Accurate Determination of the Impact of Interface Deadband Nonlinearities on Component Transient Environments

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Executive Summary

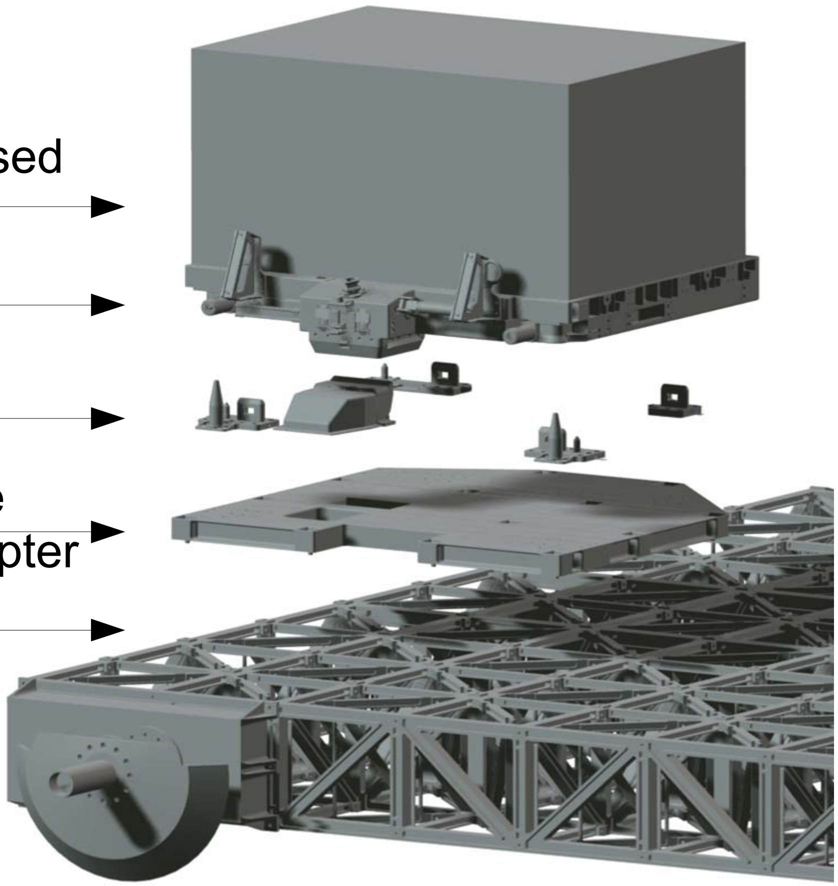
- In 2005, the NASA Space Shuttle Program (SSP) initiated an effort to simulate/investigate the impact of component interface deadbands for liftoff and landing transient environments
- It was found that the deadband sizes in these systems can be **significant** contributors to the component transient environments
- Nonlinear transient coupled loads analyses (CLAs) were established as a mission critical analysis for flight hardware certification

2005 NASA Initiative

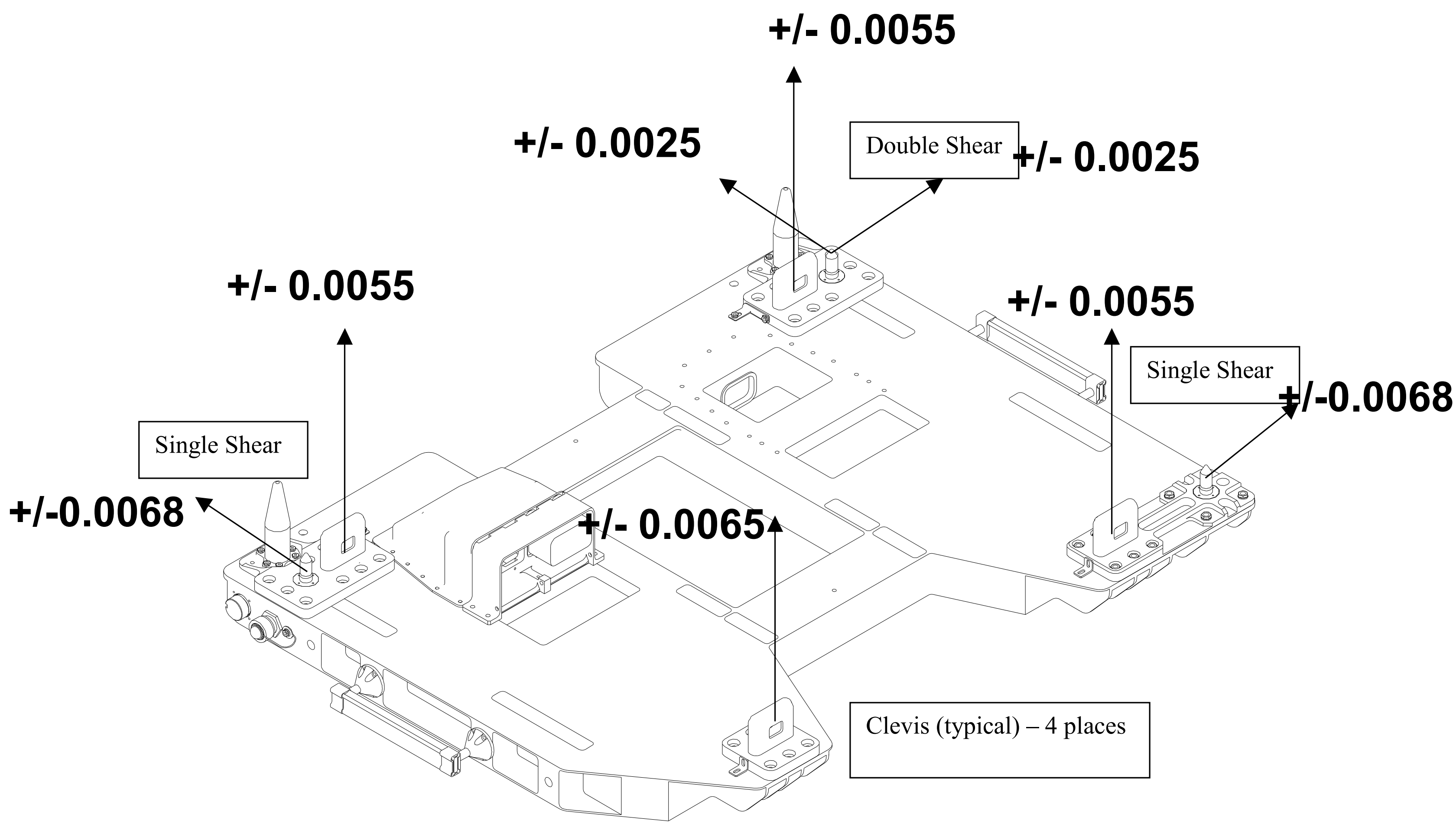
- Lockheed Martin, the SSP Cargo Mission Contractor, tasked to investigate the impact of complex component interfaces involving deadbands on Space Shuttle manifested component transient environments
  - Next few slides show typical flight hardware

FRAM

- Flight Releasable Attachment Mechanism (FRAM)
- Carries cargo to the ISS
- To be utilized on future launch programs such as Commercial Orbital Transportation Services (COTS)



AFRAM/PFRAM Interface Deadband Limits



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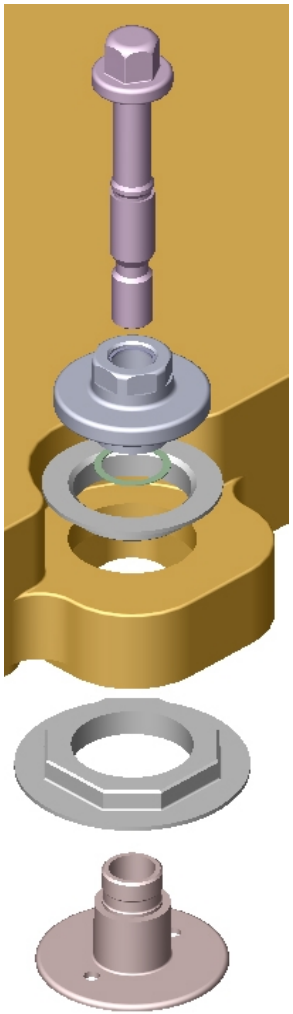
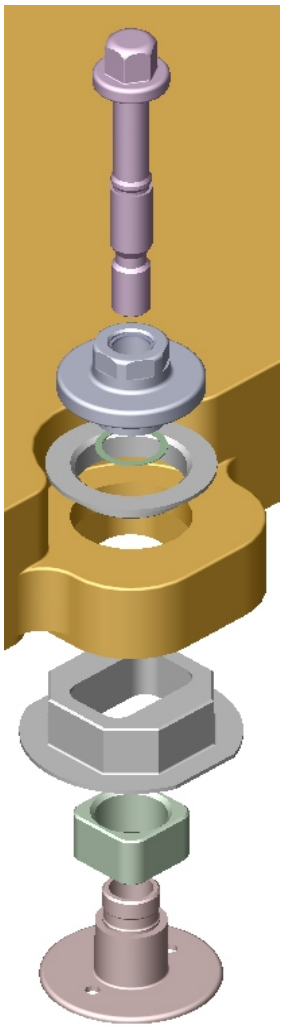
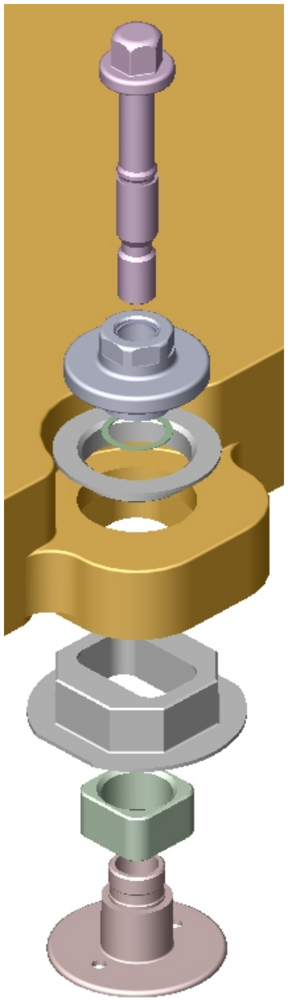
Kinematic Mounts (KM)



Tension Only

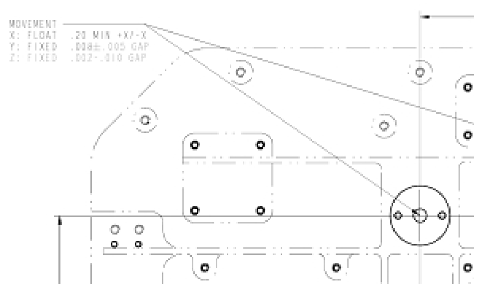


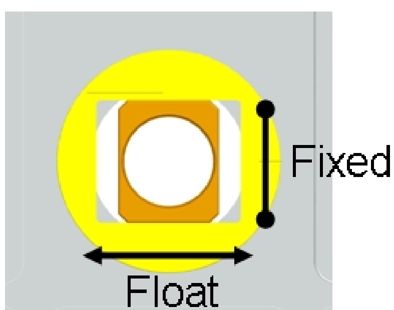
Y Shear + Tension

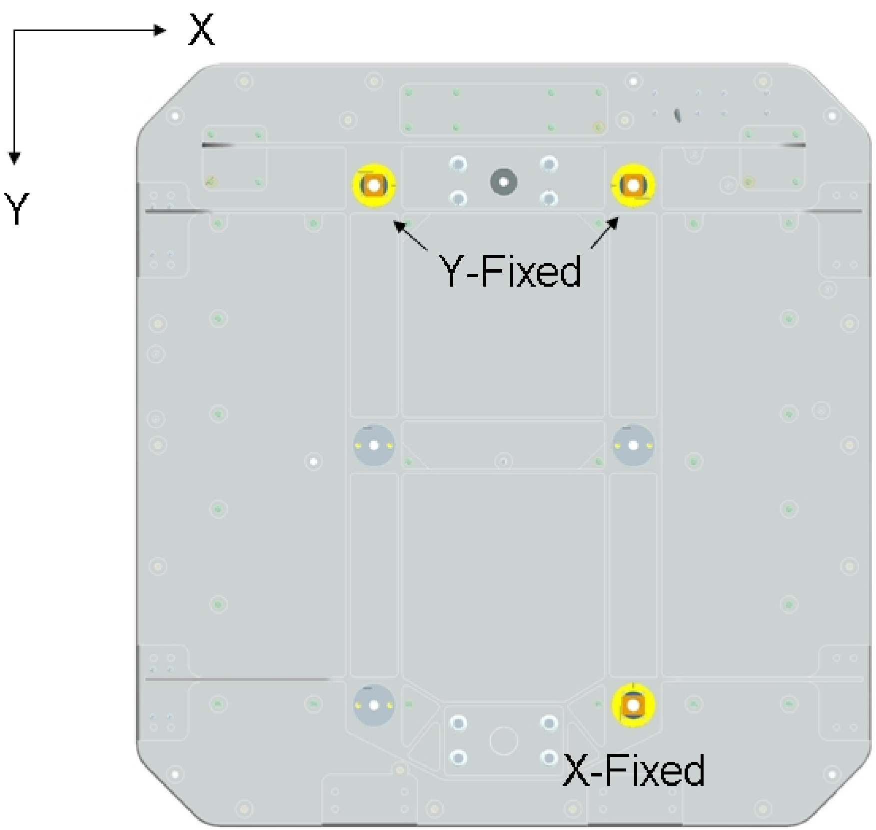


X Shear + Tension

KM Deadband Limits
Battery FSE Attach Application







Fixed Shear directions (3 per Battery): **+/- 0.0064”**
Tension directions (6 per battery): **+/- 0.0025”**

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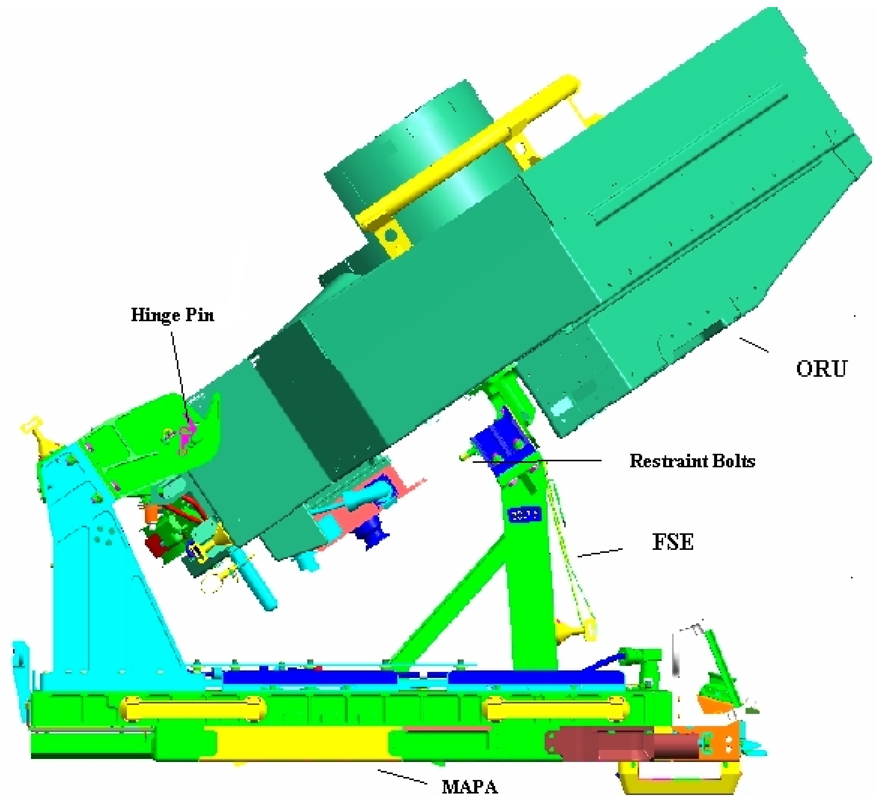
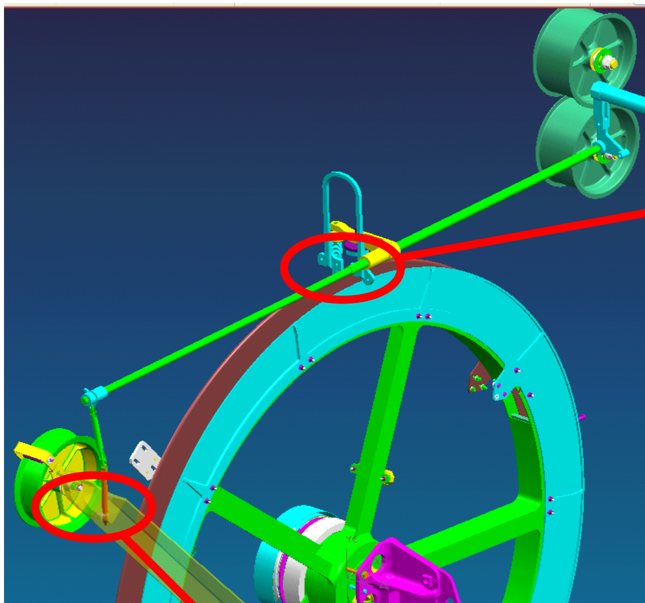
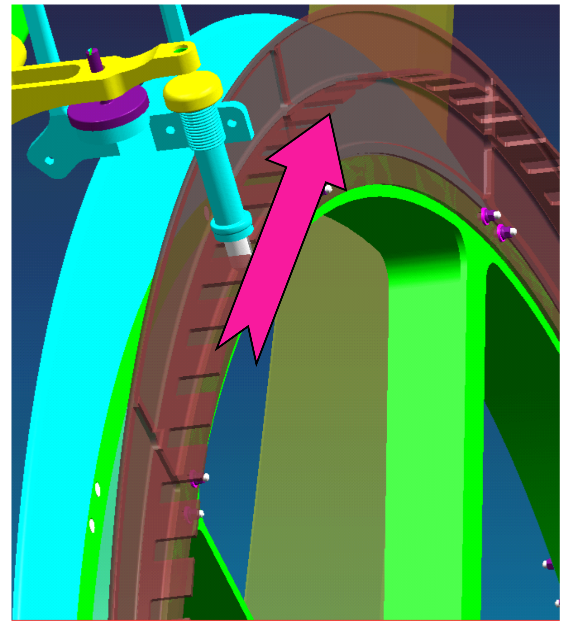
TUSRA
Internal & Interface Deadbands

- Trailing Umbilical System-Reel Assembly (TUSRA)
  - Deadbands at the launch restraints for the reel and control arm
  - Deadbands at the bearings and reel and control arm hub
  - Deadbands at the hinge pin and FSE clevis
  - Deadbands at FRAM/PFRAM

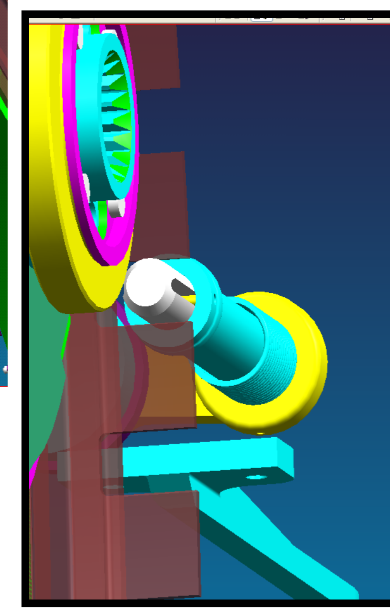


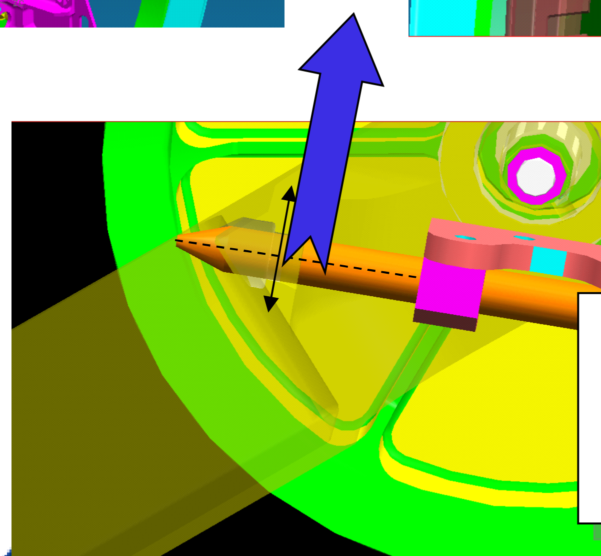
Arm and Reel Launch Locks





Max gap between reel and locking pin:
+/-.0215”

