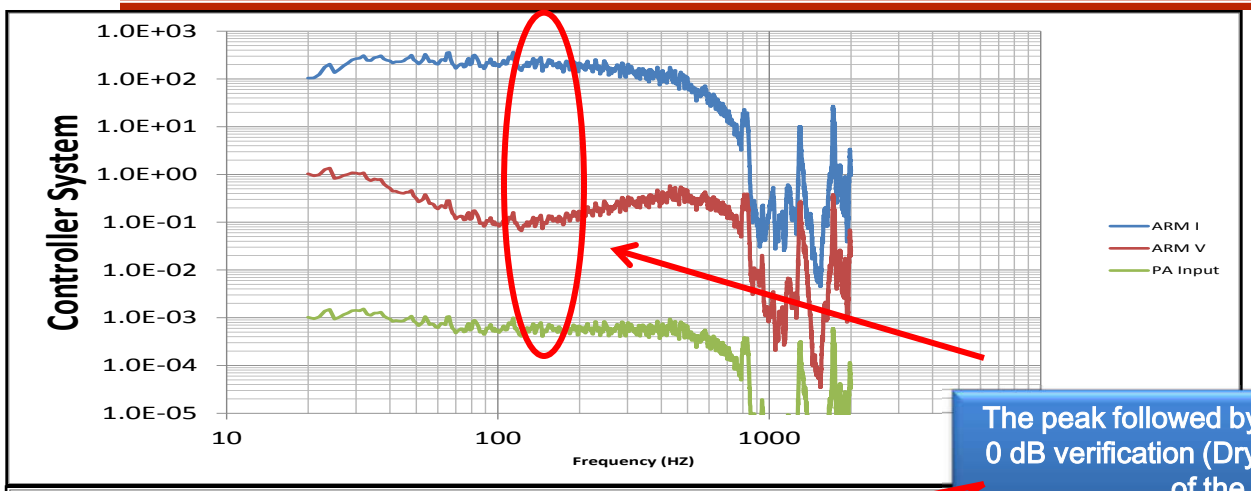
Possible Causes of Failure

1. Facility and RV Control System
   - Least likely cause of failure
2. Impact of bearing assembly
   - Internal gapping due to bearing preload being overcome
     - Bearing Shaft + Inner Cone mass = 55 lbf
     - Bearings were lightly preloaded to ~ 200 lbf
     - 3σ peak load at bearing was estimated ~ 3500 lbf
     - Most likely the cause of bearing damage

Bearing Load Estimate - Z-Axis			
Run 13 - -18dB no FL	A5-X	A5-Y	A5-Z
G_RMS@300 Hz (g)	1.66	1.52	21.56
3σ Peak Load (lb)	**271**	**249**	**3518**
Run 20 - 0dB FL	A5-X	A5-Y	A5-Z
G_RMS@300 Hz (g)	1.32	1.45	9.97
3σ Peak Load (lb)	**215**	**236**	**1627**

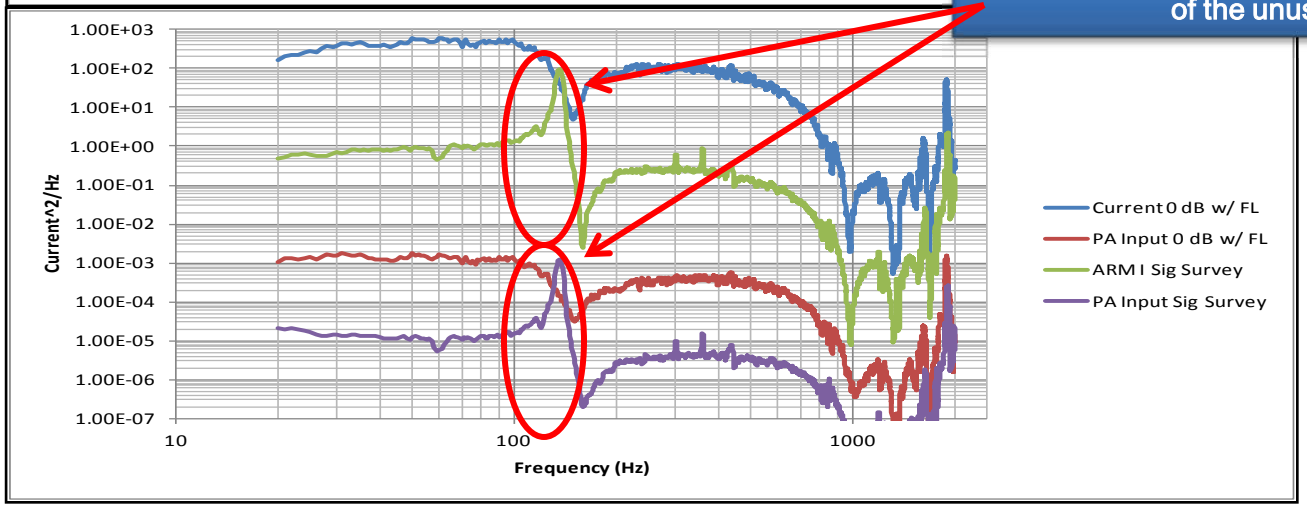
3. Structural Dynamics
   - Unusual beating phenomenon and non-linear behavior of the system
     - Non-linear bearing stiffness is likely to induce super-harmonic excitations