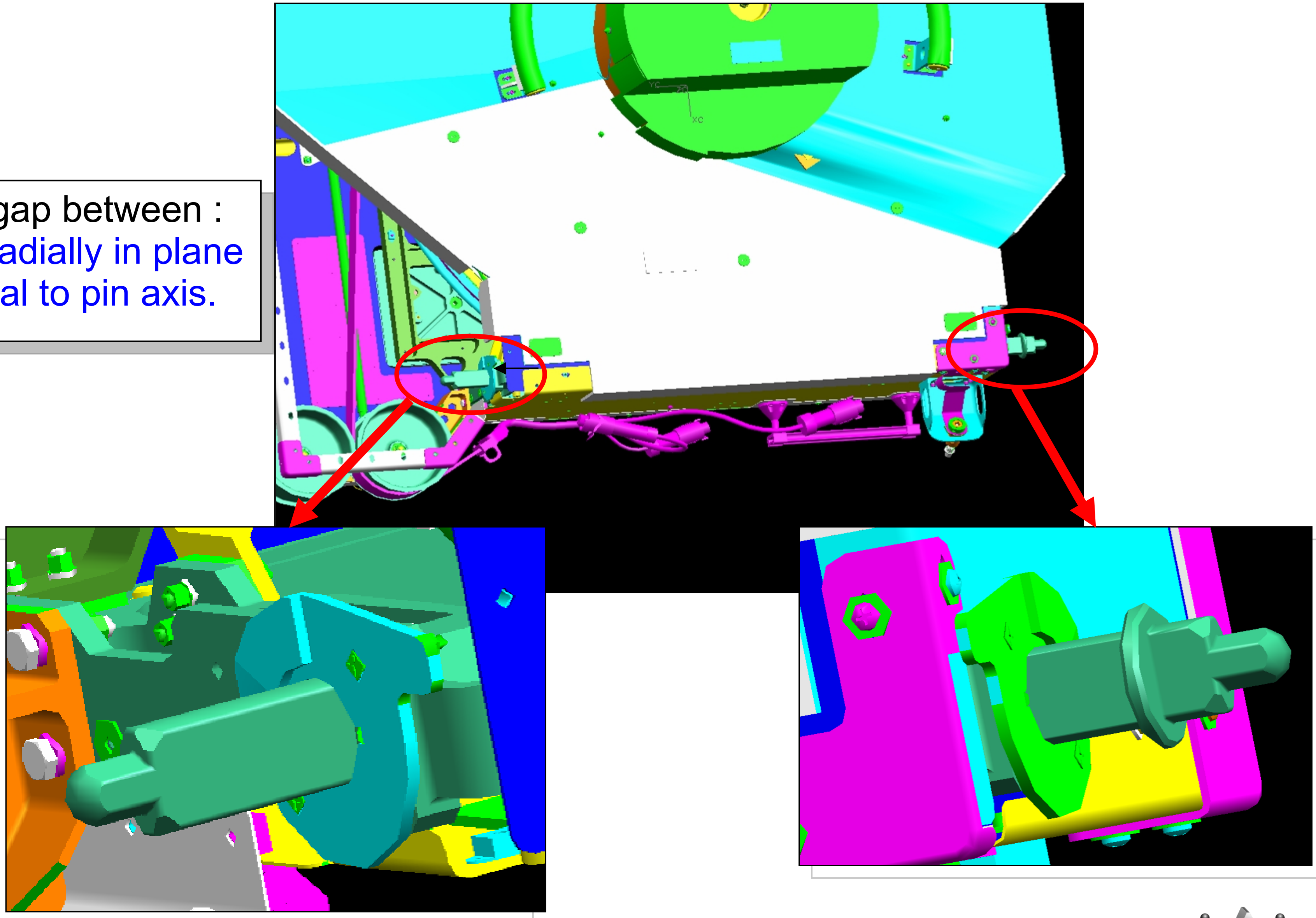




Max gap between tension arm and locking pin:
0.008" radially in plane normal to pin axis.

TUSRA Restraint Pin Gap

Max gap between :
0.02" radially in plane normal to pin axis.



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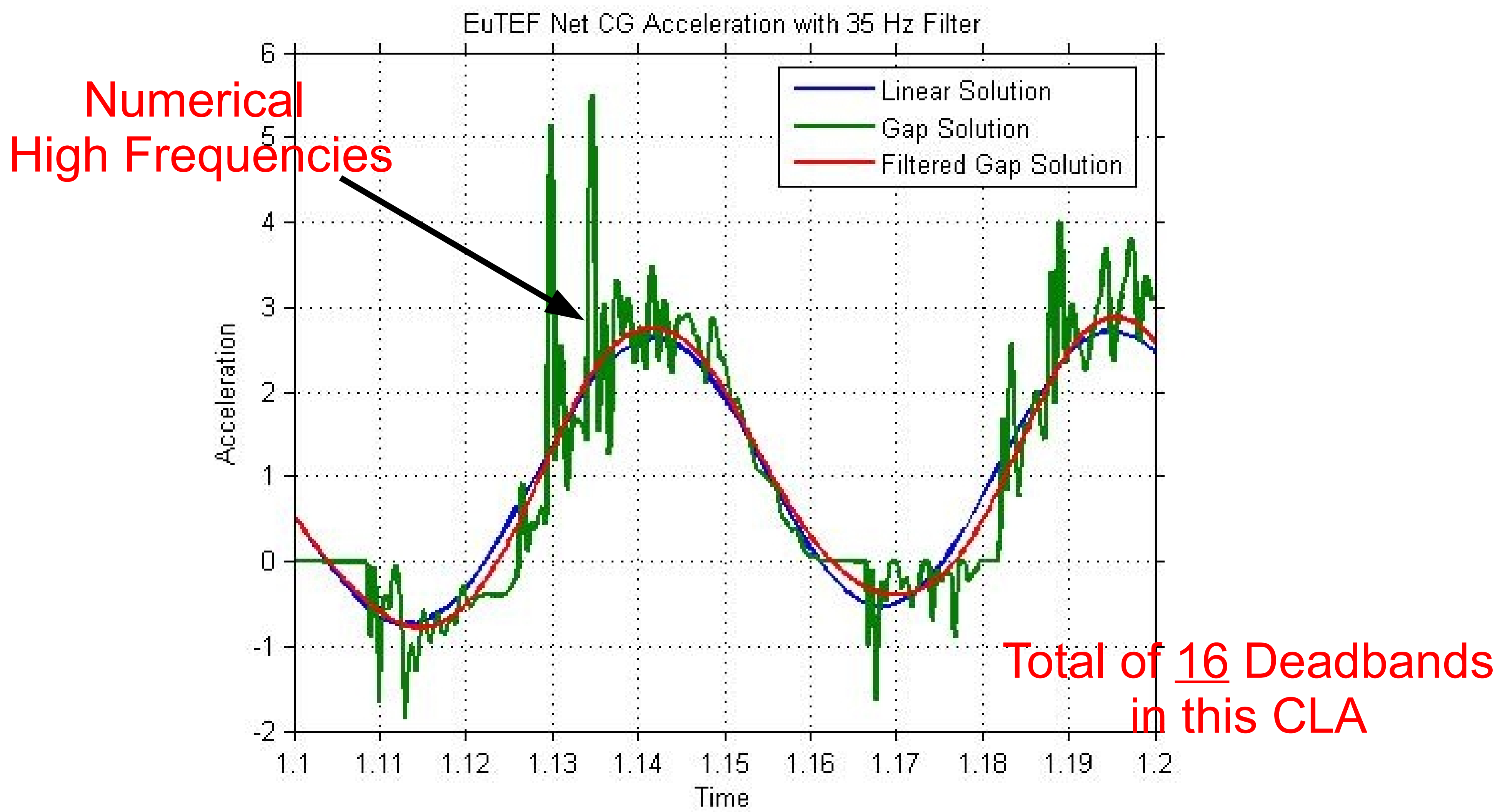
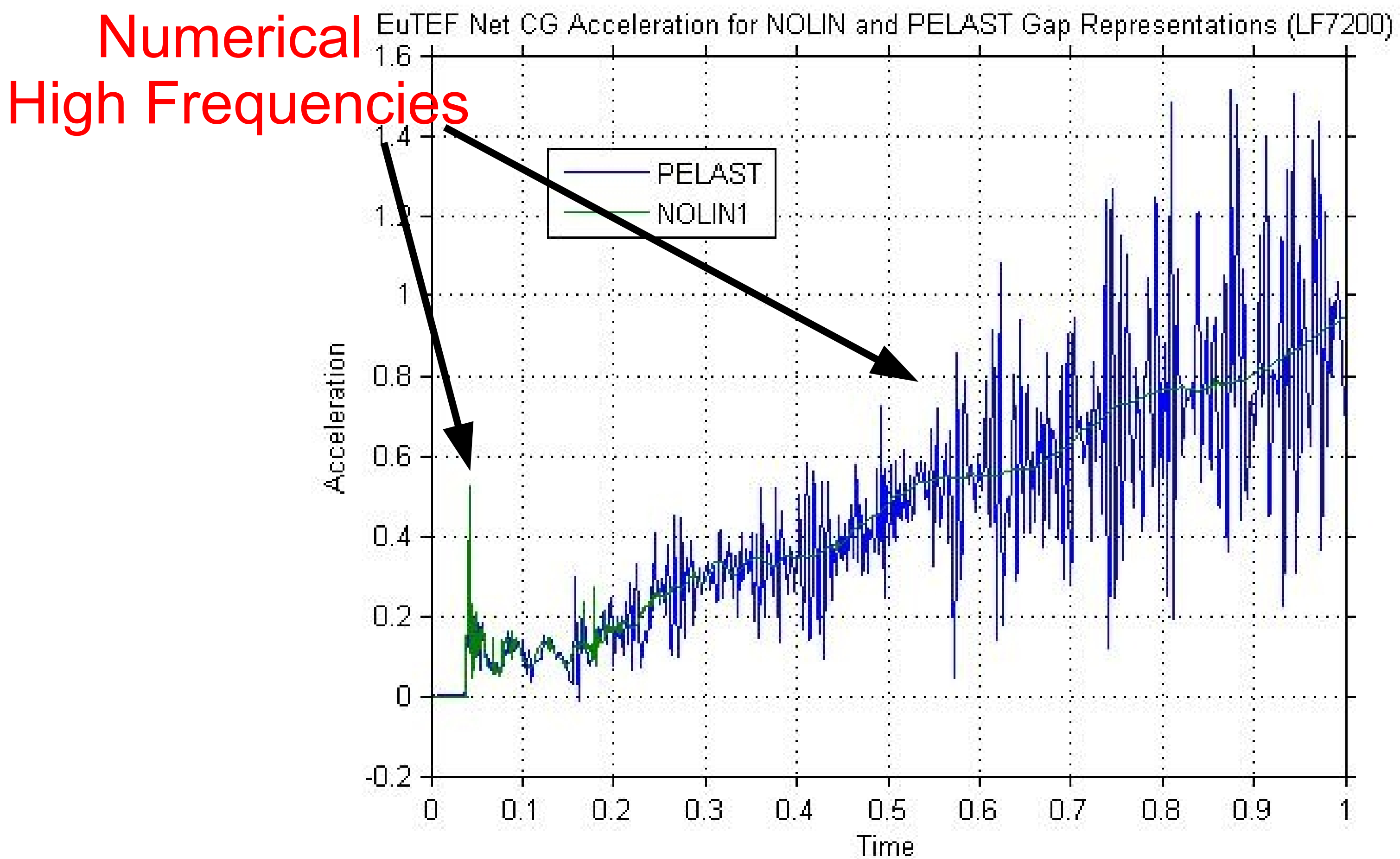
Initial Nonlinear CLA Attempts 2005-2006

- Executed within NASTRAN nonlinear solution
  - All NASTRAN nonlinear capabilities exercised
  - Resulted in “unrealistic” time-histories
  - Dominated what can be best described as “numerical noise/chatter”
- Next few slides show results from the initial Space Shuttle Mission 1E Nonlinear CLA
  - 2 Components with nonlinear interfaces
  - 16 deadbands in this nonlinear CLA

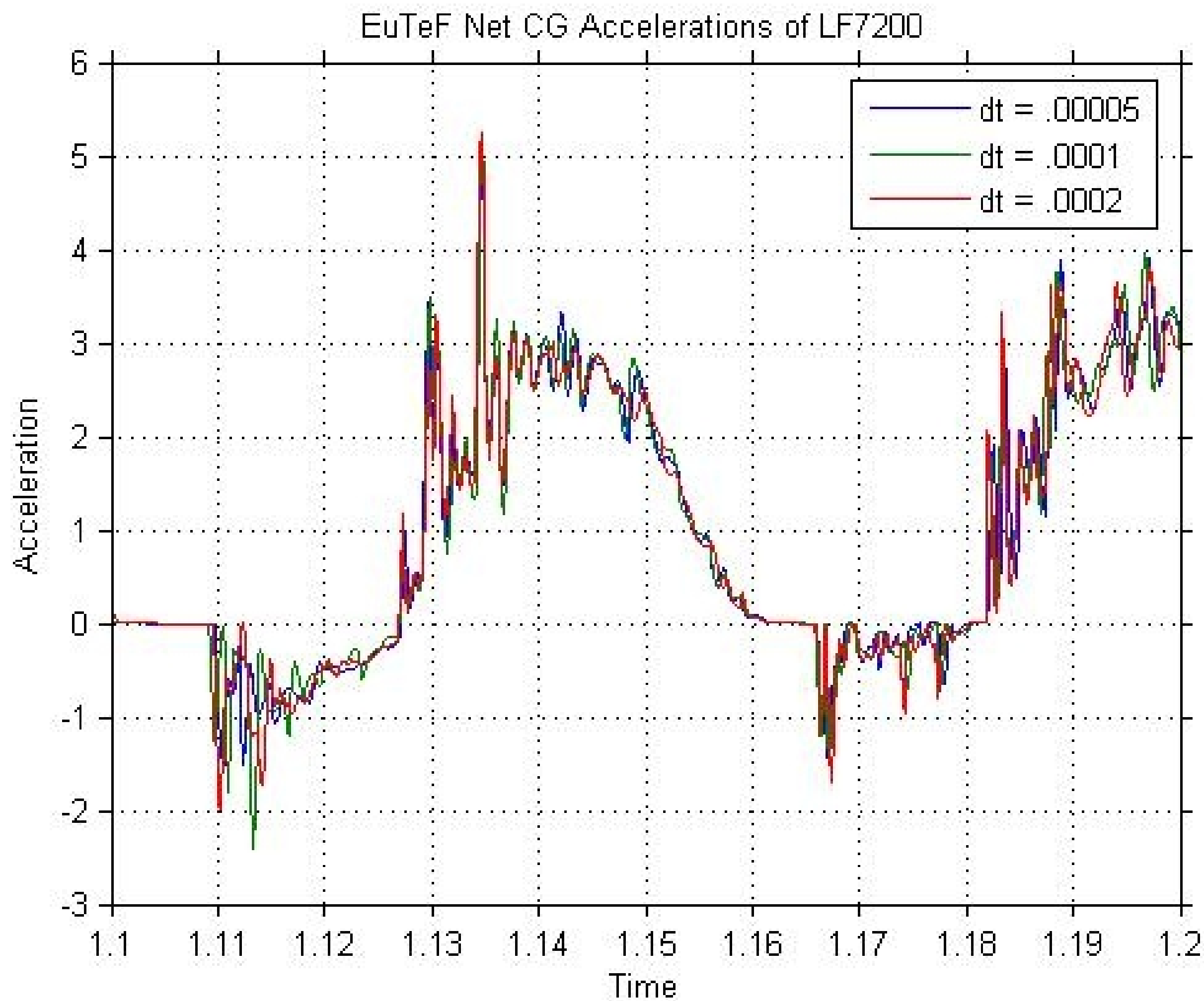
Dominated by High Frequency <u>Numerical</u> Noise/Chatter



Start-Up


Numerical
High Frequencies
EuTEF Net CG Acceleration for NOLIN and PELAST Gap Representations (LF7200)
PELAST
NOLIN1
Acceleration
Time
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

No Improvements with Decreasing Time-Steps



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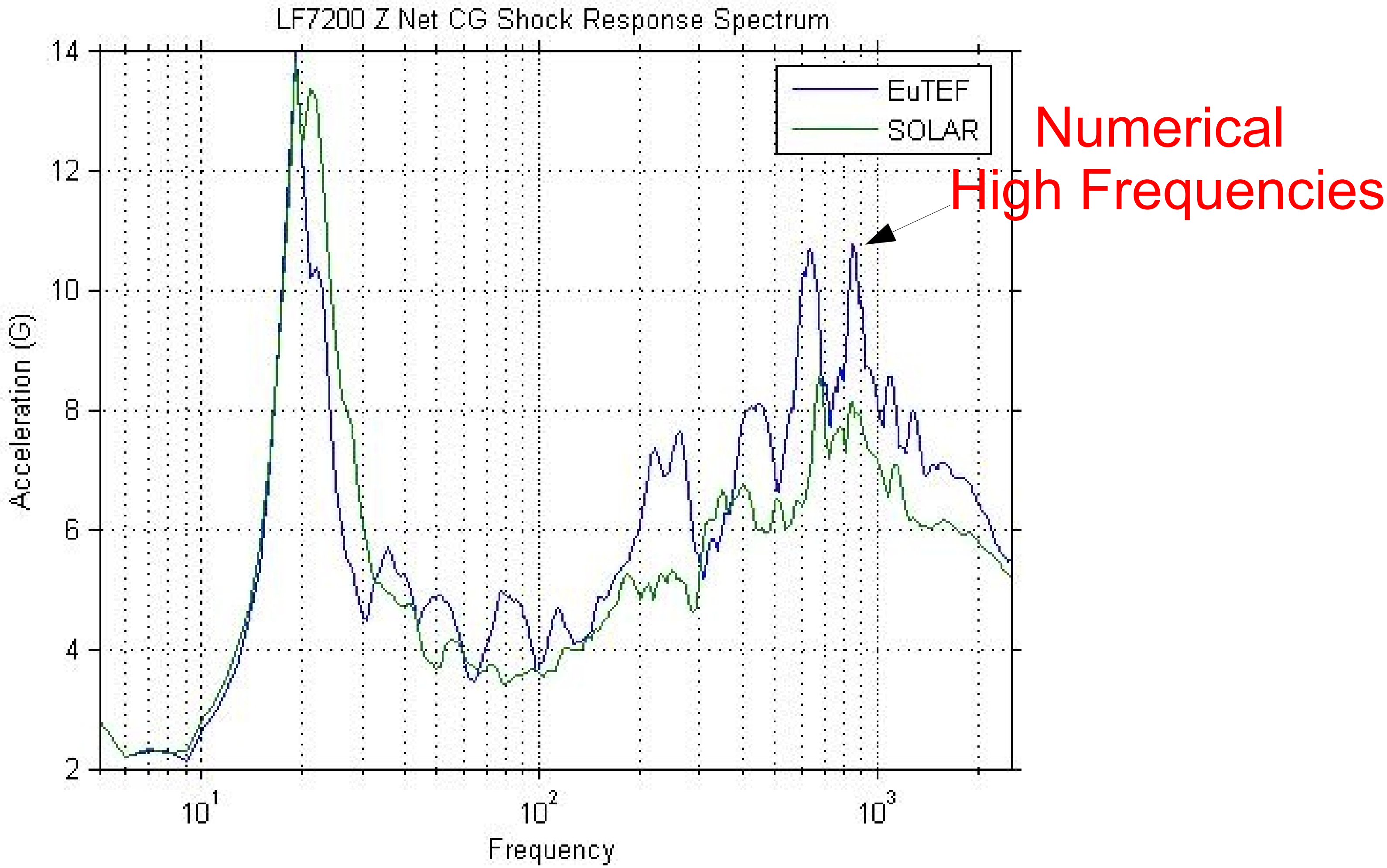
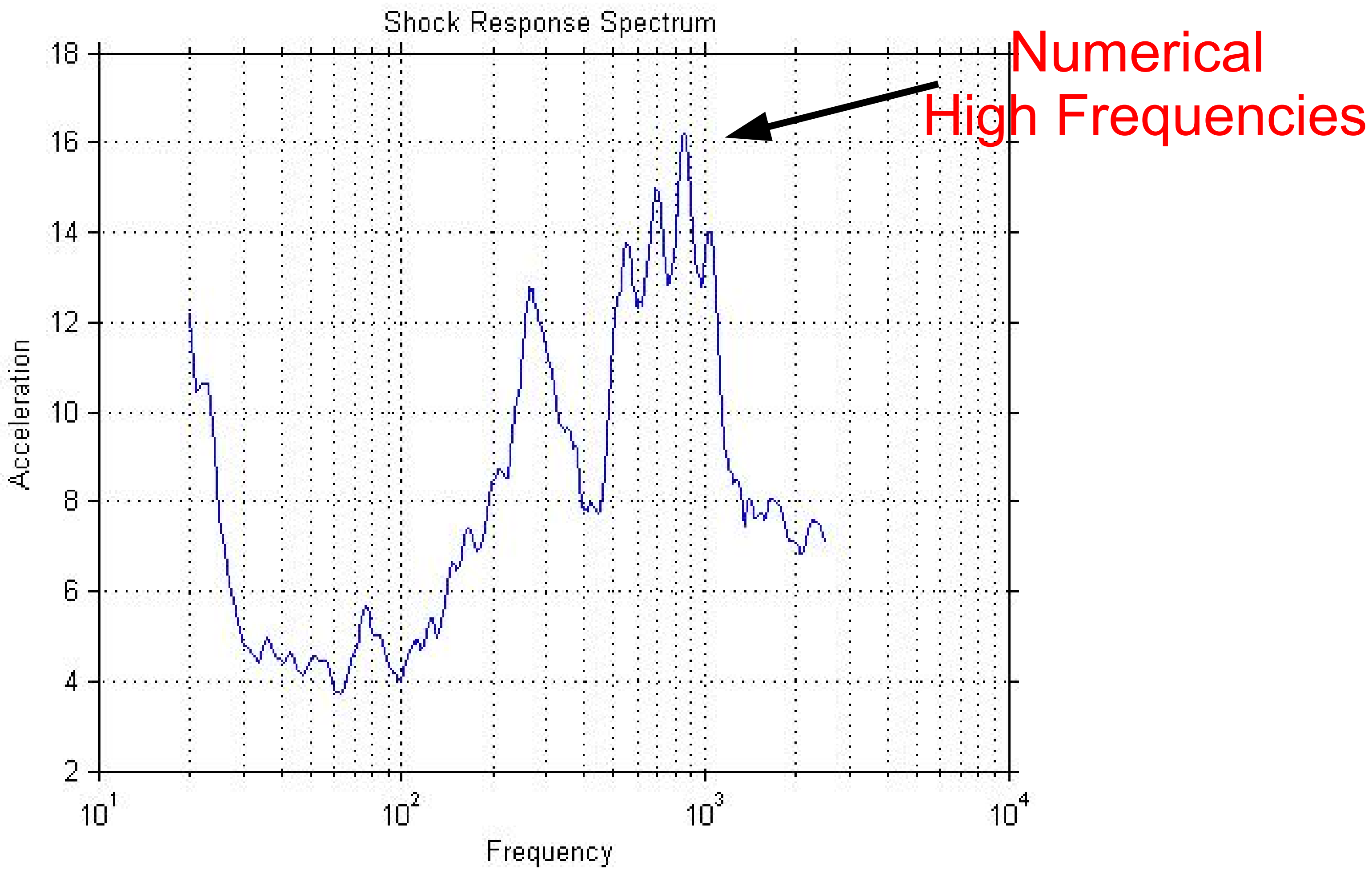
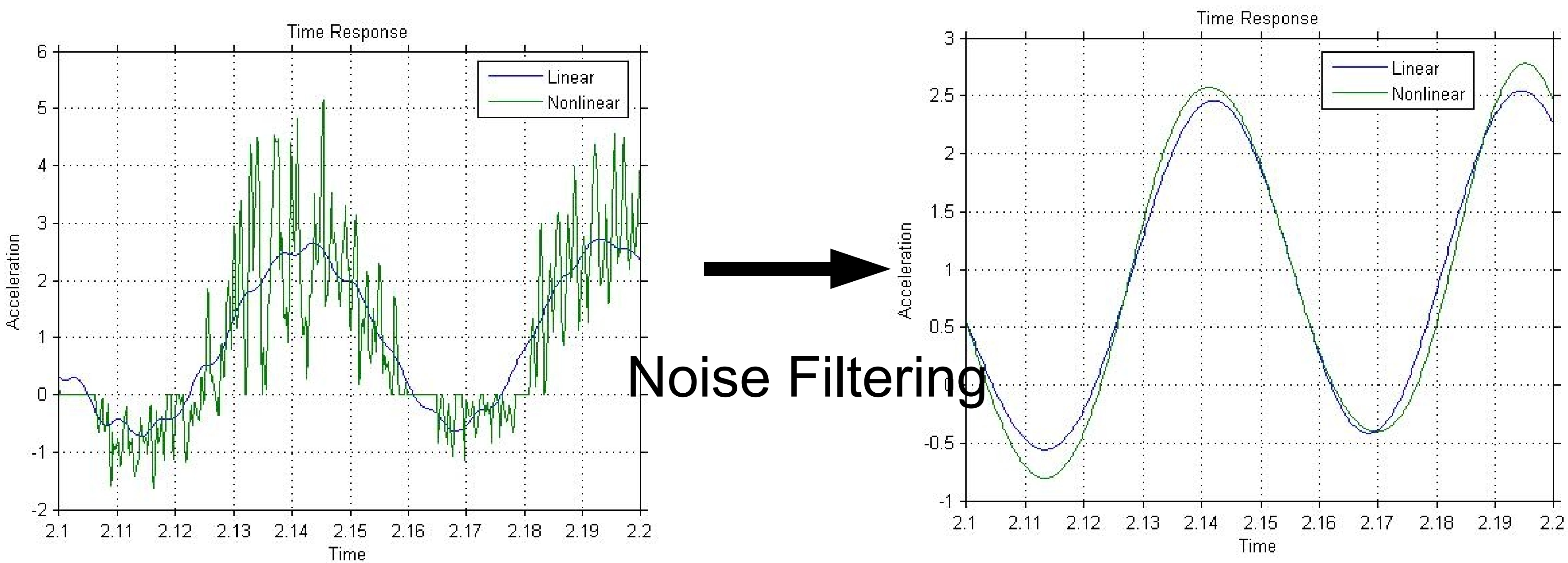
Shock Response Spectra



Shock Response Spectra



Attempted Filtering

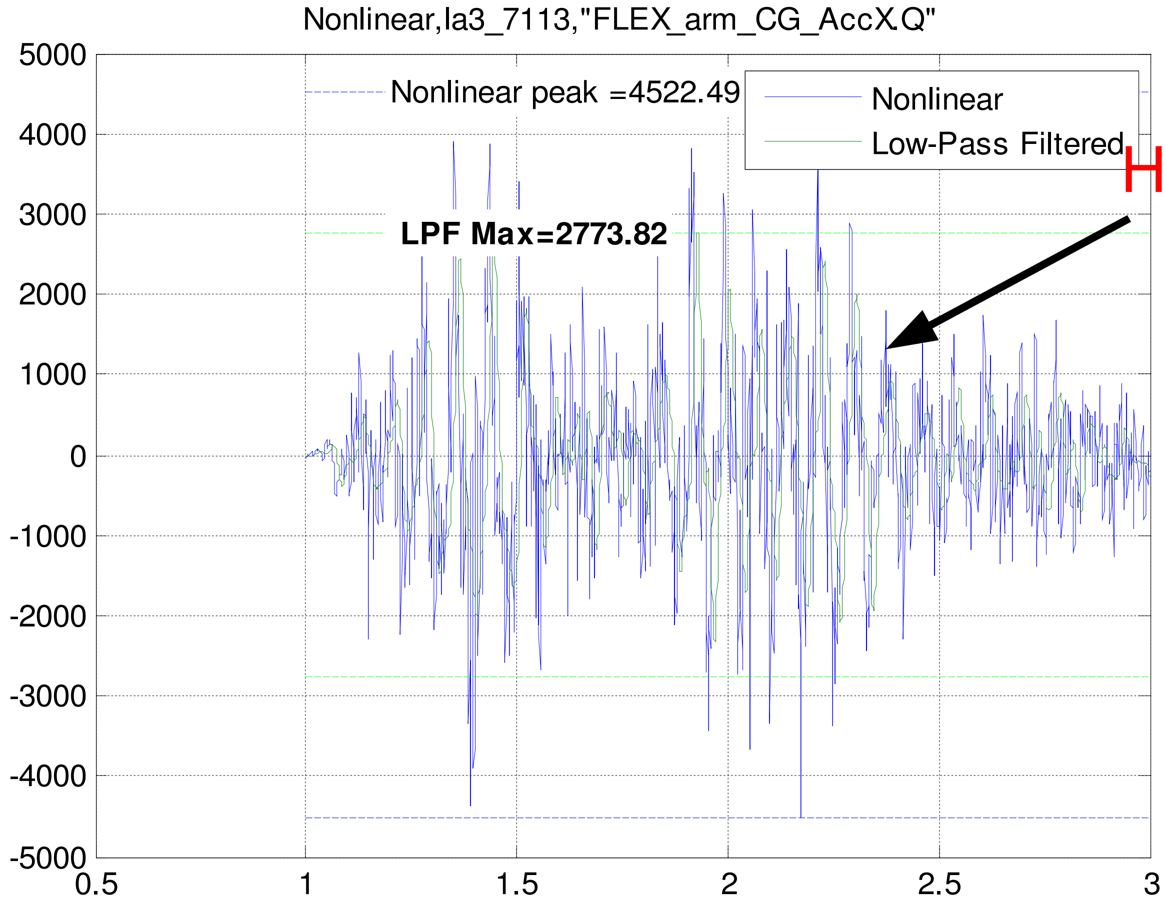


If spikes are filtered, results are almost unchanged from results without gaps

Investigated ADAMS

- Geared towards single component analysis (base-drive) rather than coupled loads analysis
- Base-shake of TUSRA component conducted
- Again, results dominated by high frequency numerical noise/chatter
  - Attempted filtering

ADAMS Nonlinear Base-Shake & Filtering of TUSRA



Numerical High Frequencies

NASA Investigation Expanded into other Vendor Capabilities: 2006

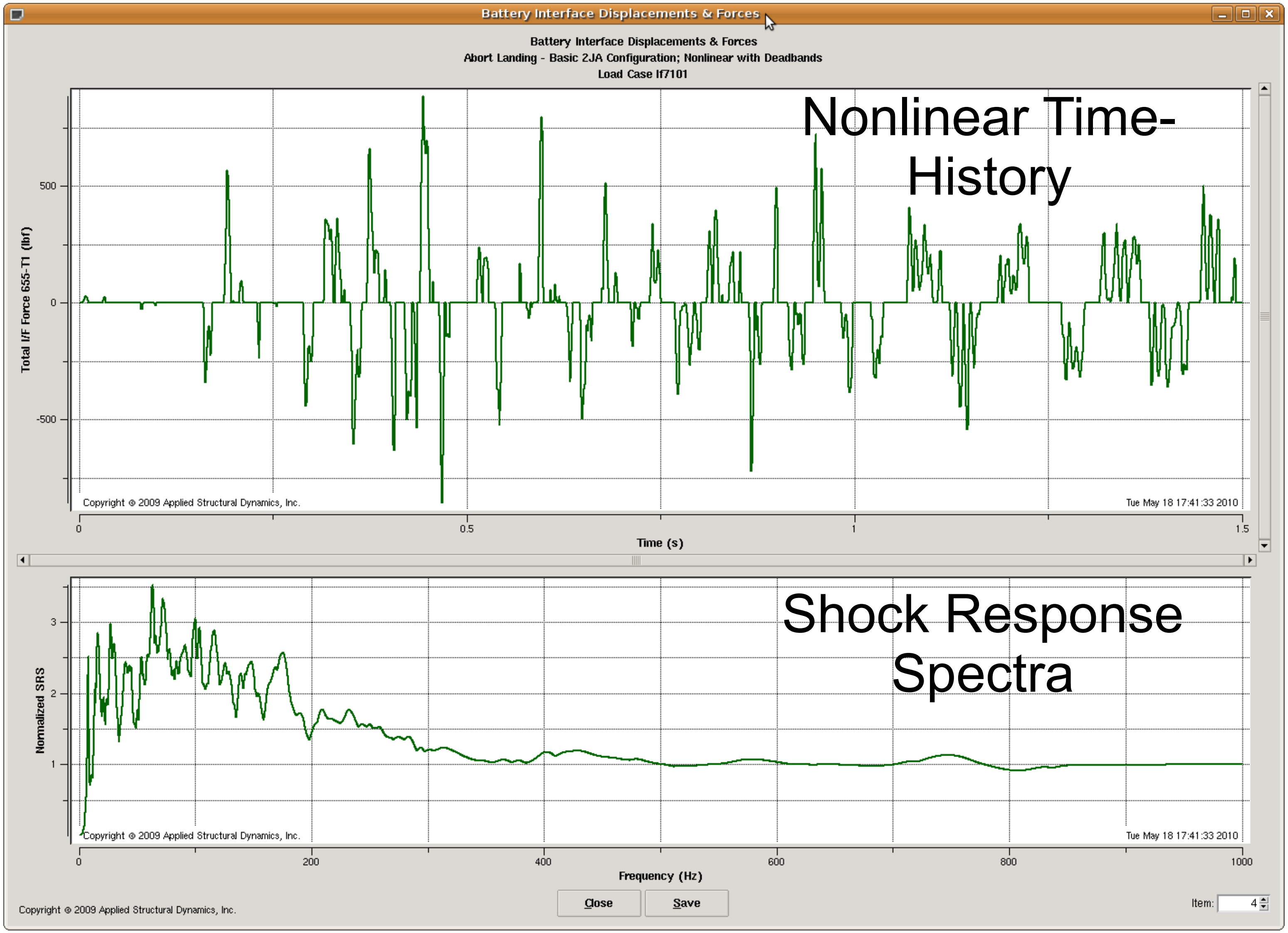
- NASA and Lockheed Martin began an investigation into other available vendor capabilities
- One candidate capability was successfully demonstrated in a 2004 Space Shuttle Technical Interchange Meeting (TIM) by Applied Structural Dynamics (ASD), Inc.

ASD's Nonlinear Deadband CLA Capability Investigated: 2006

- NASA and Lockheed Martin performed a rigorous verification process
- NASA investigation included all phases of methodology and numerical solution
  - Resulting nonlinear time-histories were shown to be physically realizable and free of any numerical noise/chatter (no filtering required)
  - Solution conformed to the physical parameters and constraints defined in the analysis

Zero Numerical Noise/Chatter

10 Nonlinear Components/78 Deadbands



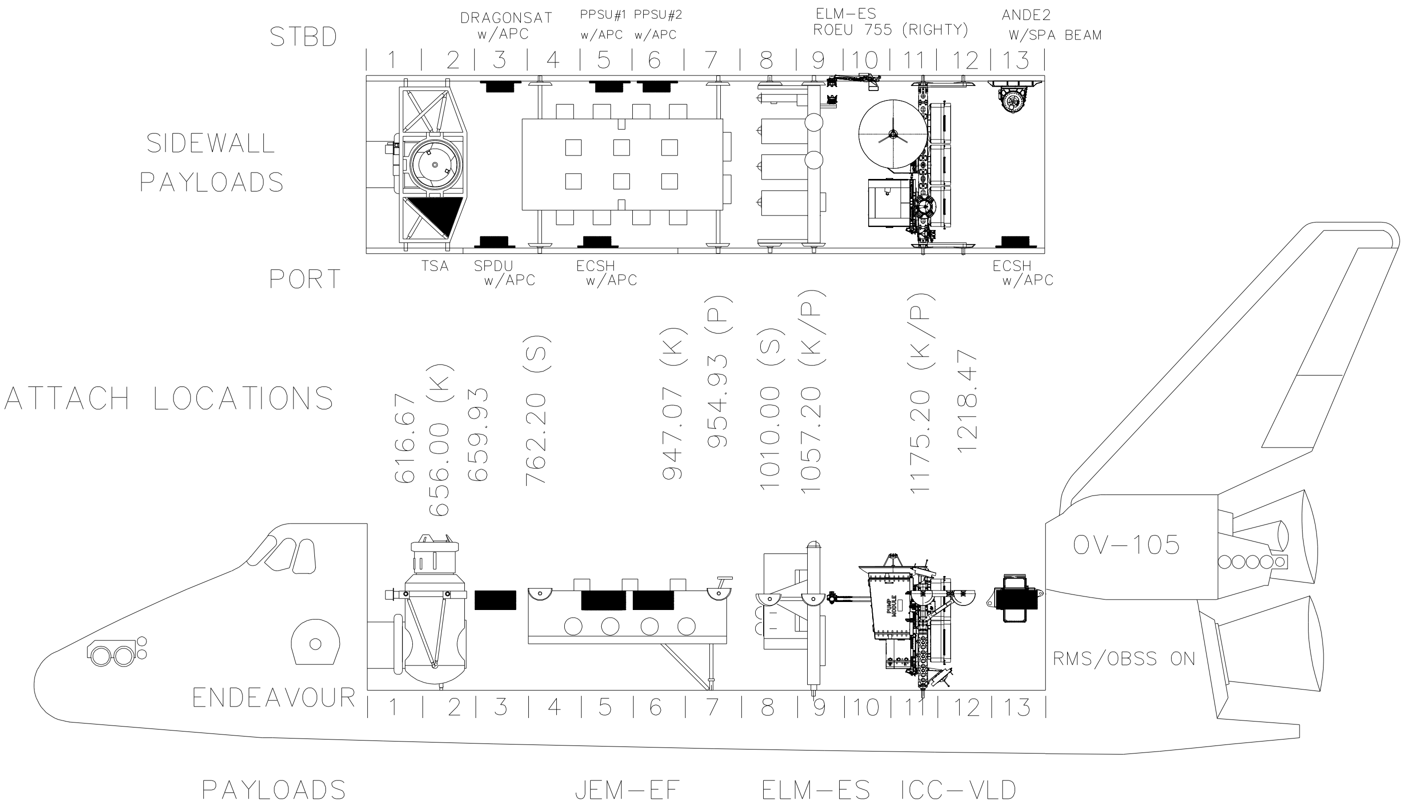
Screenshot from ASD/CLAS Software

Shuttle Mission 2J/A CLA: Landing

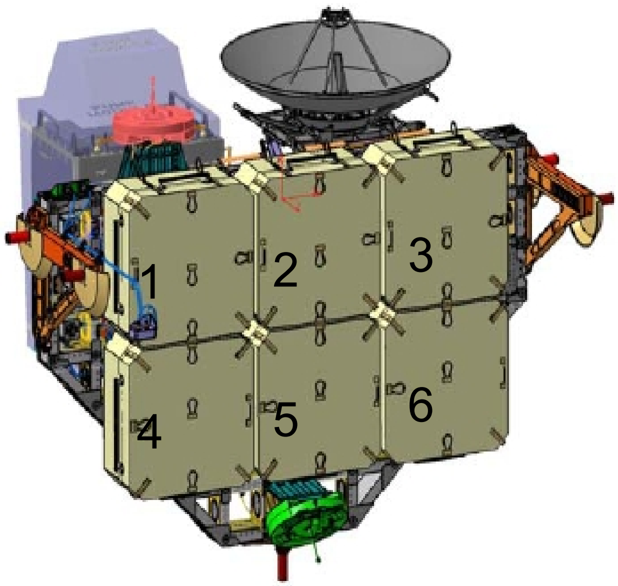
ASD's Nonlinear Deadband CLA Capability Selected

- 2006: NASA selected ASD's nonlinear deadband CLA capability to perform all Space Shuttle/payloads nonlinear CLAs
- Next few slides show results from Space Shuttle Mission 2J/A Nonlinear CLA
  - 10 Components with nonlinear interfaces
  - 78 deadbands in this nonlinear CLA