Z-Axis Shaker Controller Voltage and Current PSD



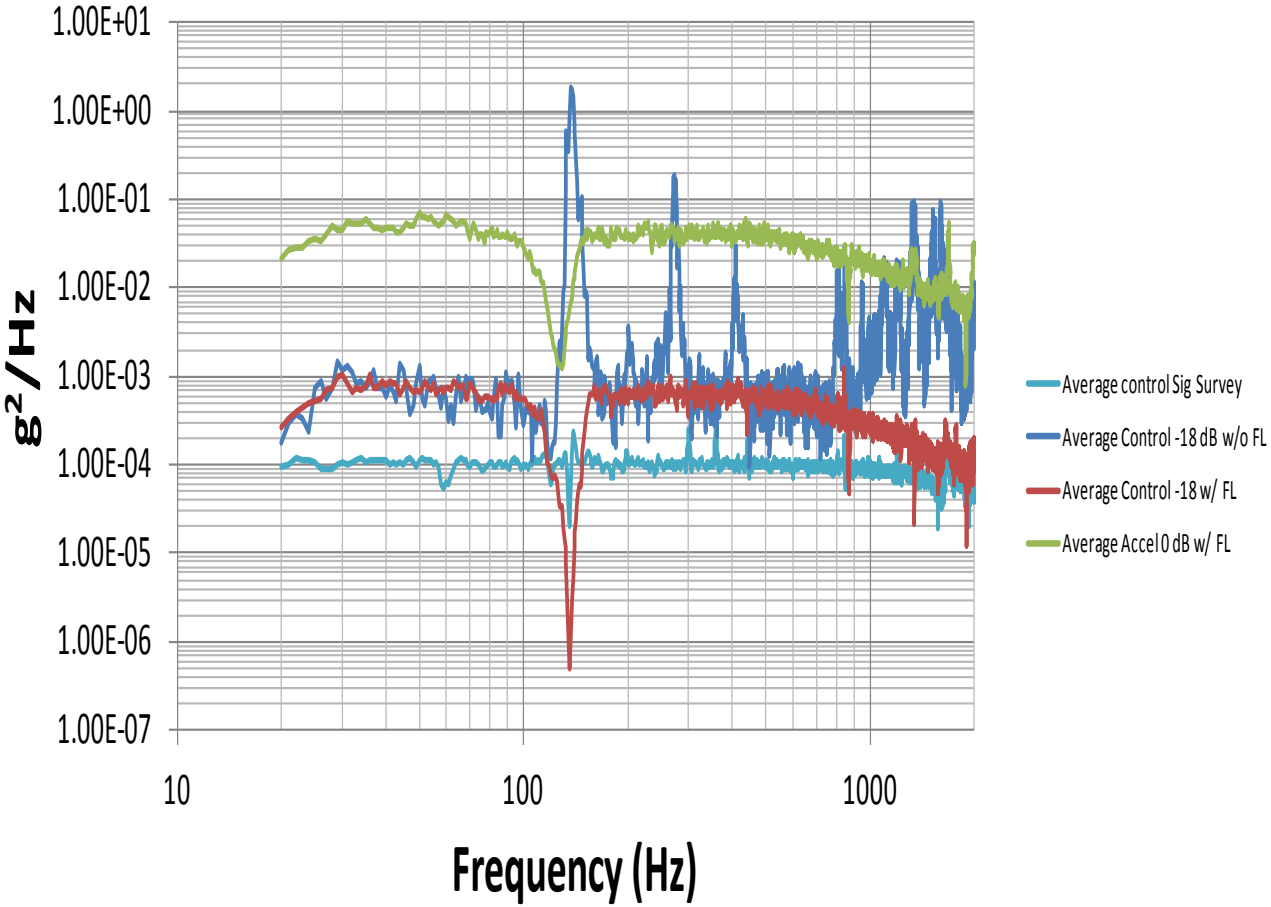
- Shaker controller Voltage and Current Power Spectral Densities measured to verify full level input acceleration w/o hardware
- Not shaker/controller related issue

The peak followed by a trough in current/amp spectra absent in 0 dB verification (Dry) run led us to eliminate this as the cause of the unusual structural behavior.