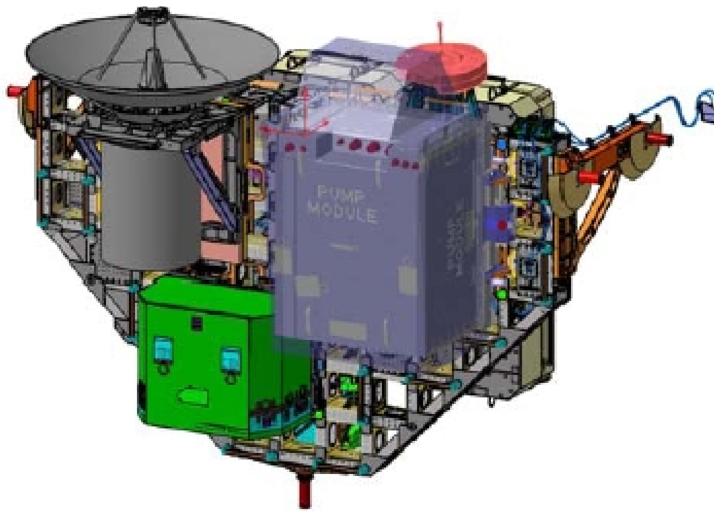
2J/A Cargo Bay Liftoff Configuration



2J/A ICC-VLD Liftoff Configuration

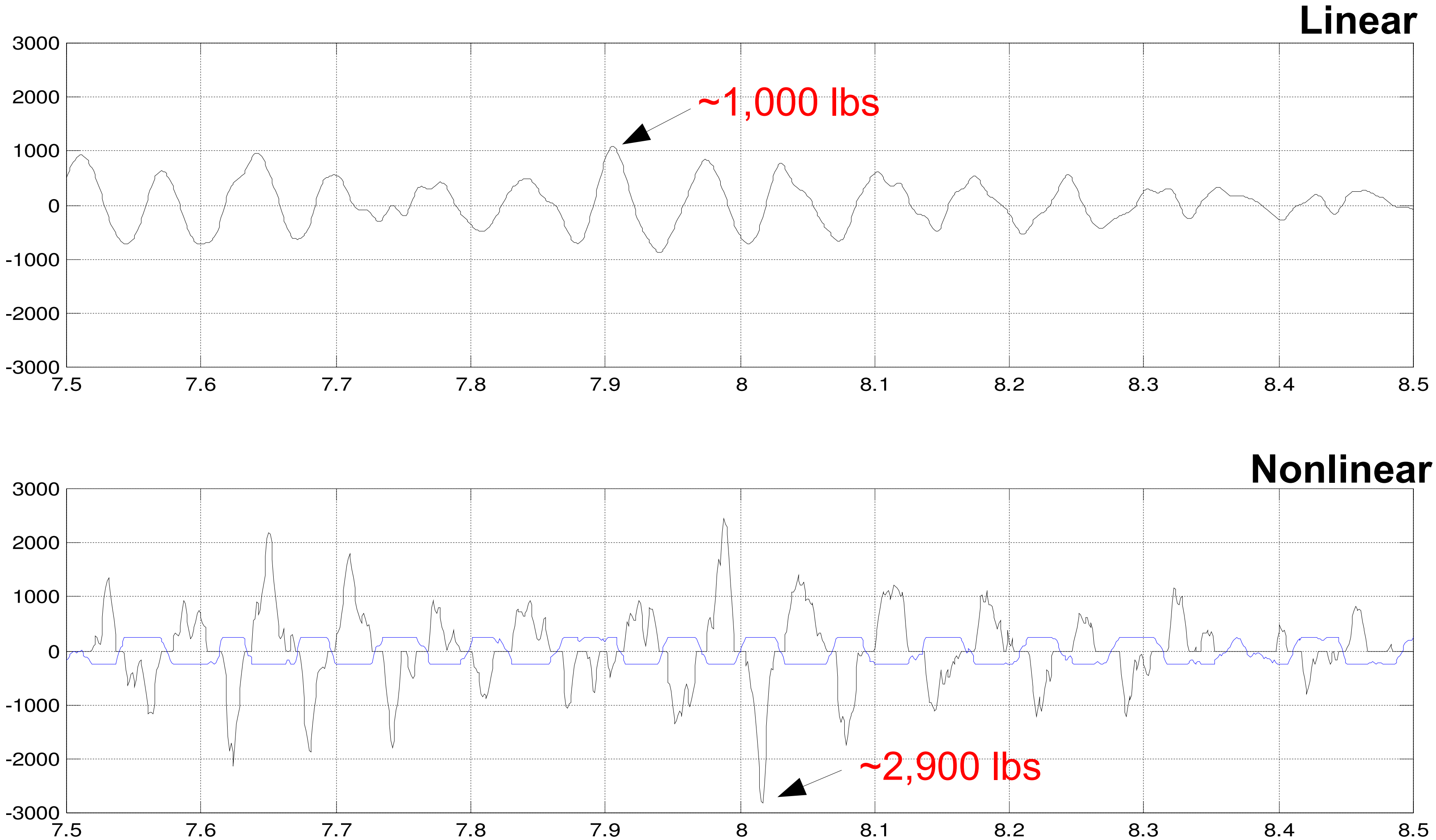


Aft View: 6 Kinematic Mounted Batteries



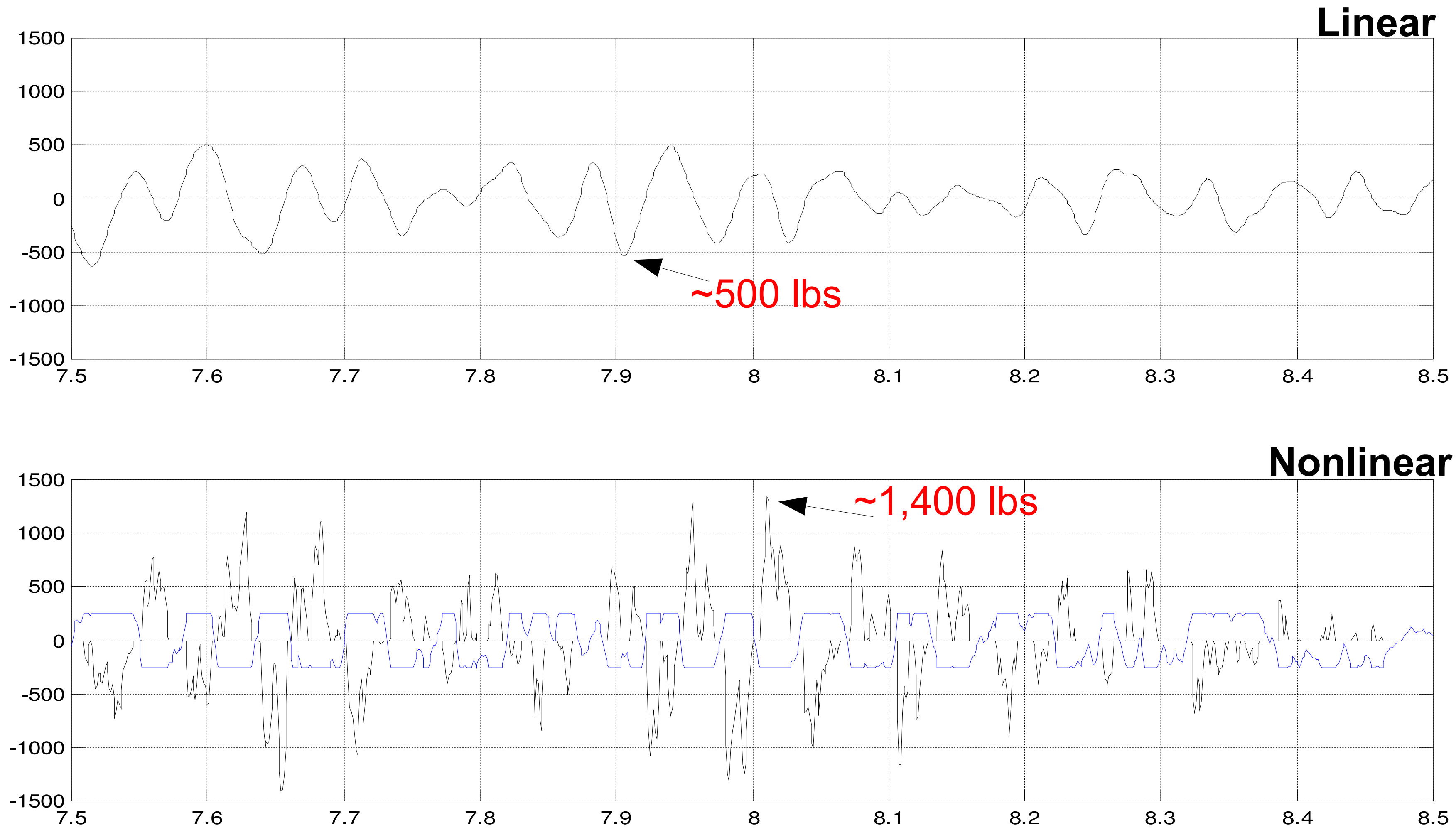
Fwd View: 3 FRAM Based ORUs
- Pump Module
- LDU
- SGANT

Battery KM Zo Shear Force Liftoff



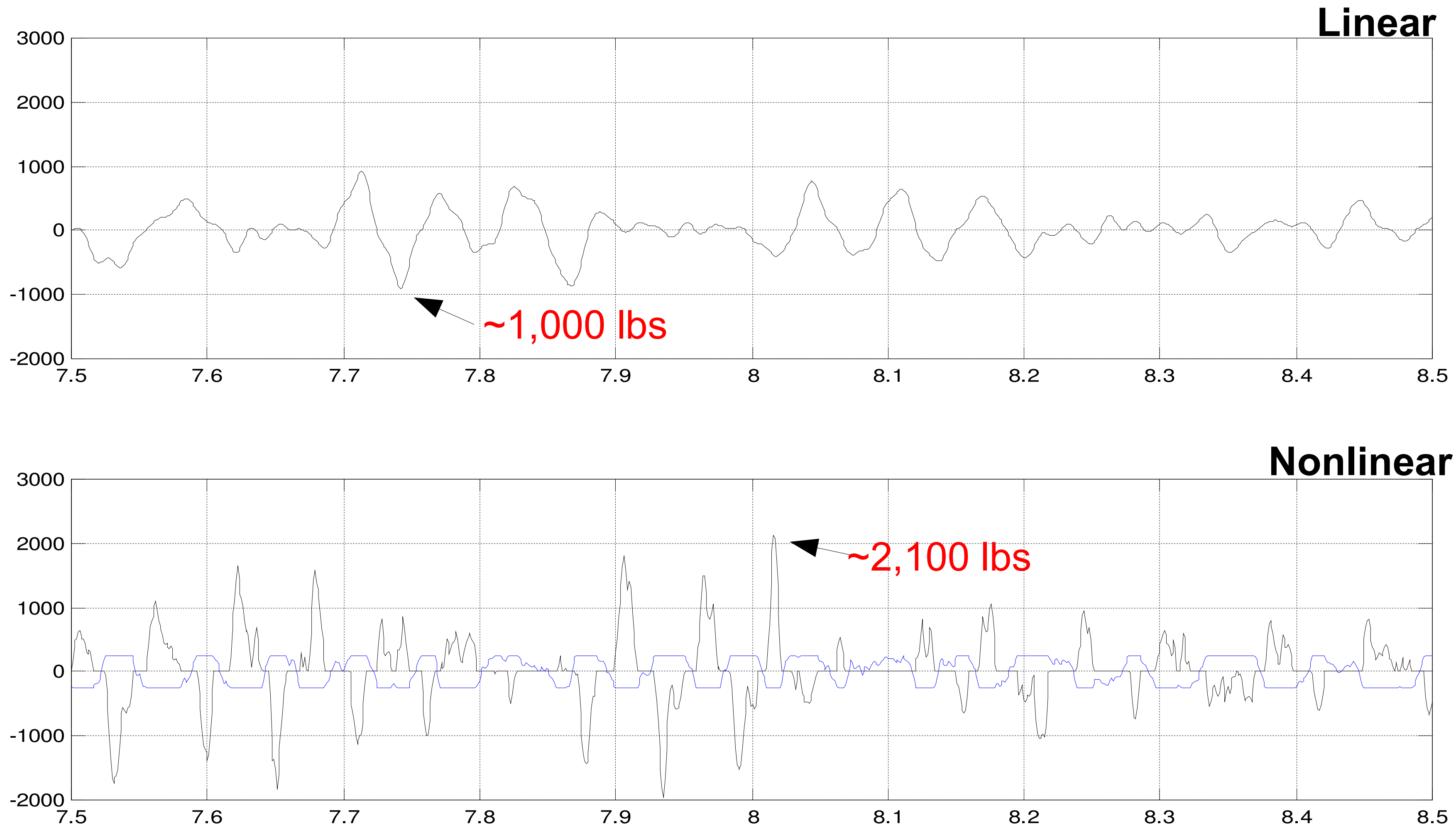
Battery 5: Shear Force (Node 653, Zorb) and Relative Displacement – (Blue Line x 40000)
Forcing Function: CLO1001; 7.5-8.5 second segment

Battery KM Yo Shear Force Liftoff



Battery 5: Shear Force (Node 655, Yorb) and Relative Displacement – (Blue Line x 40000)
Forcing Function: CLO1001; 7.5-8.5 second segment

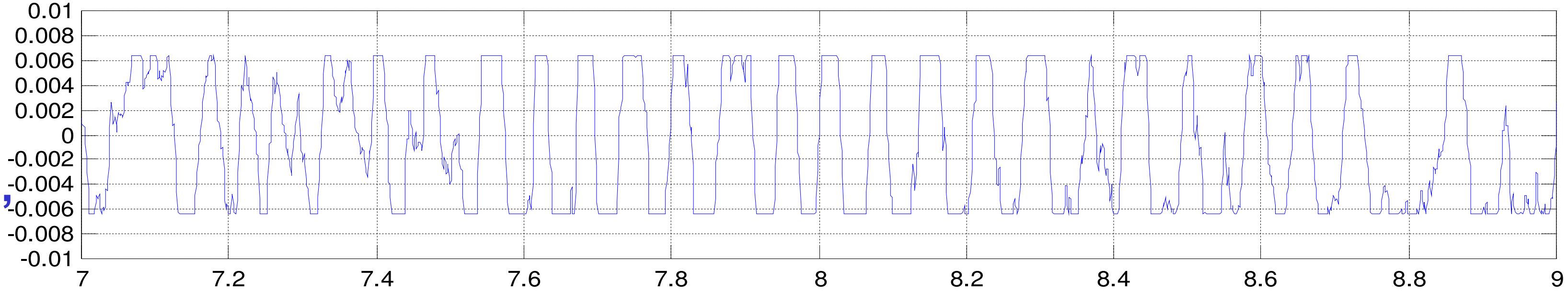
Battery KM Zo Shear Force Liftoff



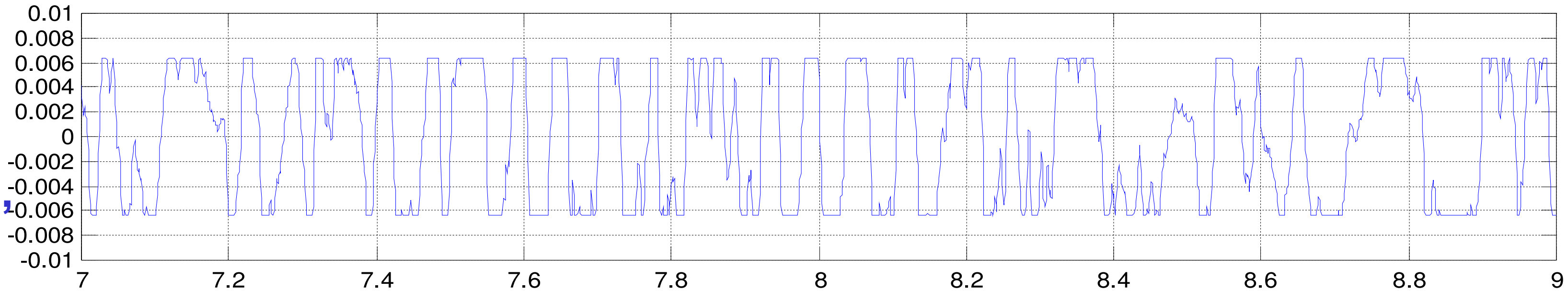
Battery 5: Shear Force (Node 2183, Zorb) and Relative Displacement – (Blue Line x 40000)
Forcing Function: CLO1001; 7.5-8.5 second segment

Battery KM Interface Rel. Displ. Liftoff

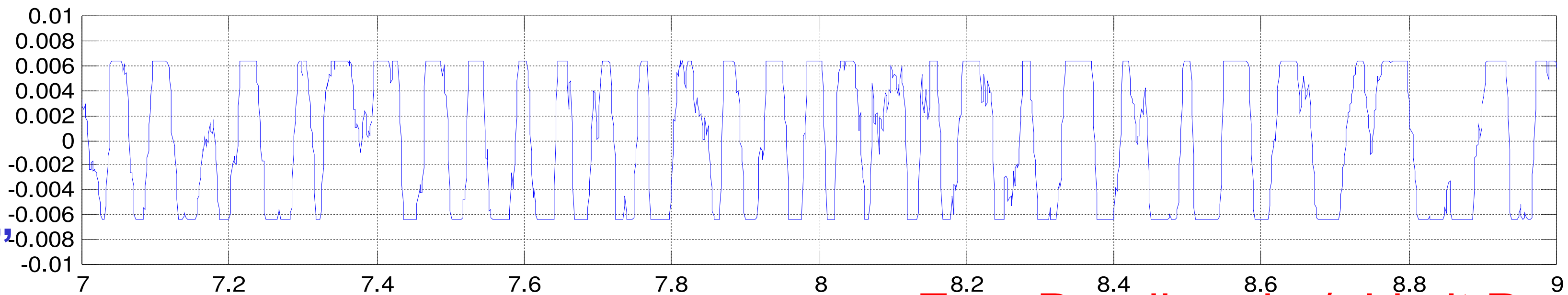
Shear Zorb +/- 0.0064”



Shear Yorb +/- 0.0064”



Shear Zorb +/- 0.0064”



Zero Deadband +/- Limit Penetration

Battery 5: Kinematic Mounts Interface Relative Displacements(in) Nodes 653, 655, and 2183
Forcing Function: CLO1001; 7-9 second segment

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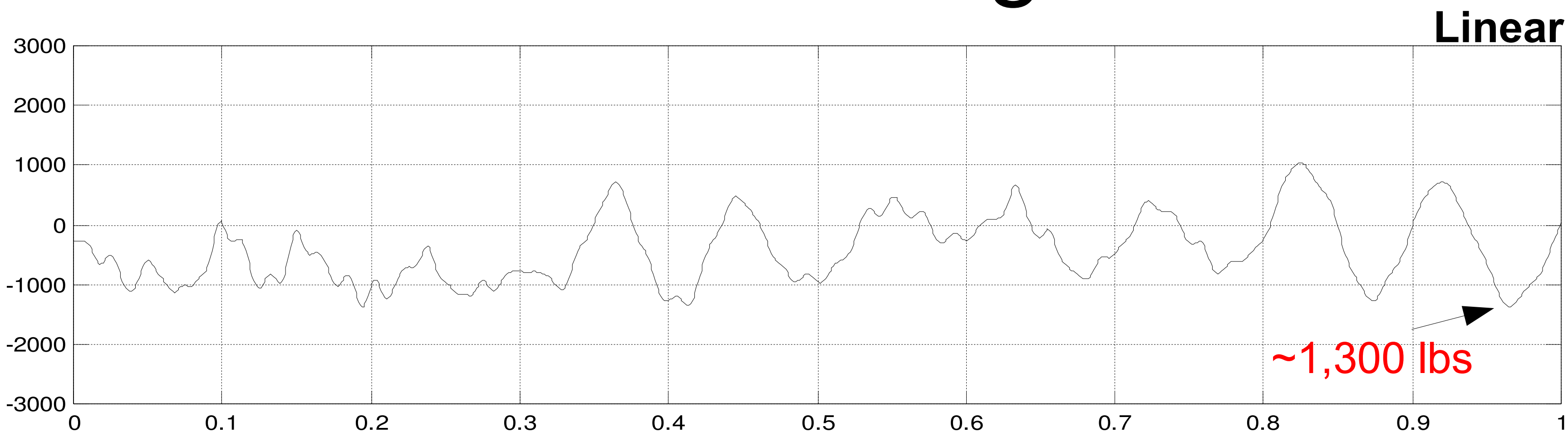
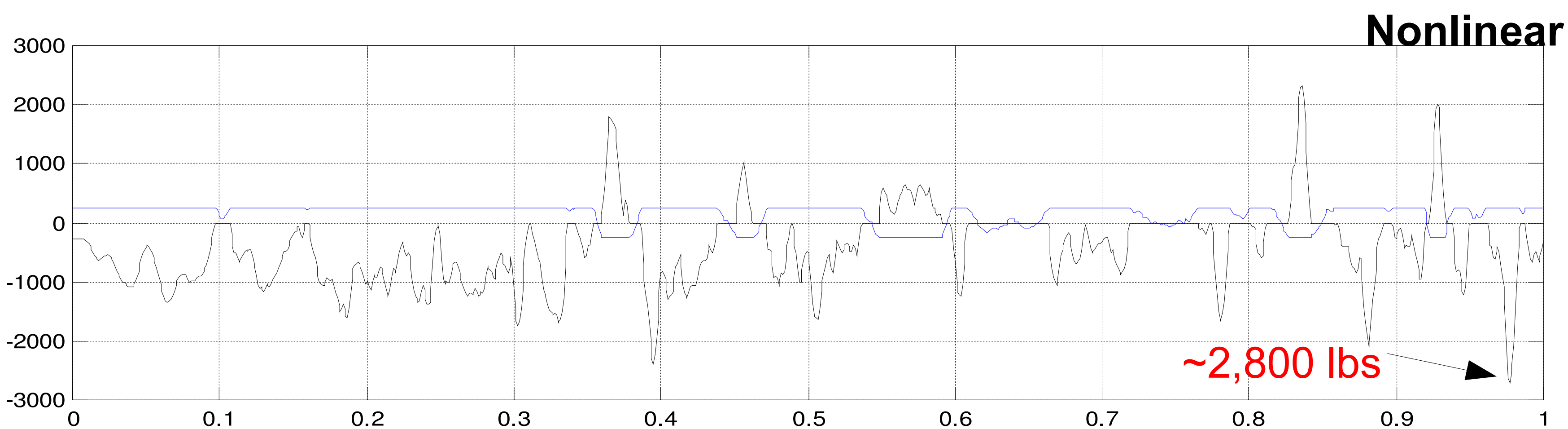
Battery KM Zo Shear Force Landing





Battery 5: Shear Force (Node 653, Zorb) and Relative Displacement – (Blue Line x 40000)
Forcing Function: LG7525

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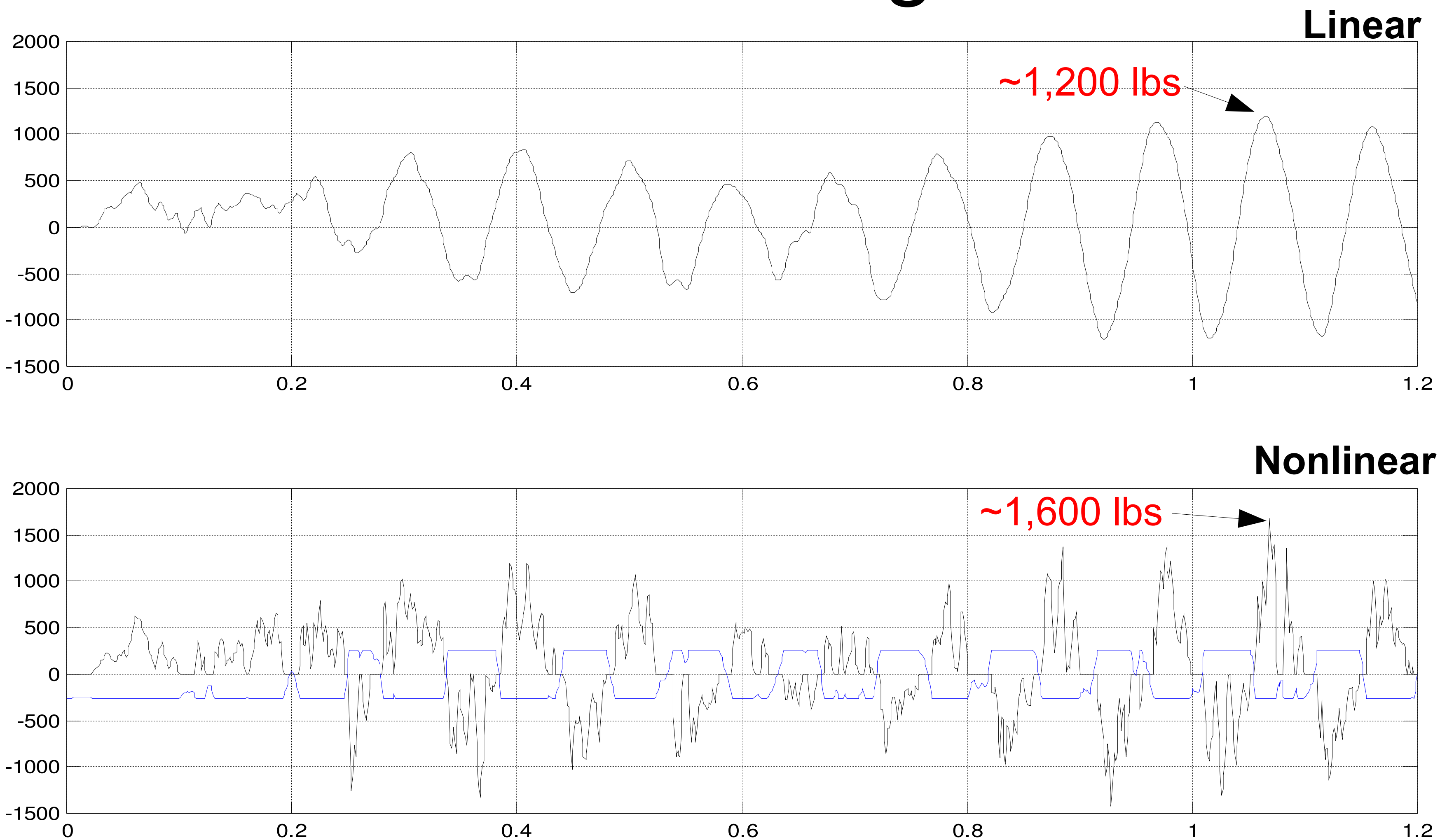
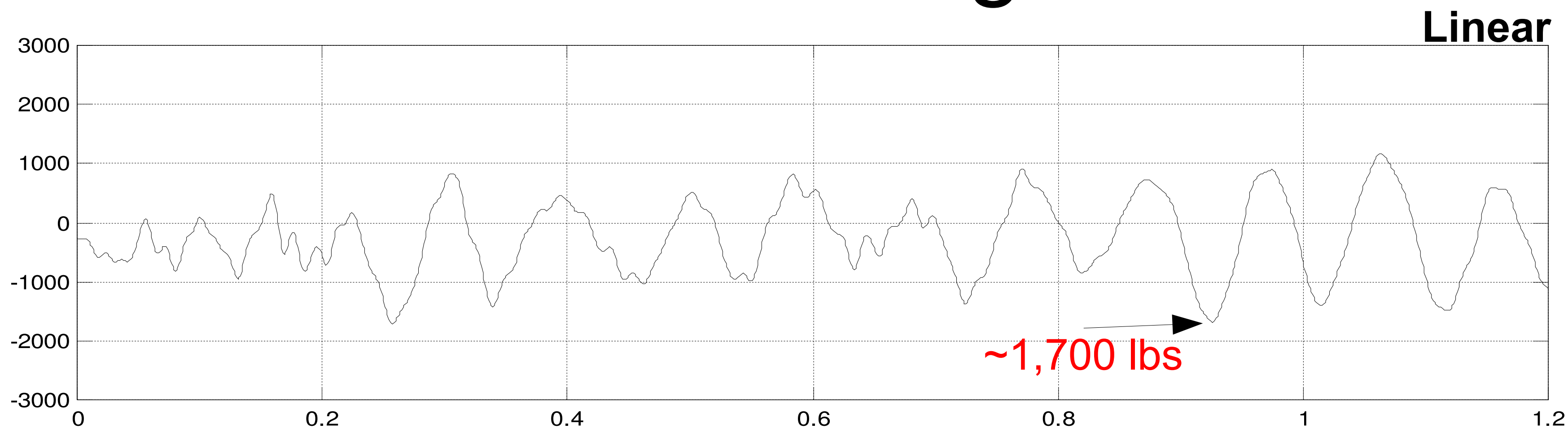
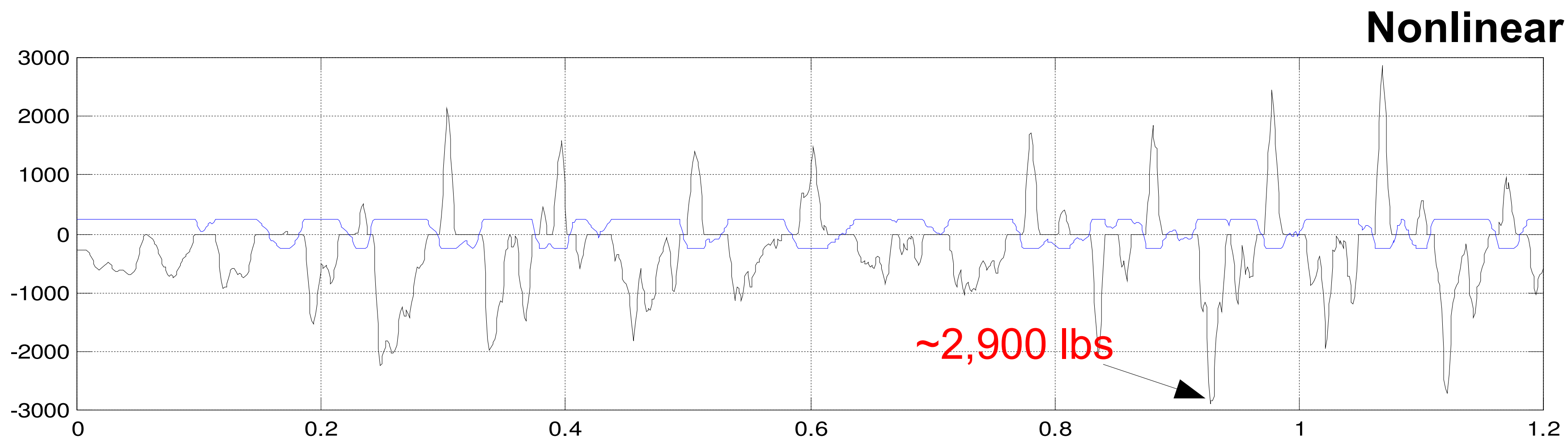
Battery KM Yo Shear Force Landing



Battery 5: Shear Force (Node 655, Yorb) and Relative Displacement – (Blue Line x 40000)
Forcing Function: LG7525

Battery KM Zo Shear Force Landing





Battery 5: Shear Force (Node 2183, Zorb) and Relative Displacement – (Blue Line x 40000)
Forcing Function: LG7525

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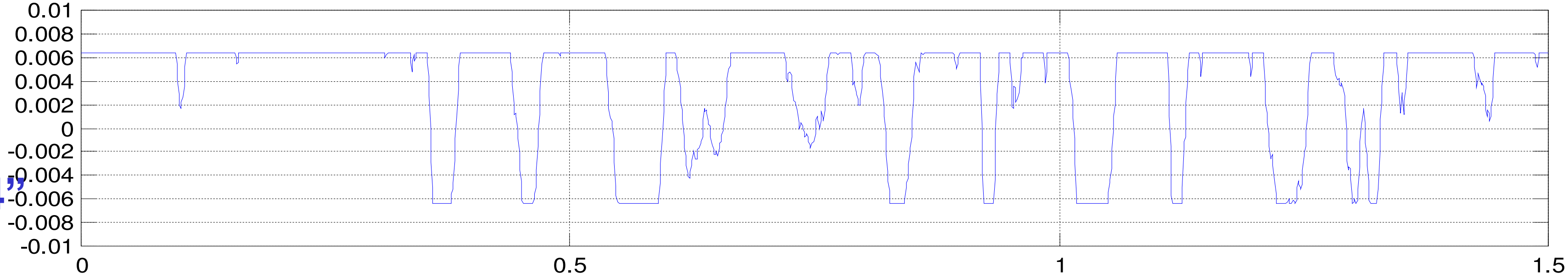
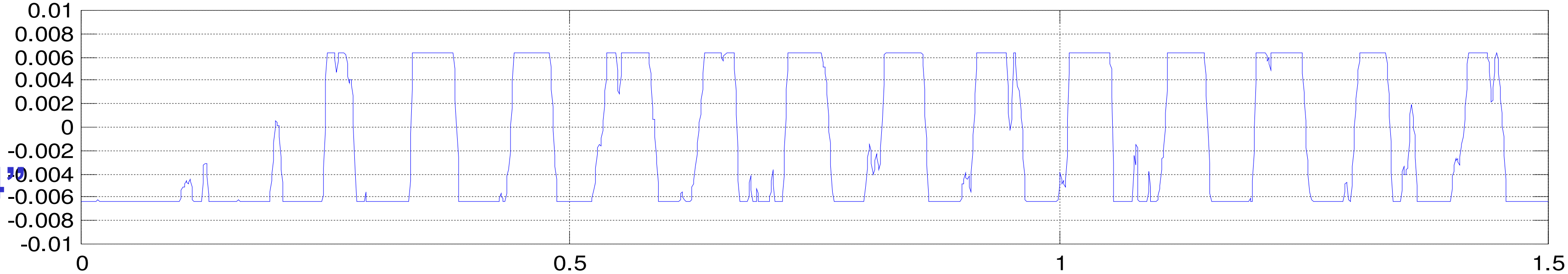
Battery KM Interface Rel. Displ. Landing

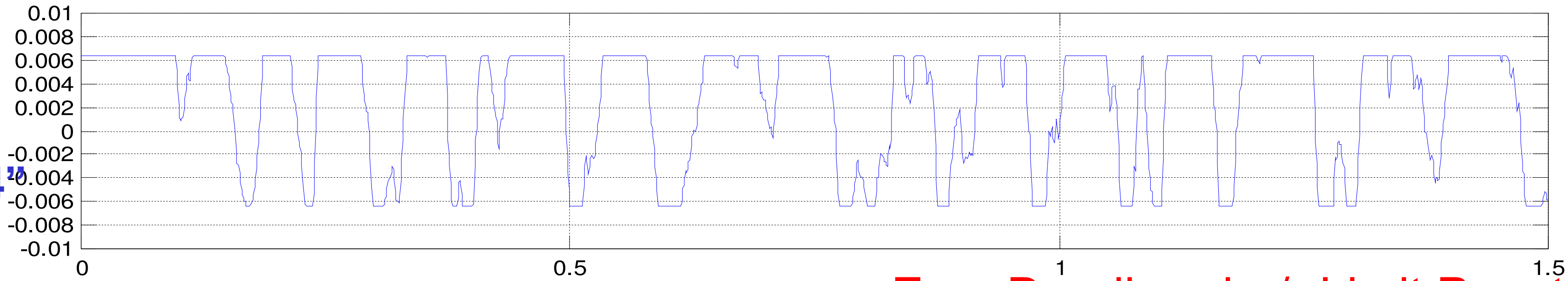
Shear
Zorb
+/- 0.0064”



Shear
Yorb
+/- 0.0064”



Shear
Zorb
+/- 0.0064”



Zero Deadband +/- Limit Penetration

Battery 5: Kinematic Mounts Interface Relative Displacements(in) Nodes 653, 655, and 2183
Forcing Function: LG7525

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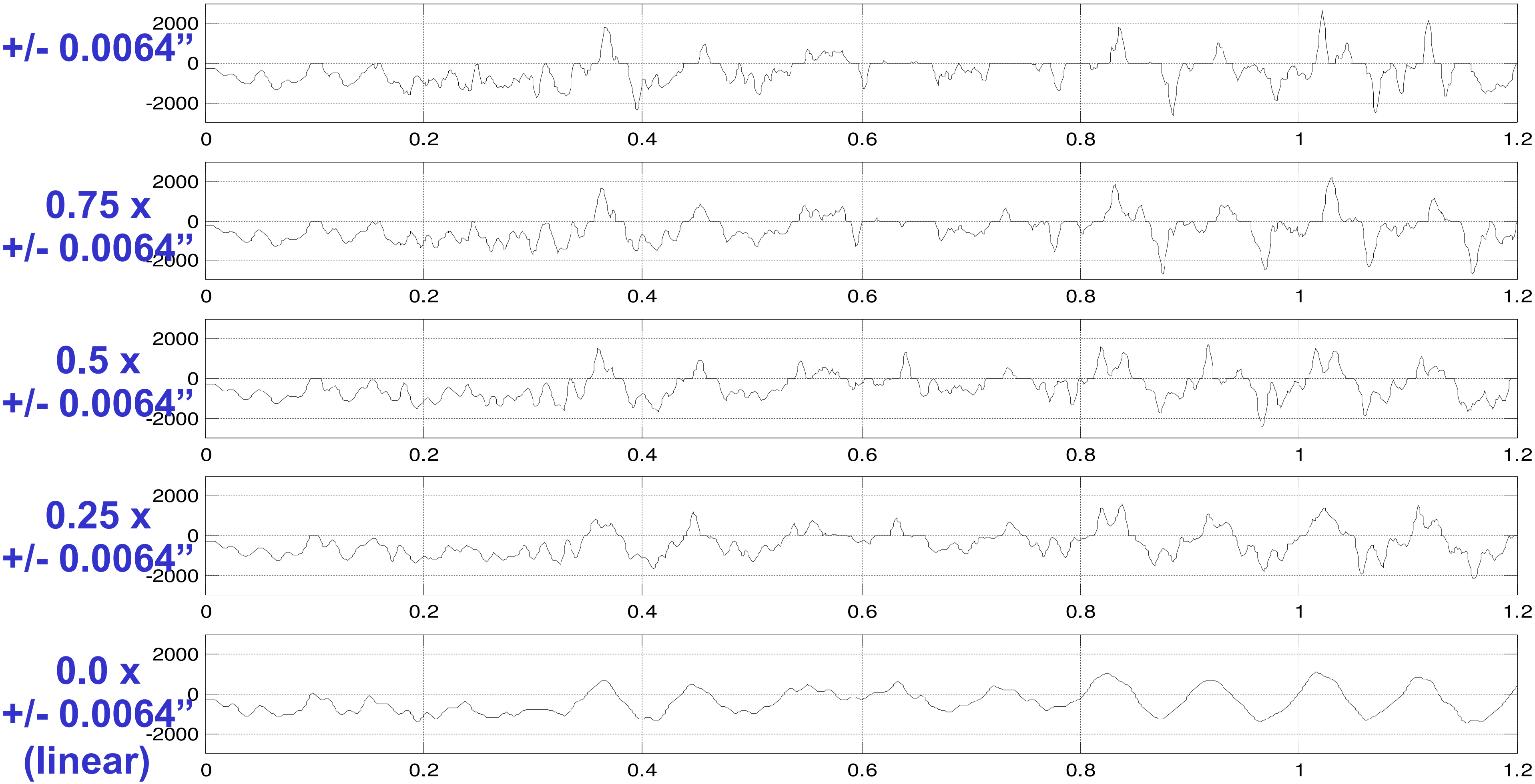
Convergence
Battery KM Zo Shear Force



Evolution of Nonlinearity

Battery 5: Shear Force Node 653 Zorb
Forcing Function: LG7525

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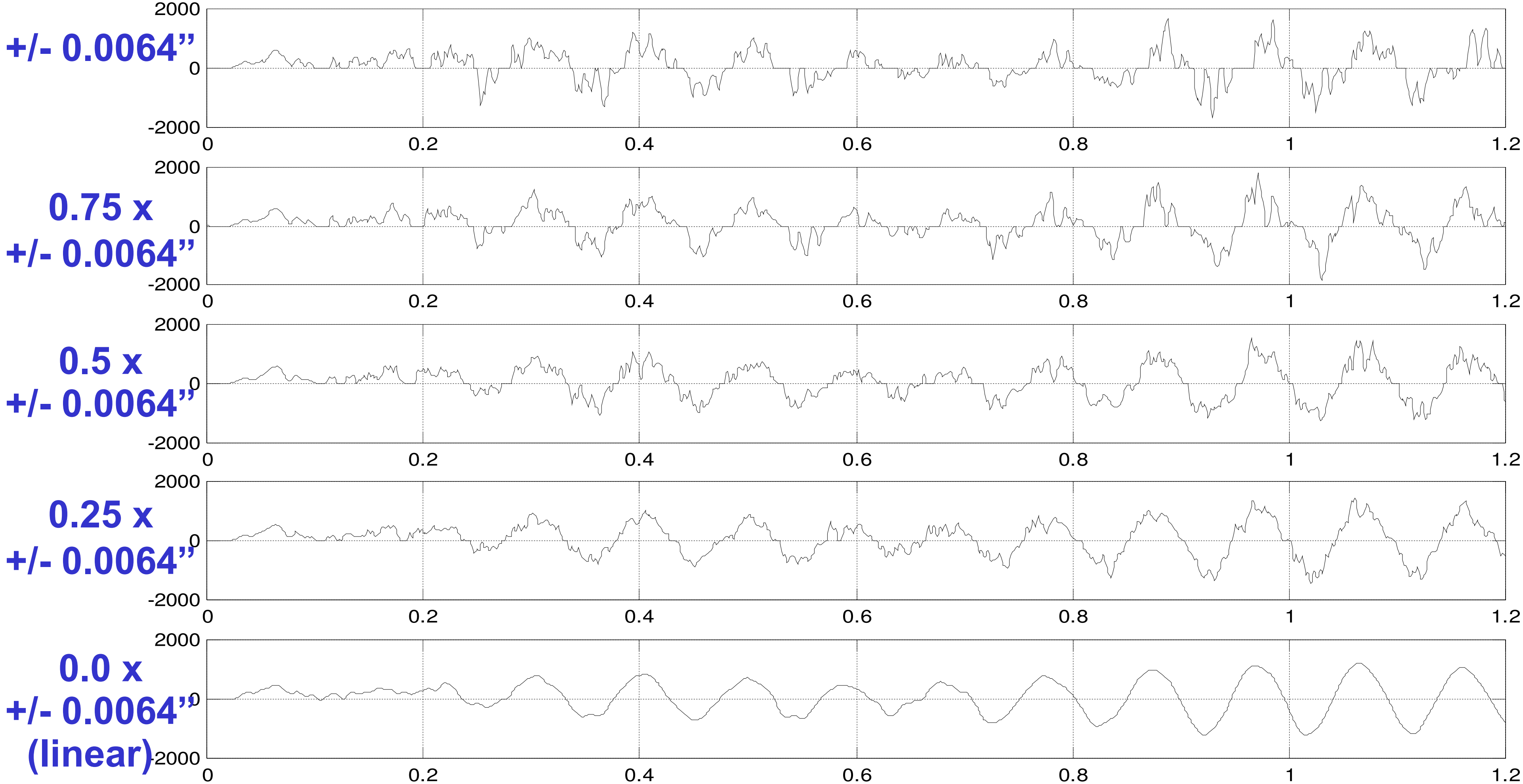
Convergence
Battery KM Yo Shear Force



Evolution of Nonlinearity

Battery 5: Shear Force Node 655 Yorb
Forcing Function: LG7525

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Convergence
Battery KM Zo Shear Force