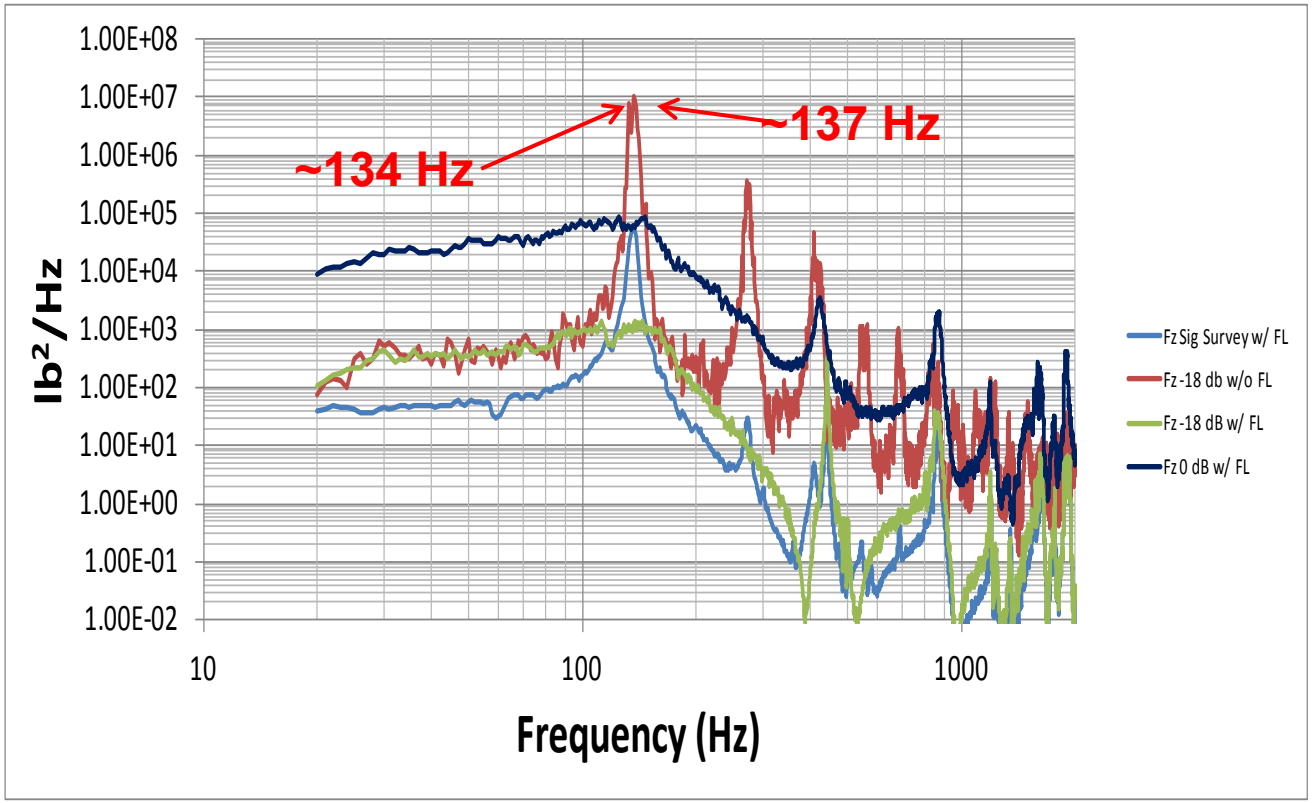
- Shaker controller Voltage and Current Power Spectral Densities measured at full level and low-level signature input acceleration w/ hardware
- The signature survey shaker current and amps indicate issues with structural responses!

Z-Axis Control Accels with and w/o Force Limiting



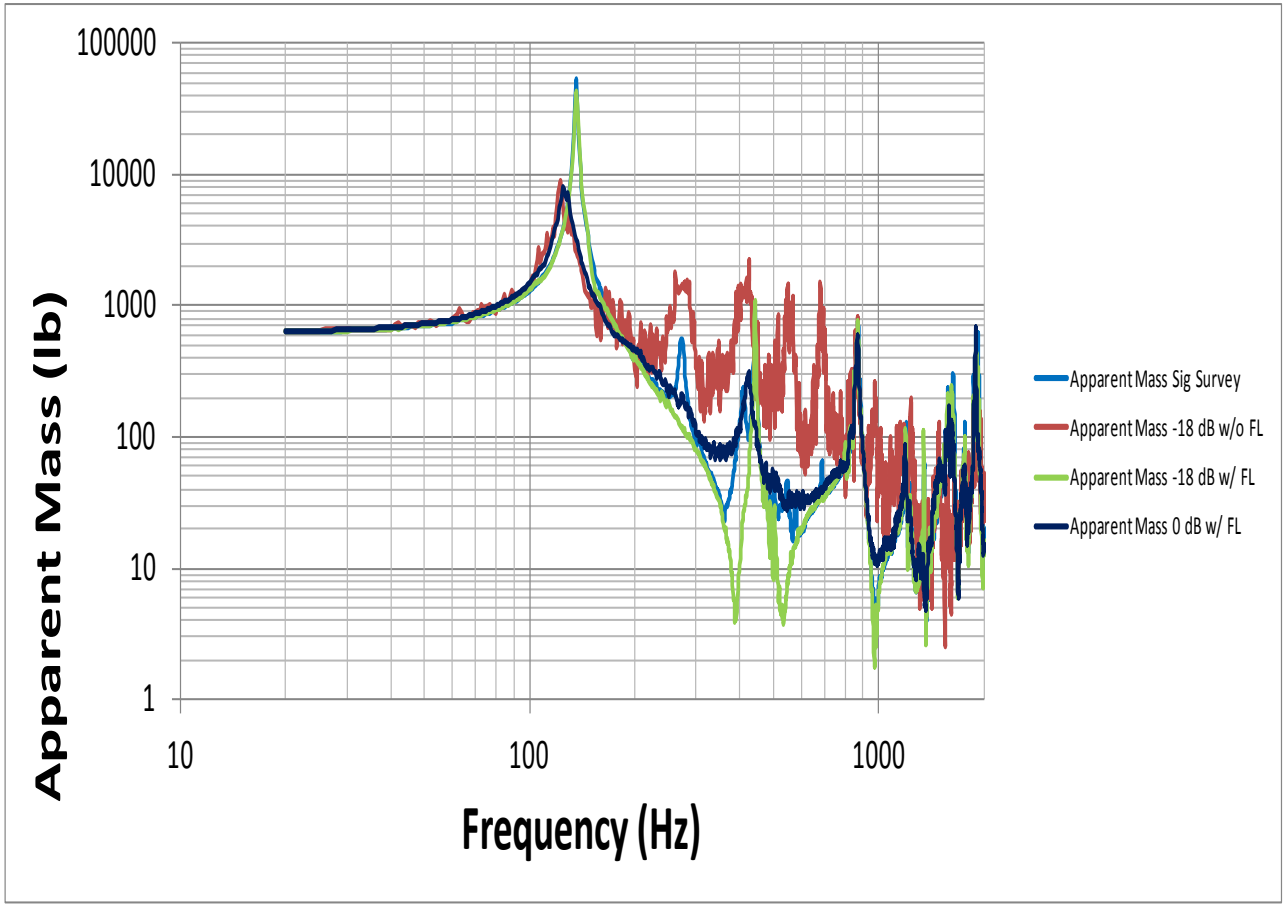
- **Signature Survey (light blue curve): Input Acceleration appears to be normal**
- **-18 dB w/o FL (dark blue curve): strong nonlinearity (super harmonic excitation) and chatter with controller not being able to control input signal to keep the acceleration within the required tolerances**
- **Force limiting significantly reduced the nonlinearity of the system (see red curve for -18 dB and green curve for 0 dB)**