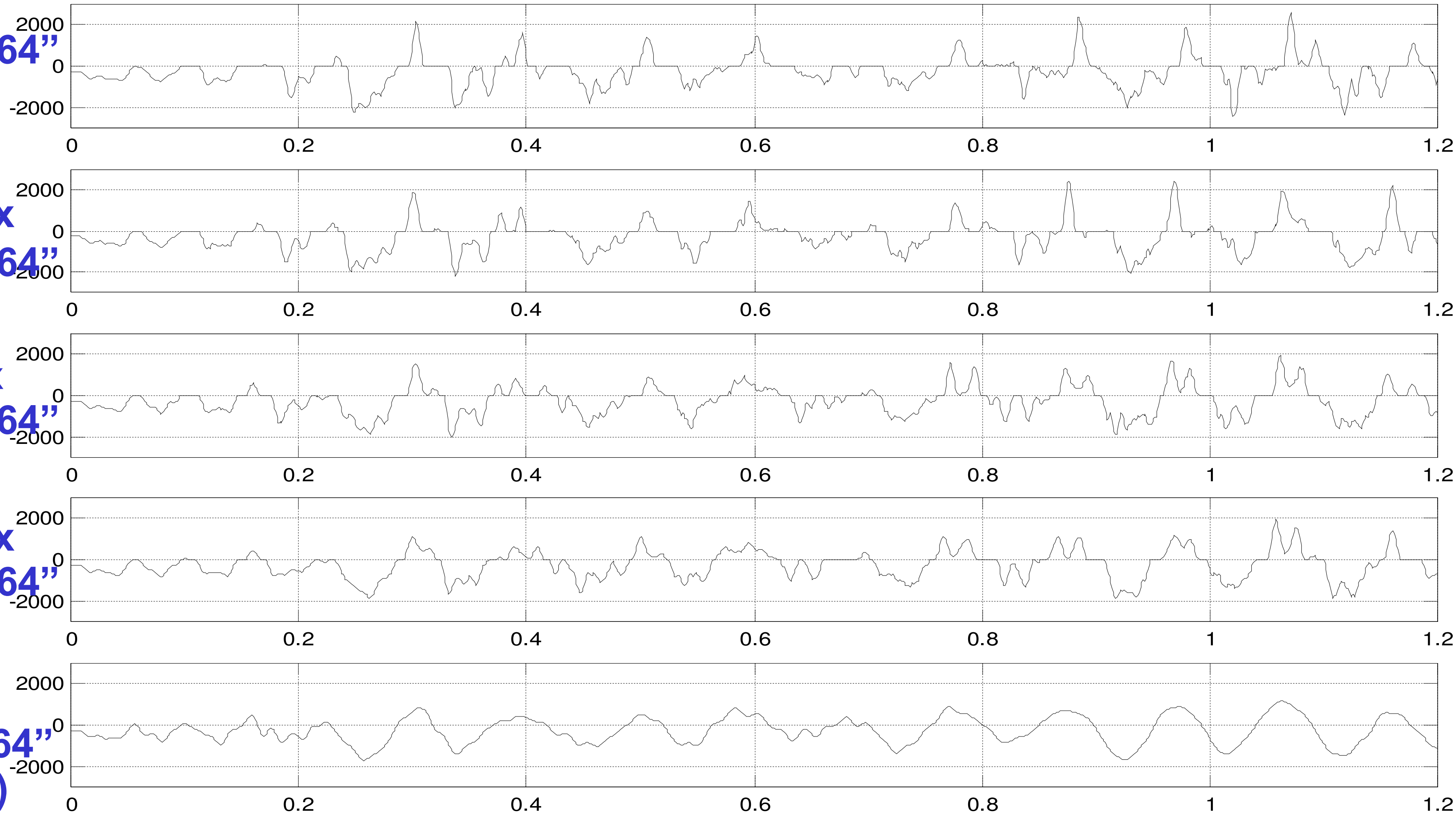
+/- 0.0064”

0.75 x
+/- 0.0064”

0.5 x
+/- 0.0064”

0.25 x
+/- 0.0064”

0.0 x
+/- 0.0064”
(linear)



Evolution of Nonlinearity

Battery 5: Shear Force Node 2183 Zorb
Forcing Function: LG7525

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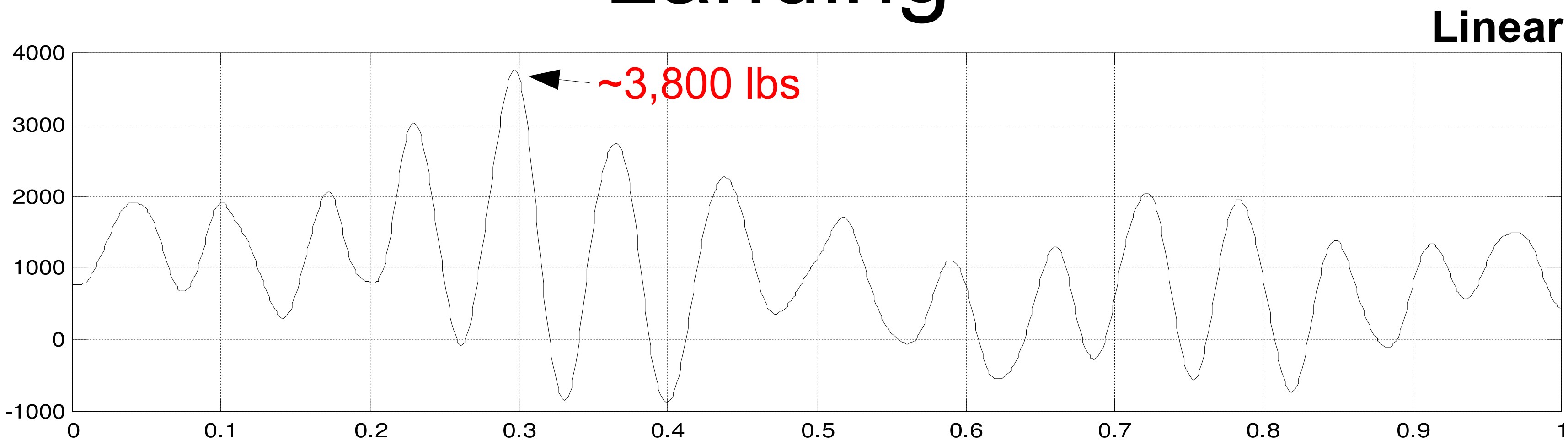
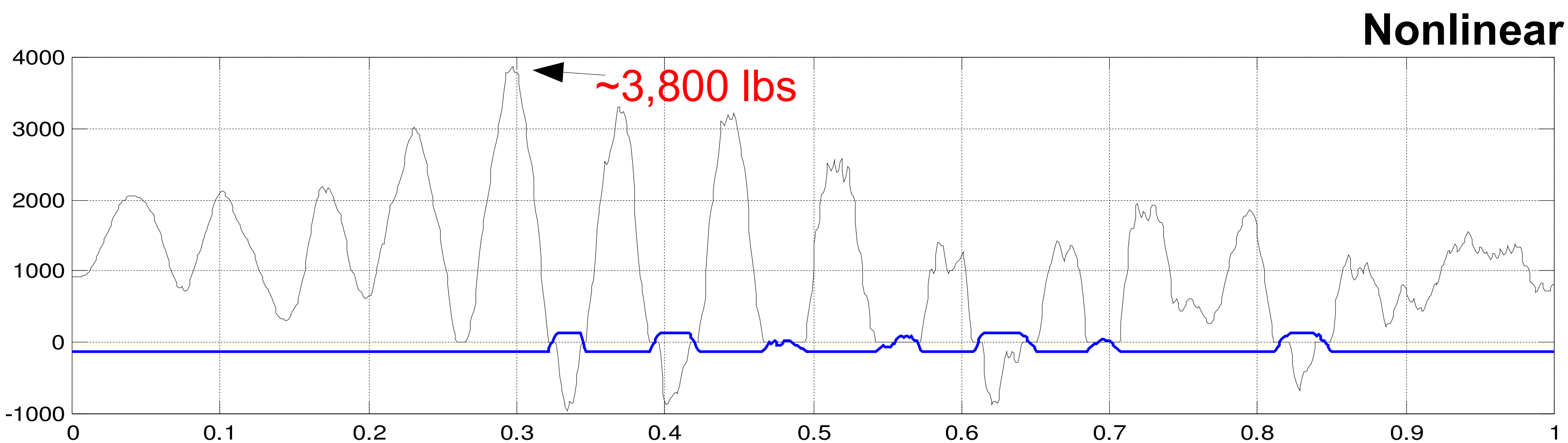
Pump Module Zo Shear Force Landing



PM Zo Shear Not Sensitive



PM: Single Shear Interface Force (Zorb) and Relative Displacement – (Blue Line x 20000)
Forcing Function: LF7101

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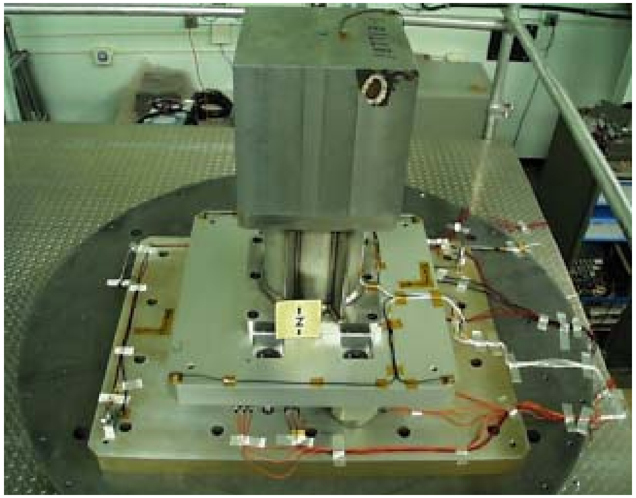
Deadband Dynamic Testing

- NASA conducted dynamic testing to simulate KM deadbands
- Sine-burst input
  - Varying amplitudes
  - Nominal & Increased gap size cases
- Measure interface forces and dummy mass accelerations



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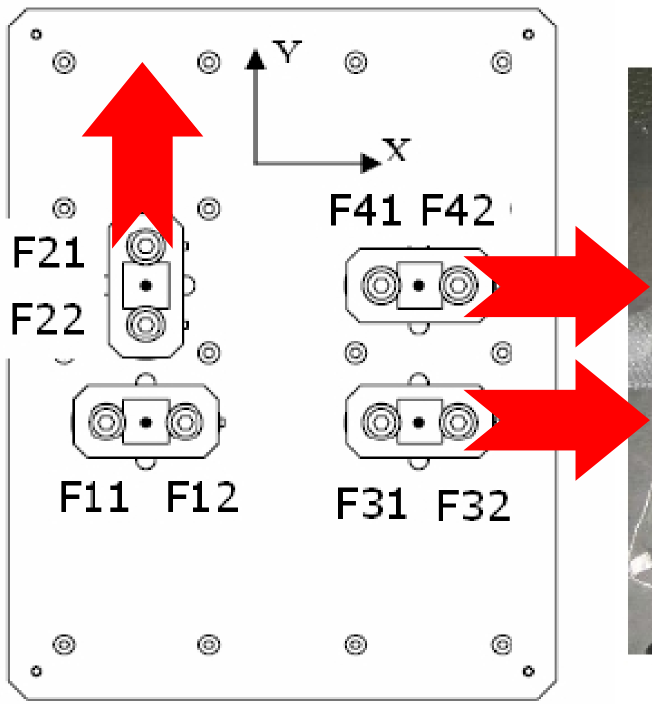
Test Setup

- Test hardware
  - Red arrows depict dedicated shear force reactions
  - All 4 fittings react Z forces



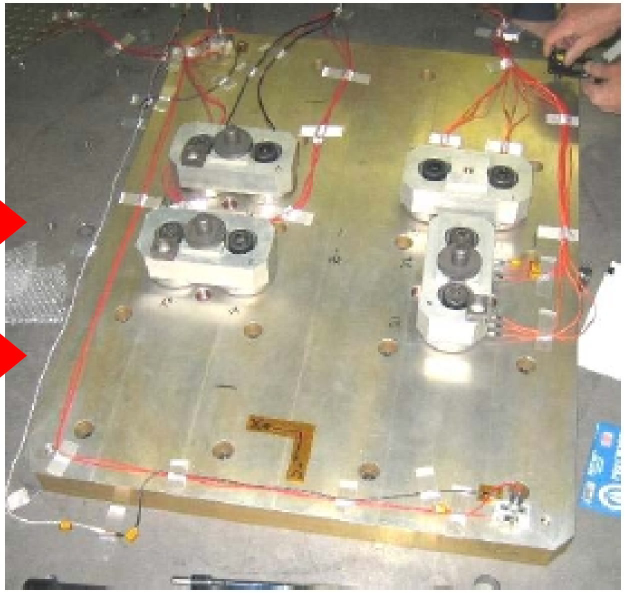


Figure 2-3. Force transducer locations.

Test Results

- Interface force amplifications of up to 2.83 times the linear (shimmed) interface force measured due to the KM deadbands

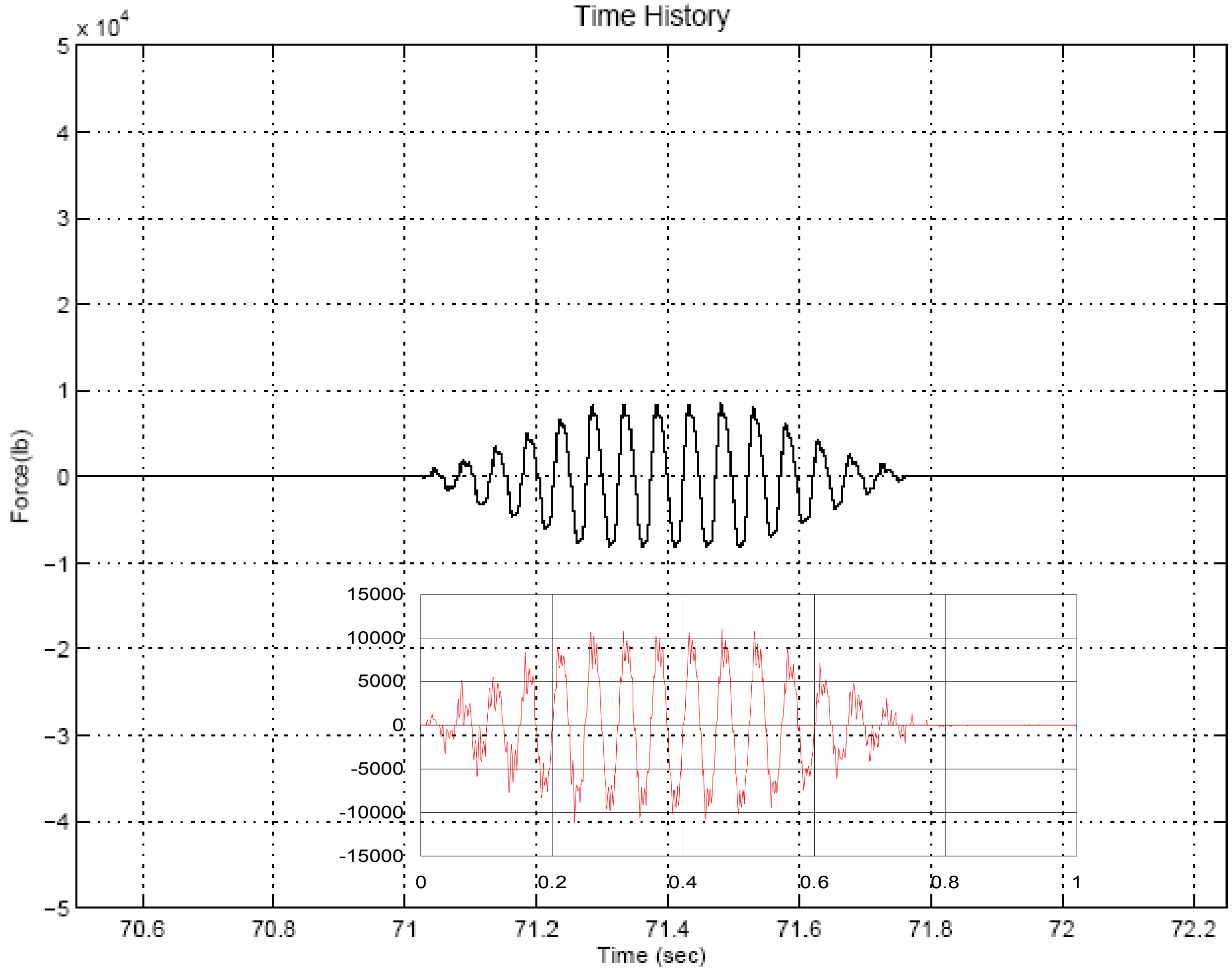
Table 3-1. Z-Axis sine burst data summary.

		Sine Burst Run			
		-12 dB	-6 dB	-3 dB	-0 dB
	Control Max Accel (g)	2.39	4.76	6.72	9.54
	A5 Response Max Accel (g)	4.4	9	10.64	14.43
	Accel Amplification Factor	**1.84**	**1.89**	**1.58**	**1.51**
	Linear Interface Force (lbs)	469	934	1319	1872
Max In-Axis Force (lbs)	F11 & F12	946	1682	1882	2545
	F21 & F22	1093	1925	2116	2583
	F31 & F32	1322	1977	2432	3016
	F41 & F42	1163	2119	2485	3463
Force Amplification Factor	F11 & F12	2.02	1.80	1.43	1.36
	F21 & F22	2.33	2.06	1.60	1.38
	F31 & F32	2.82	2.12	1.84	1.61
	F41 & F42	2.48	2.27	1.88	1.85
	Avg. Force Amp. Factor	**2.41**	**2.06**	**1.69**	**1.55**

Test/Analysis Comparisons

- NASA Ground Rules:
  - Run nonlinear simulation of each test
  - Perform comparisons
  - Do not perform any correlation
    - Supply comparison results “as is”
  - Do not simulate friction
    - Test friction levels small/moderate in X & Z
    - Test friction levels significant in Y ($\mu=0.22$)
      - Faulty surface treatment caused dry lube film to wear off quickly
      - Too far removed from “zero friction” simulation requirement to provide a meaningful comparison

Run-41X: F3 X Force



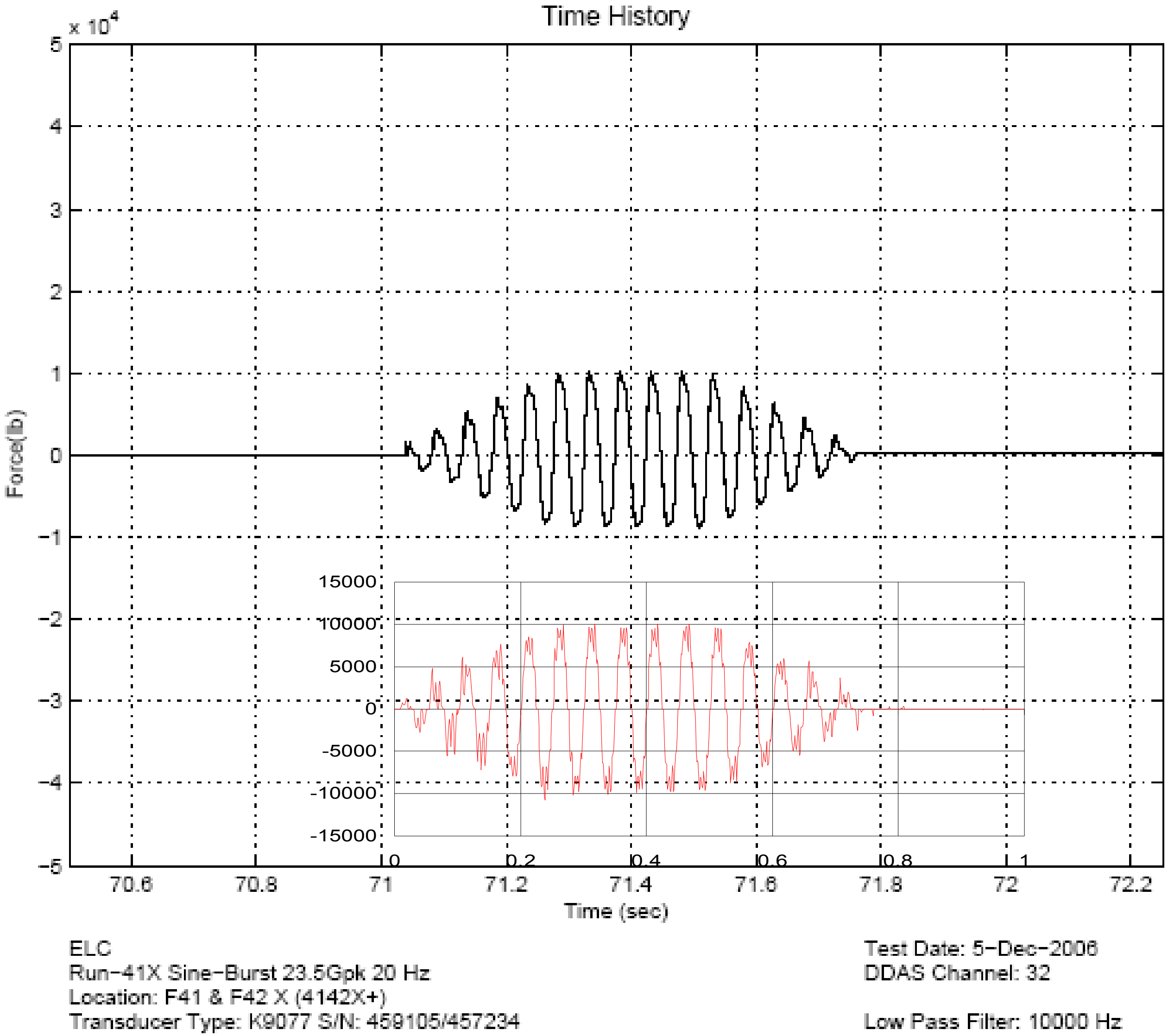
ELC
Run-41X Sine-Burst 23.5Gpk 20 Hz
Location: F31 & F32 X (3132X+)
Transducer Type: K9077 S/N: 636133/636134