Z-Axis Interface Forces with and w/o Force Limiting



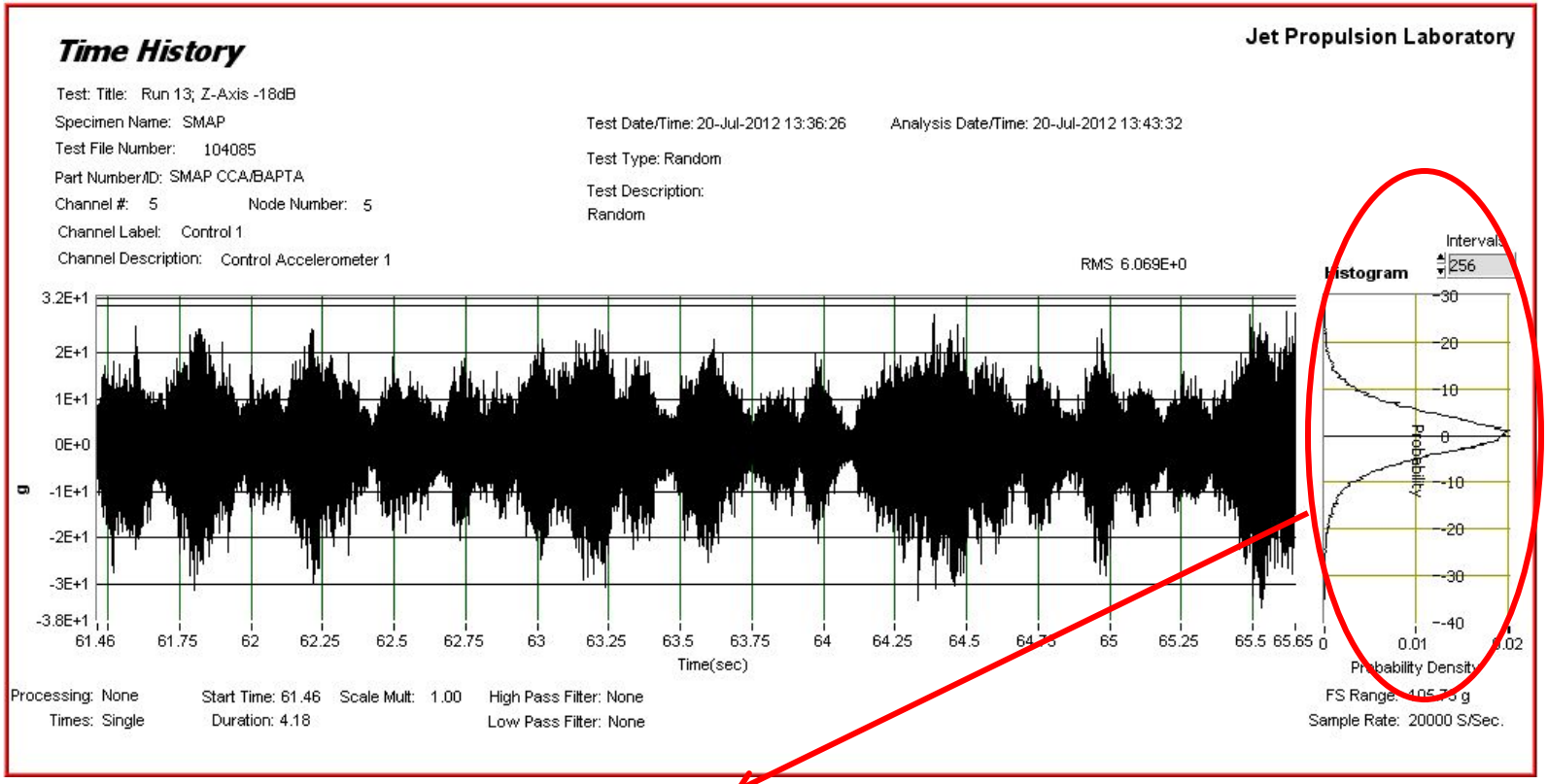
- **Primary structural mode ~135 Hz**
- **Signature Survey(light blue curve): Evidence of weak nonlinearity (super harmonic excitations)**
- **-18 dB w/o FL (red curve): strong nonlinearity and evidence of beating excitation with frequency of 3-5 Hz**
- **Force limiting significantly reduced the nonlinearity of the system (green curve for -18 dB and dark blue curve for 0 dB)**

Z-Axis Apparent Masses with and w/o Force Limiting



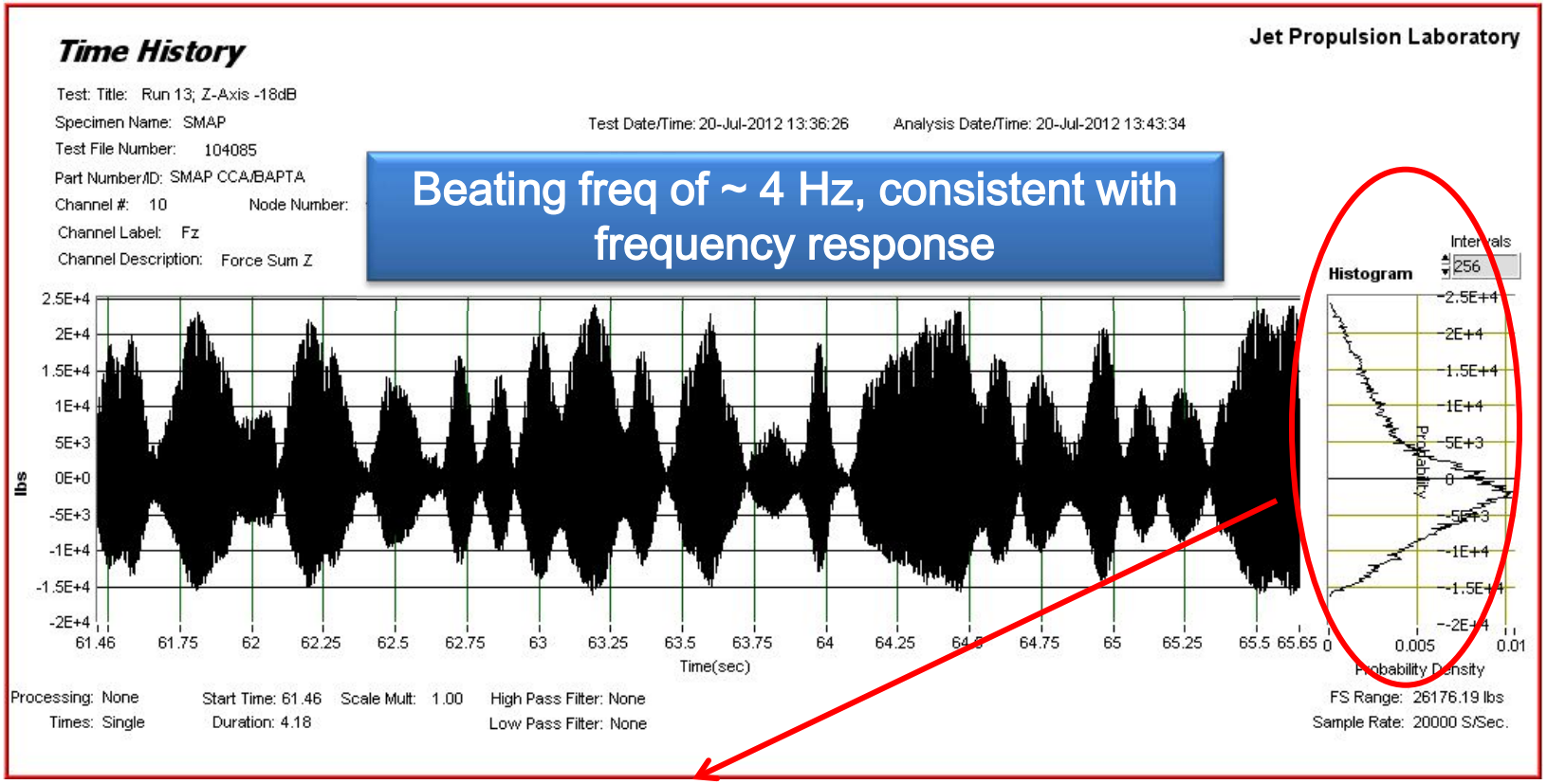
- **Primary structural mode ~135 Hz**
- **-18 dB w/o FL (brown curve): strong nonlinearity w/ significant apparent masses at two nearby resonance frequencies (134 Hz and 137 Hz)**
- **Apparent mass expected to be similar to green and light blue curves (-18 dB w/ FL and low-level signature) for all higher runs**
- **Force limiting significantly reduced the nonlinearity of the system; however the apparent masses spectral shape different than the low level runs!**