Test Date: 5-Dec-2006
DDAS Channel: 29

Low Pass Filter: 10000 Hz

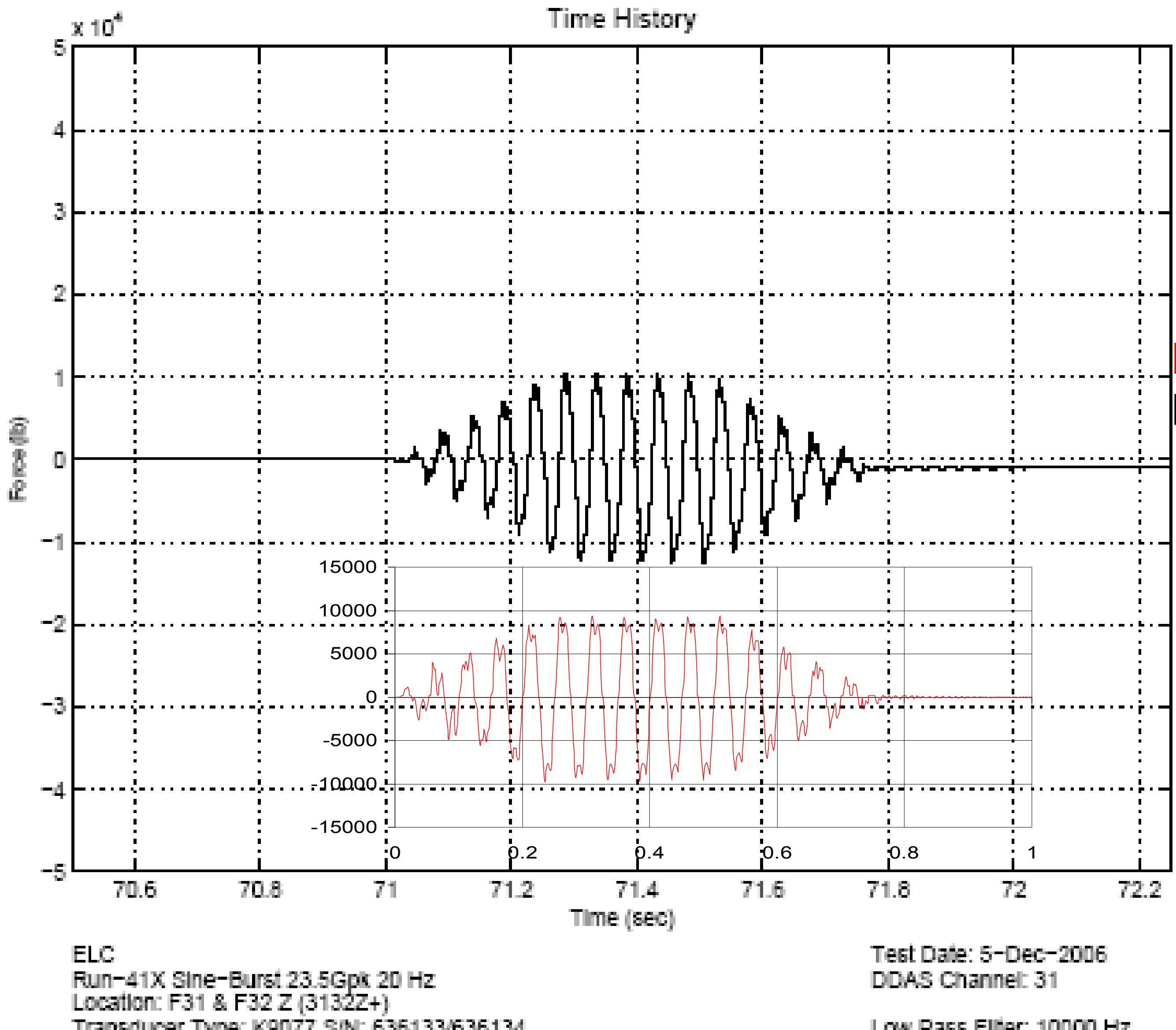
Red: Simulation
Black: Test

Run-41X: F4 X Force



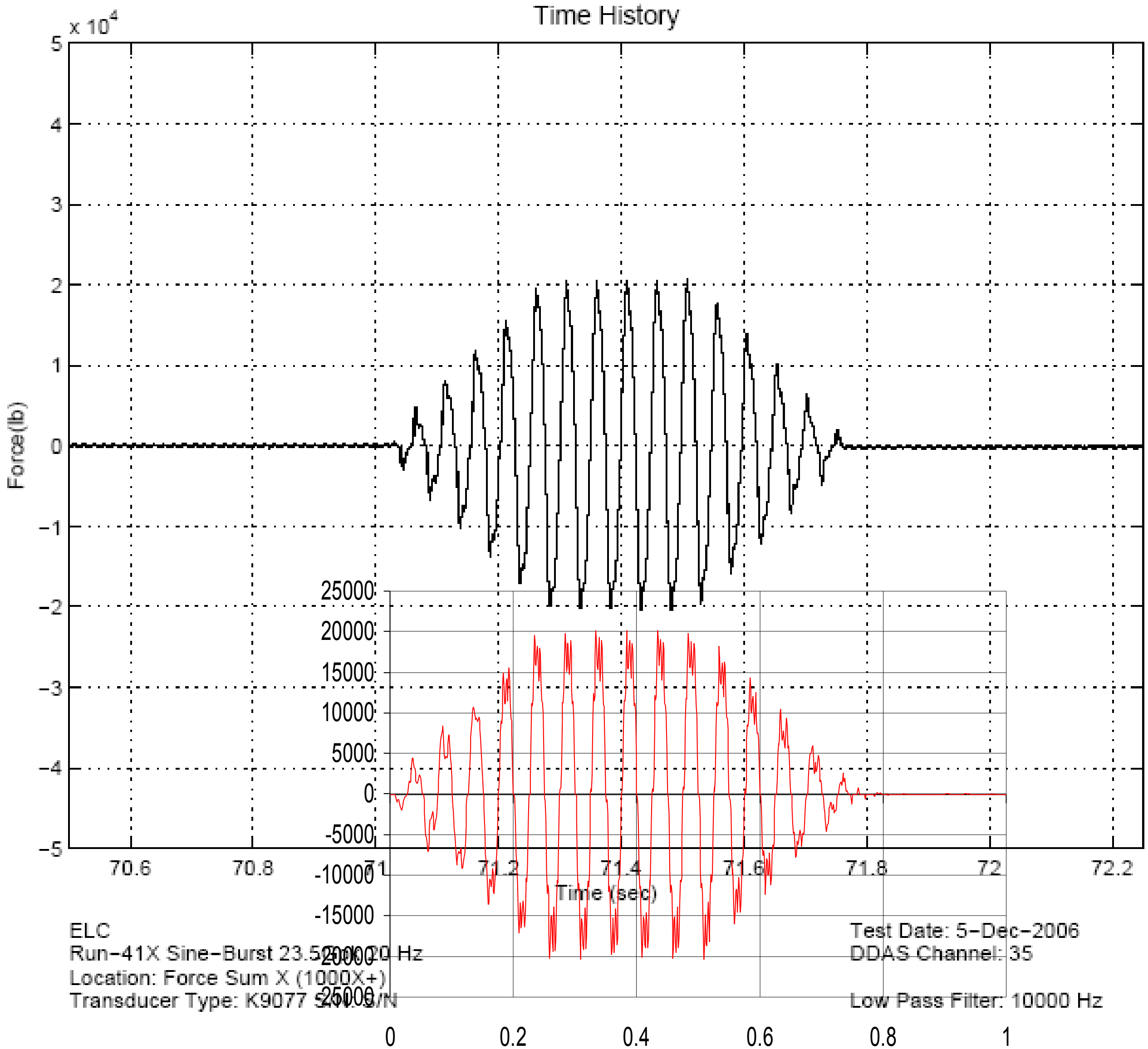
Red: Simulation
Black: Test

Run-41X: F3 Z Force



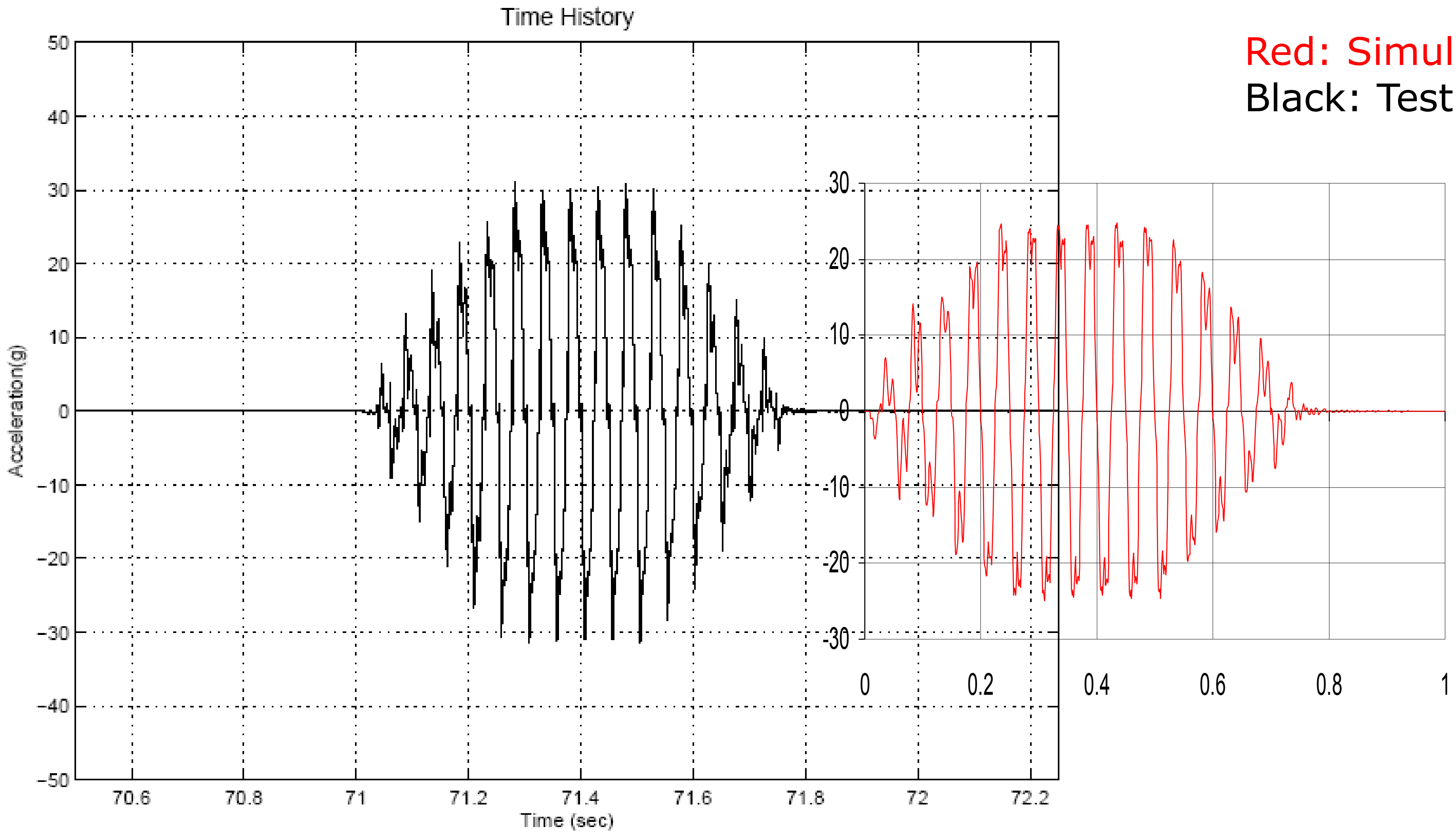
Red: Simulation
Black: Test

Run-41X: X Force Summation



Red: Simulation
Black: Test

Run-41X: Top Mass X Acceleration



Red: Simulation
Black: Test

ELC
Run−41X Sine−Burst 23.5Gpk 20 Hz
Location: Mass Simulator, Top Center (5X−)
Transducer Type: K8791 S/N: 131583X

Test Date: 5−Dec−2006
DDAS Channel: 20

Low Pass Filter: 10000 Hz

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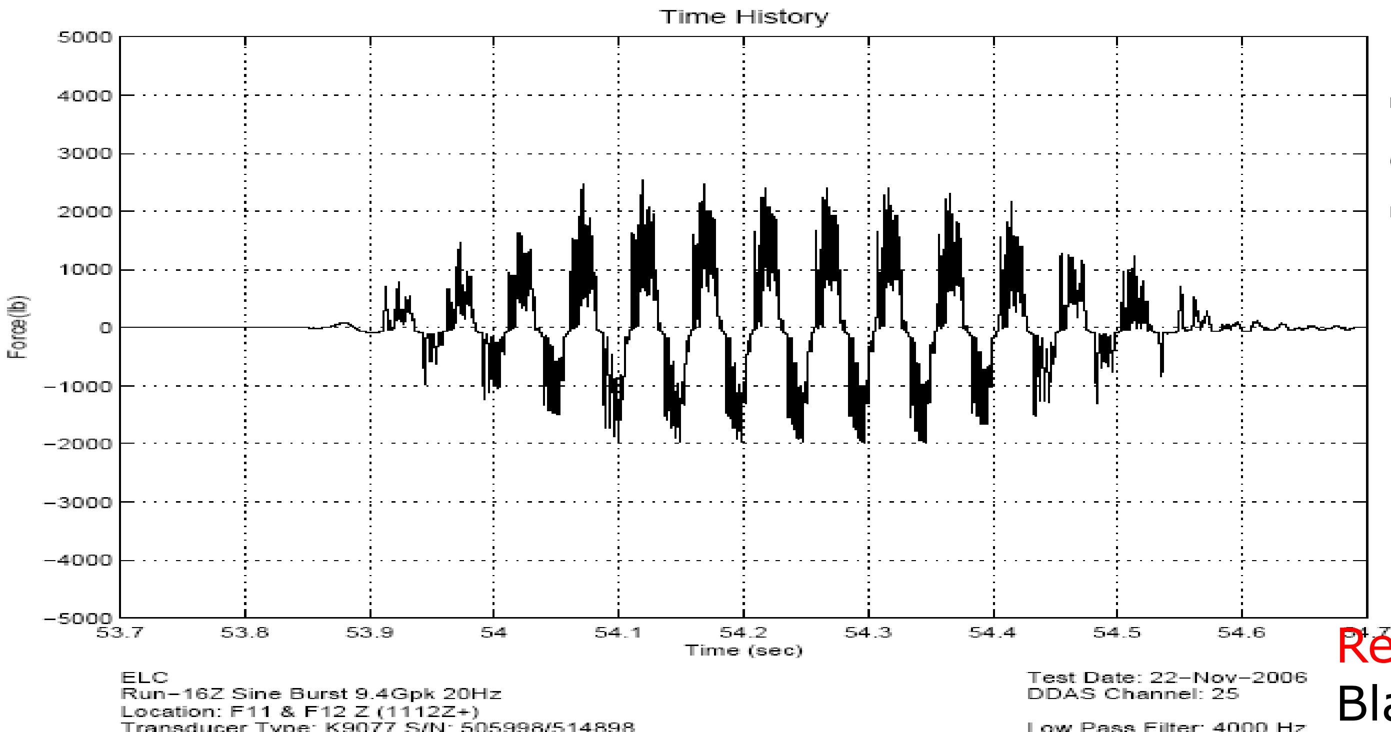
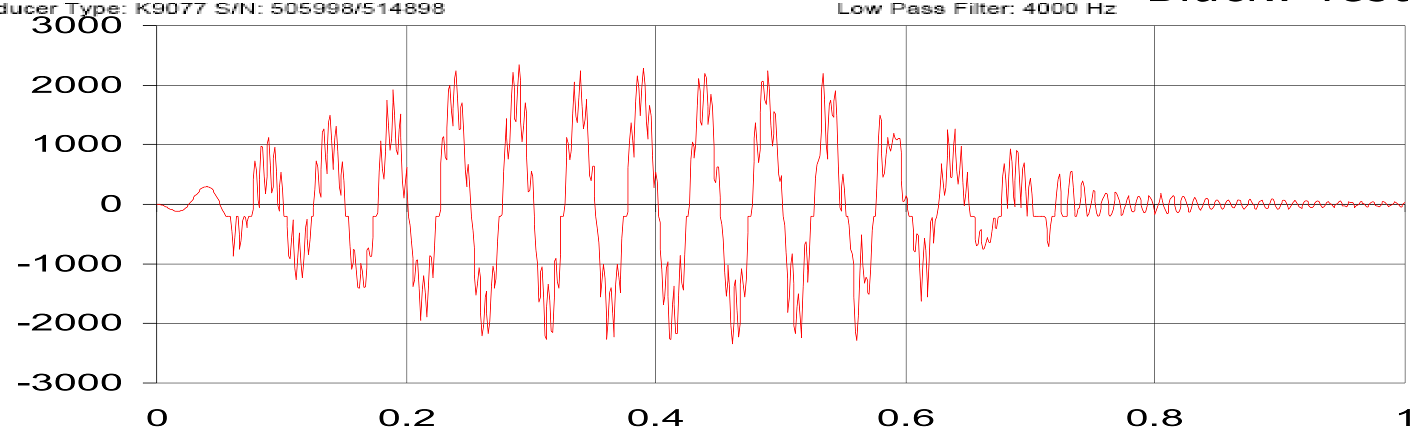
Run-16Z: F1 Z Force