Z-Axis -18dB w/o FL Control Accel Time-History



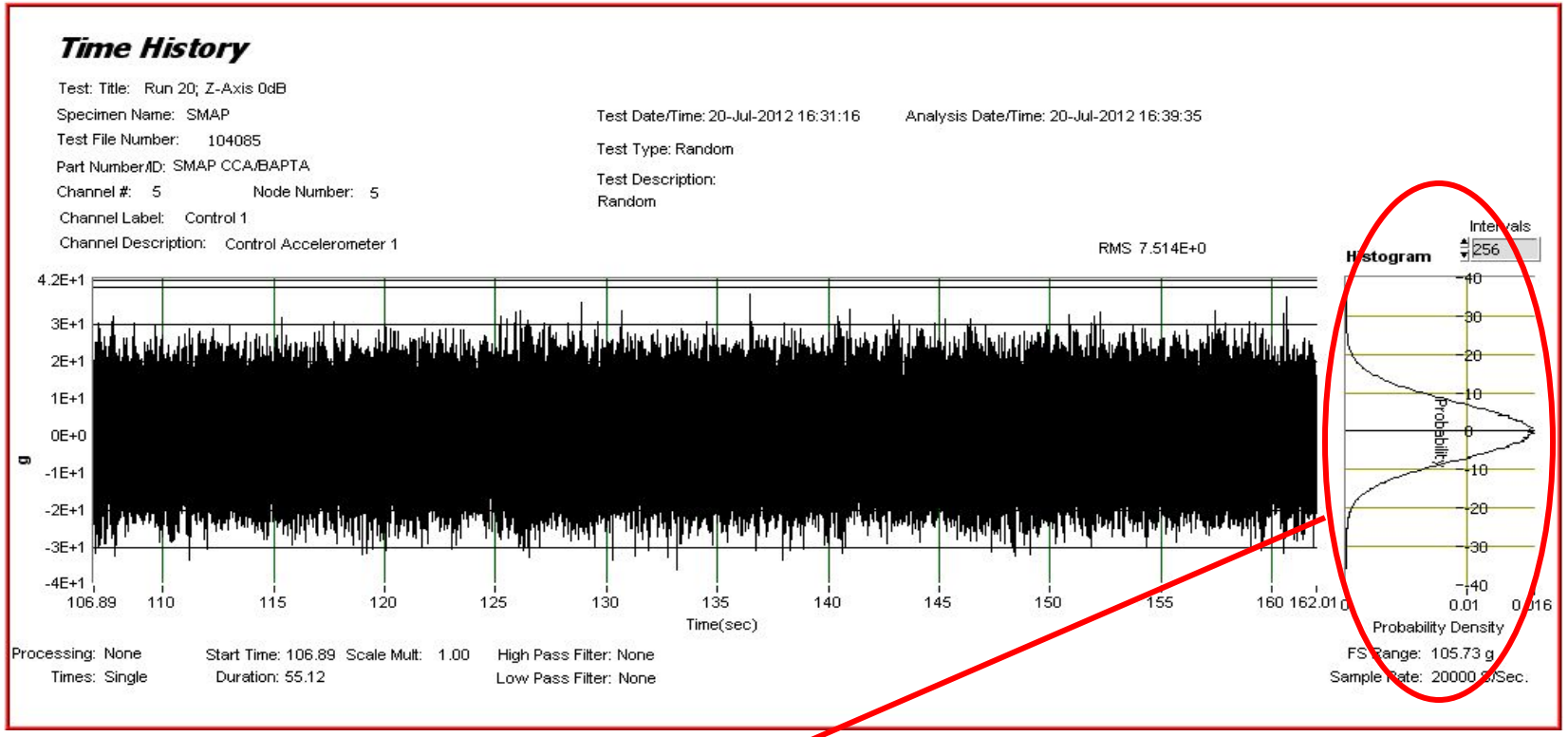
Non-Gaussian Input Acceleration: Caused by excitation of two structural frequencies spaced by ~3-5 Hz with significant apparent masses

Z-Axis -18dB w/o FL Force Time-History



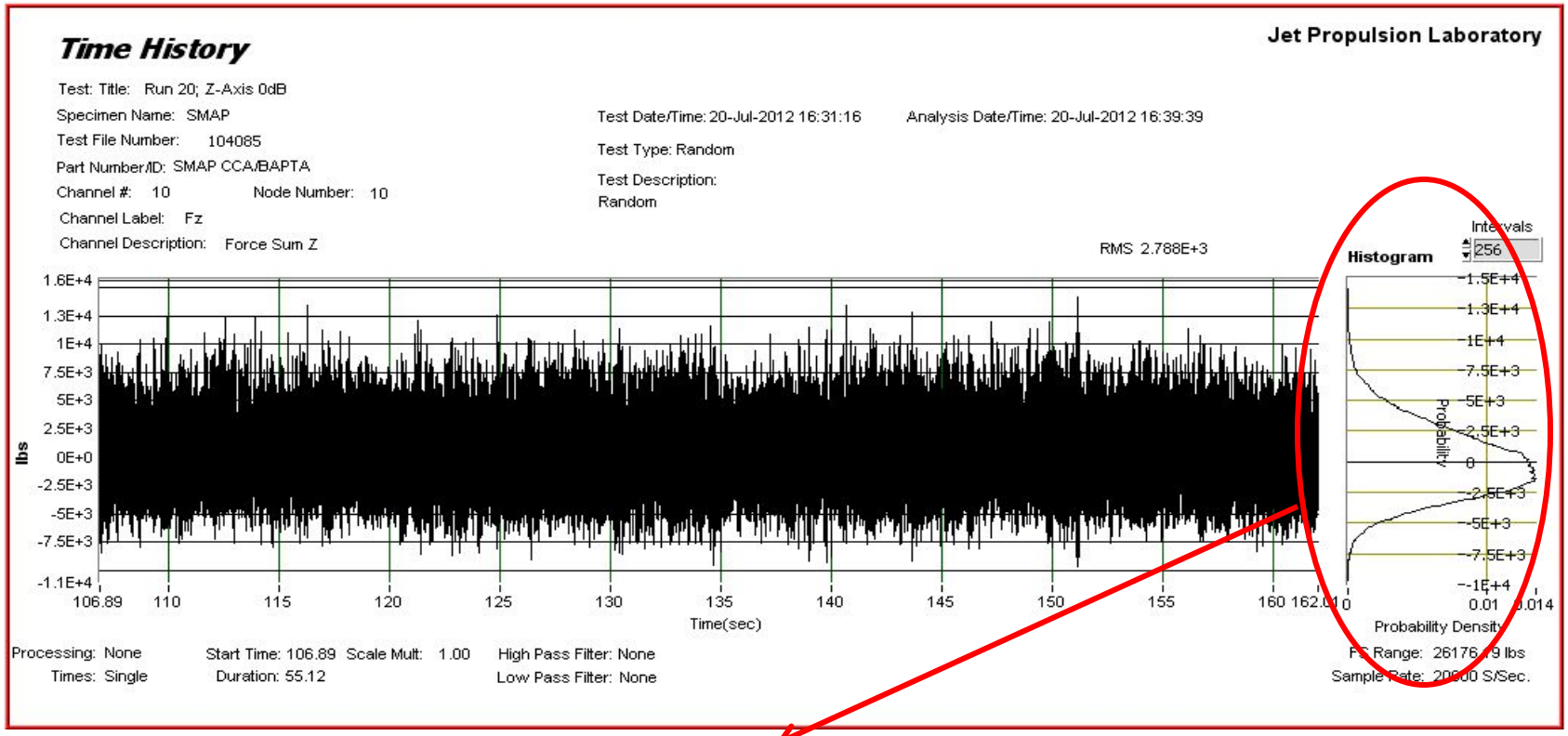
Non-Gaussian Interfaces Summed Force

Z-Axis 0-dB w/ FL Control Accel Time-History



Gaussian Input Acceleration: Force limiting helped reduce the nonlinearity and the beating phenomenon, but did not completely eliminate!

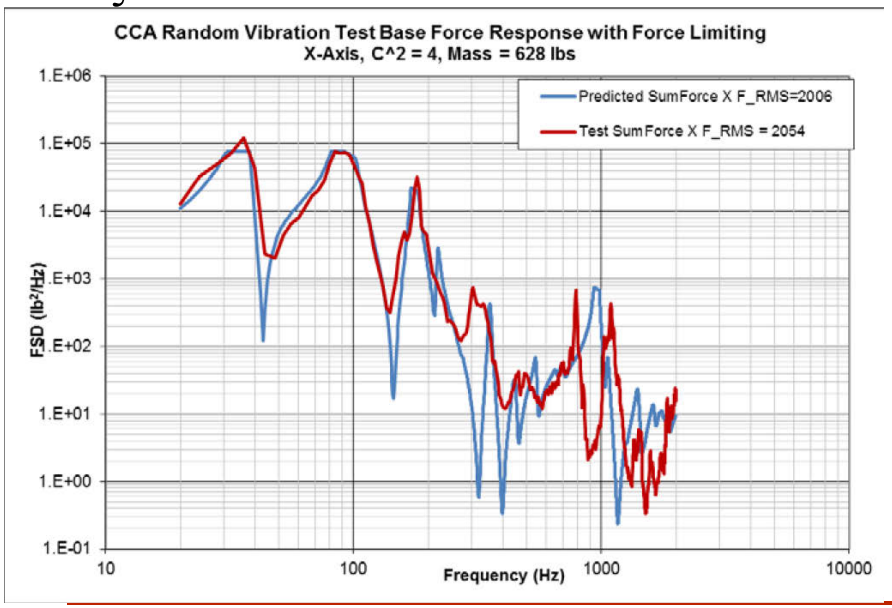
Z-Axis 0-dB w/ FL Summed Forces Time-History

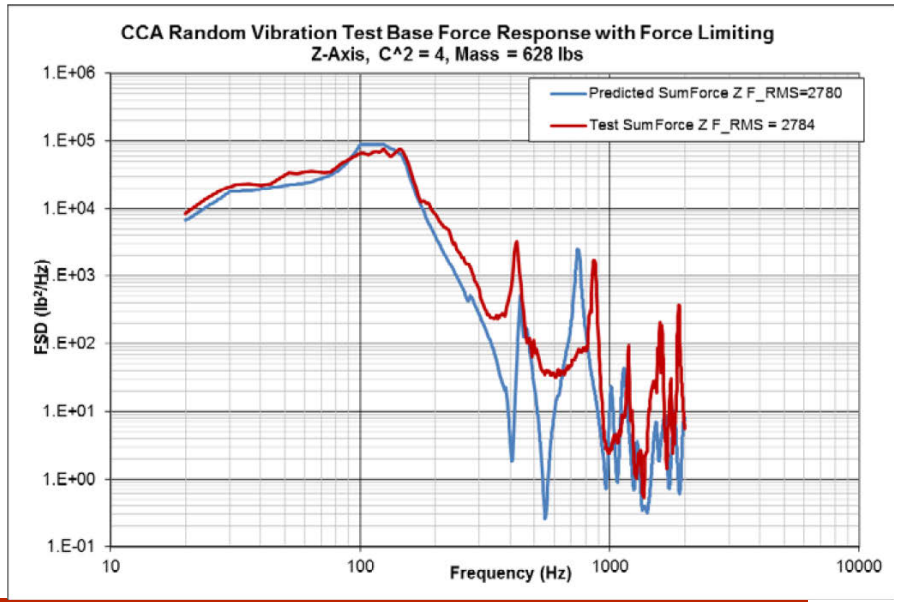


Near Gaussian Interface Force: Force limiting helped reduce the nonlinearity and the beating phenomenon, but did not completely eliminate!

Analysis Correlation

- Force-limited random vibration analysis and test correlated well at 0-dB
  - Super-harmonic behavior was suppressed due to force limiting
  - $C^2 = 4$
  - $\zeta = 1.5\%$





Summary

- In general the rotor bearing assembly dynamics tend to exhibit non-linear responses which may result in super-harmonic excitations
  - Such conditions are usually related to non-linear bearing hertzian contact stiffness
- A conventional approach to minimize the non-linear behavior is to preload the bearings high enough such that dynamic load becomes small portion of the total bearing load during vibration
  - High preload prevents bearings from gapping
- At low level vibration input, the bearing contact stiffness may cause the nonlinear structural dynamic responses in particular when two resonant frequency with significant effective masses are close to each other (aka, beating)
- Force Limiting is shown to be an effective way to suppress the non-linear dynamic responses for the case under consideration
- Due to the failure, the CCA/Bearing Assembly has since be re-designed and will undergo random vibration test
  - High external preload is implemented for the bearing assembly
  - Force Limiting will be implemented at low random vibration test levels