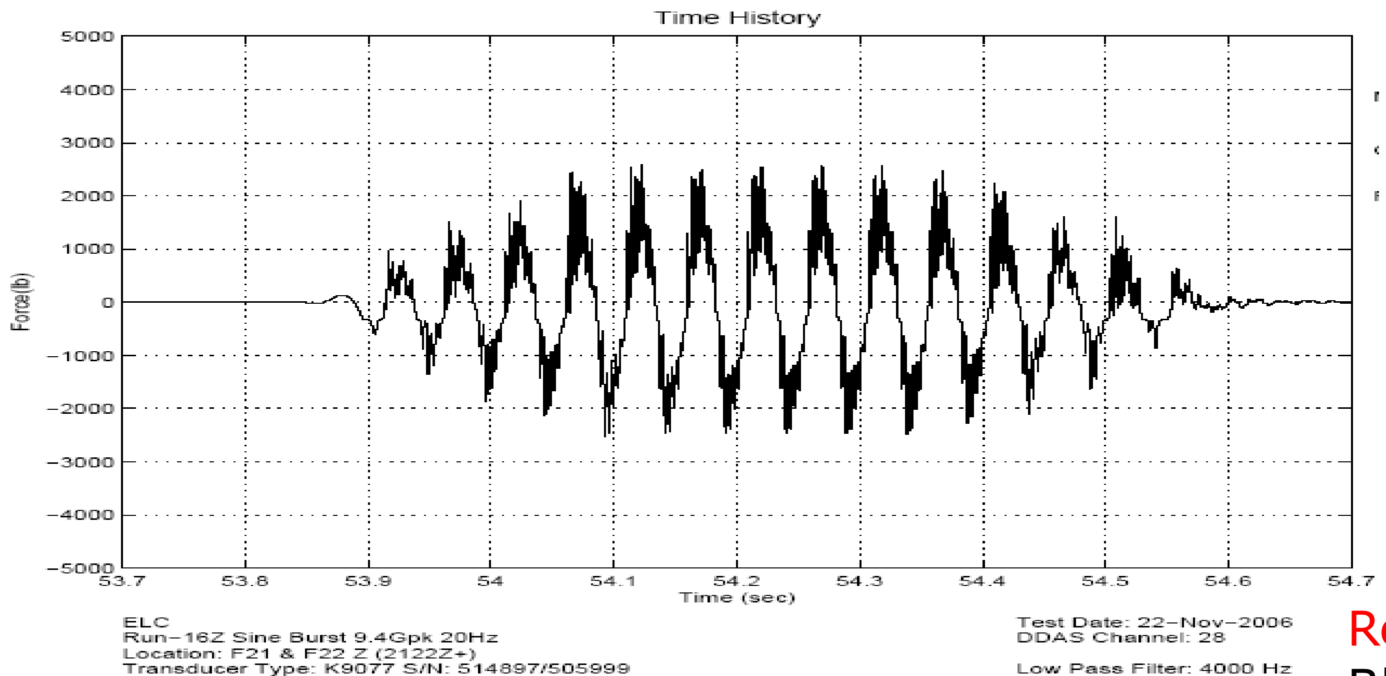




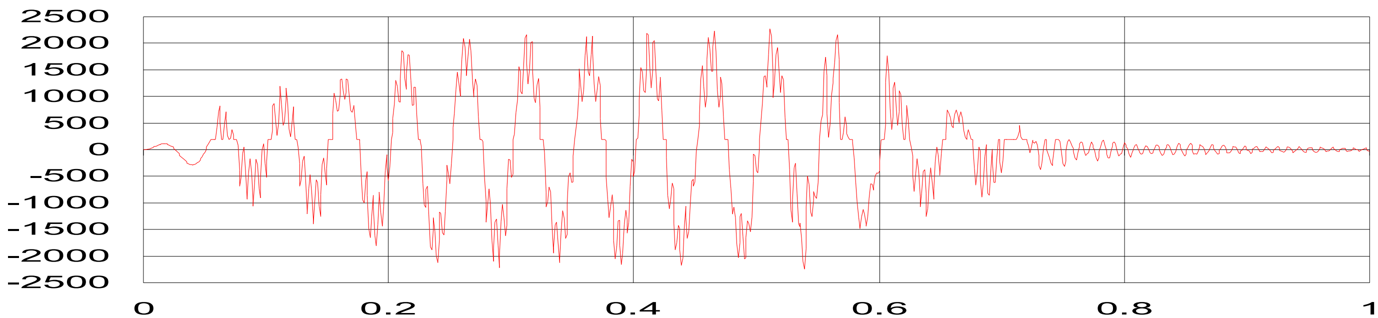
Red:Simulation

Black: Test

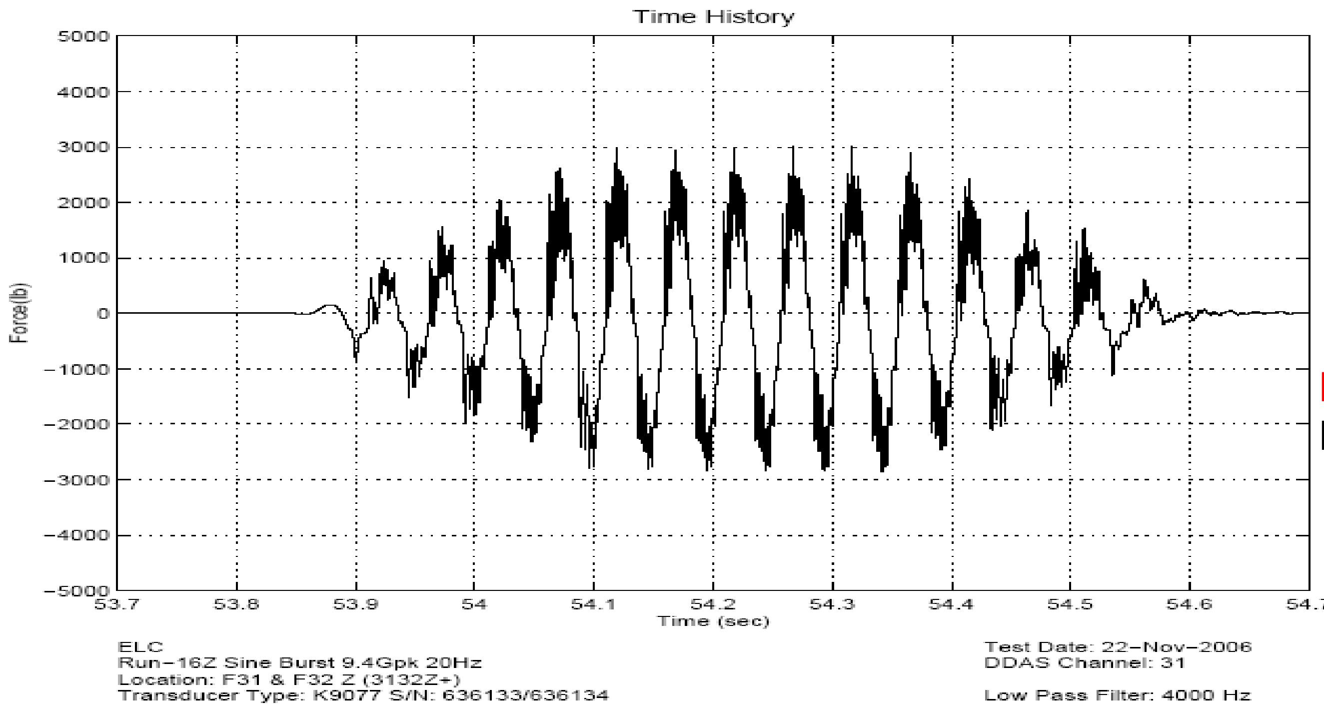
Run-16Z: F2 Z Force



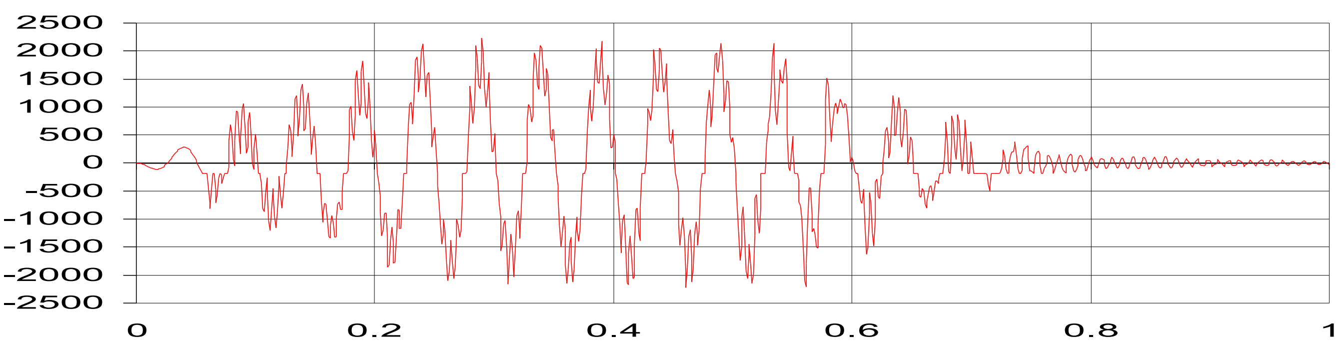
Red: Simulation
Black: Test



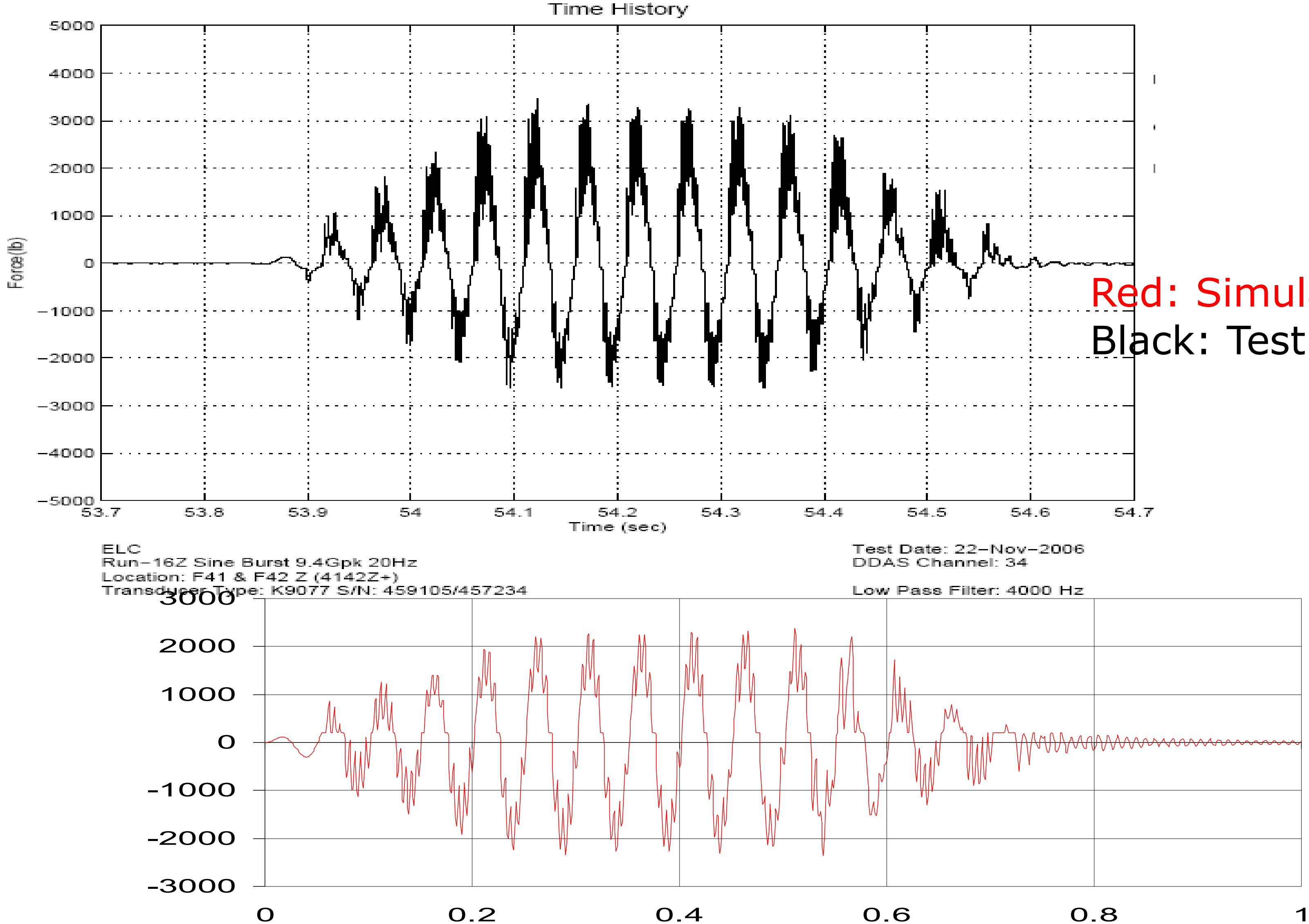
Run-16Z: F3 Z Force



Red: Simulation
Black: Test

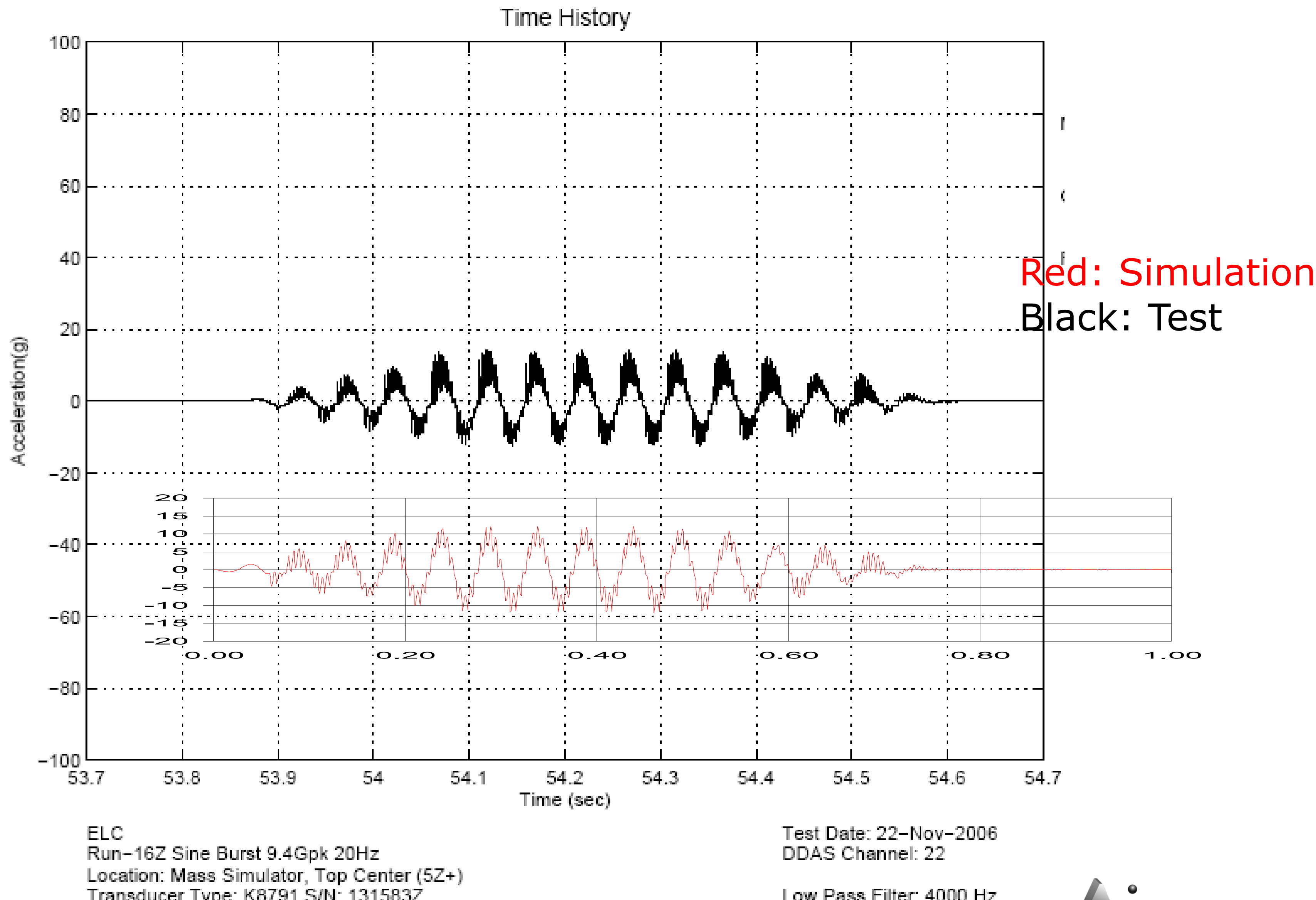


Run-16Z: F4 Z Force



Red: Simulation
Black: Test

Run-16Z: Top Mass Z Acceleration



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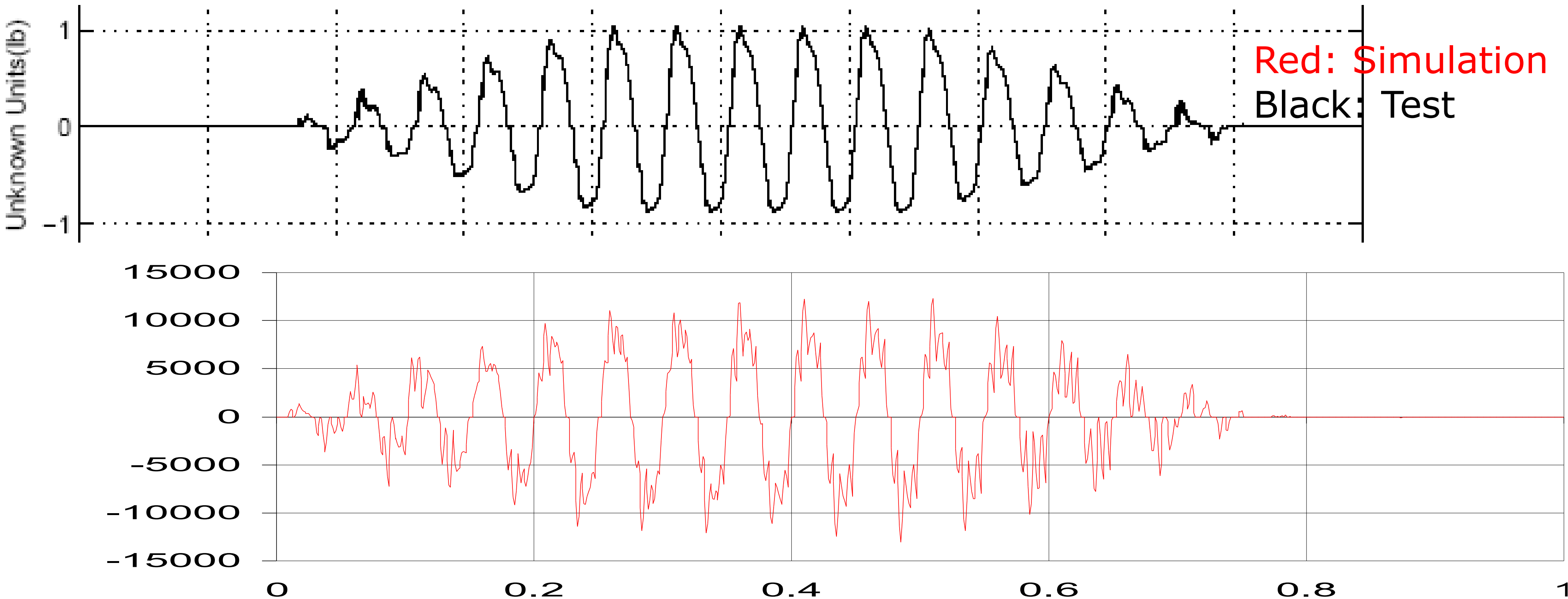
Run-51X: F4 X Force

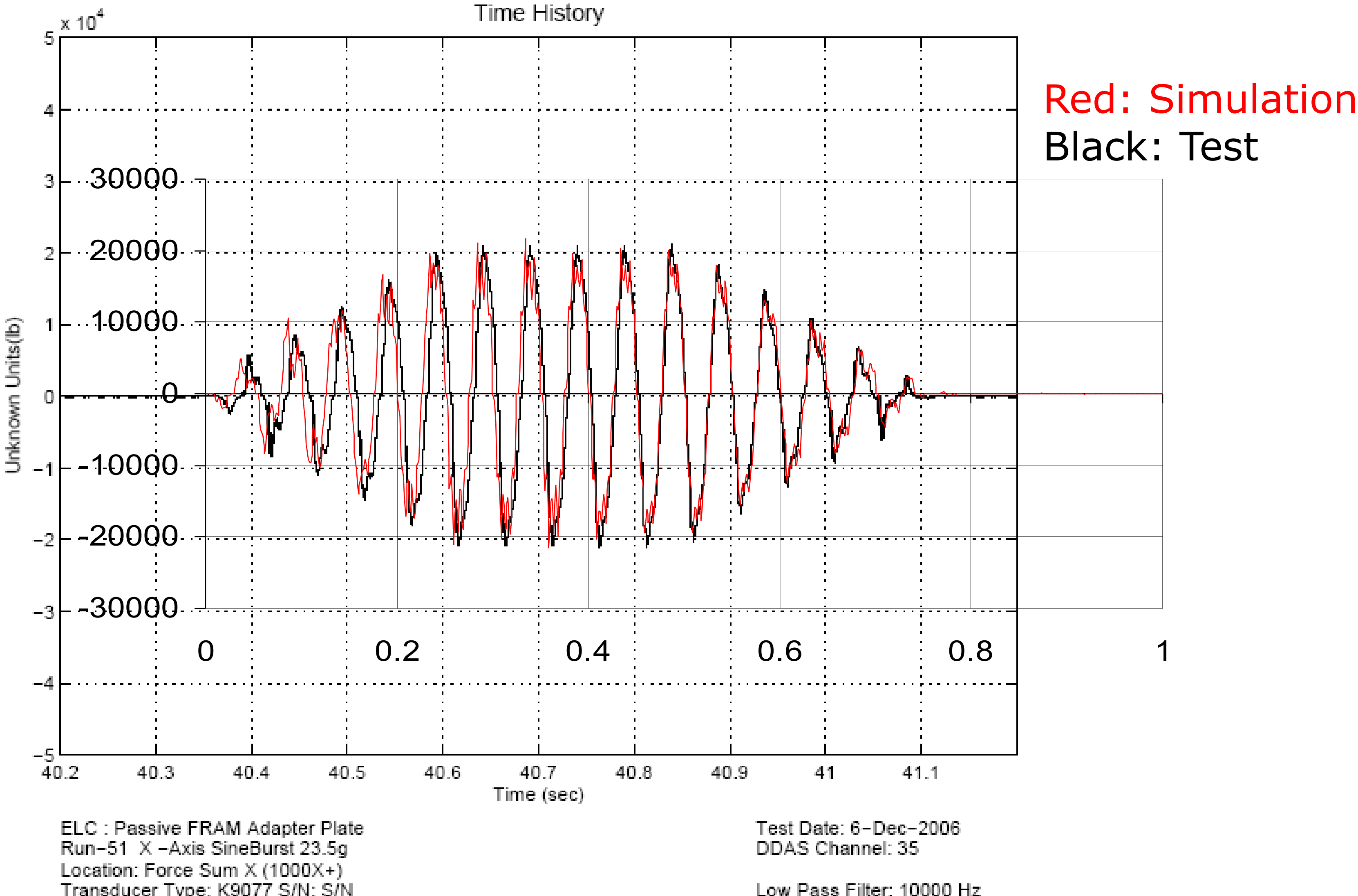


ELC : Passive FRAM Adapter Plate
Run−51 X −Axis SineBurst 23.5g
Location: F41 & F42 X (4142X+)
Transducer Type: K9077 S/N: 459105/457234

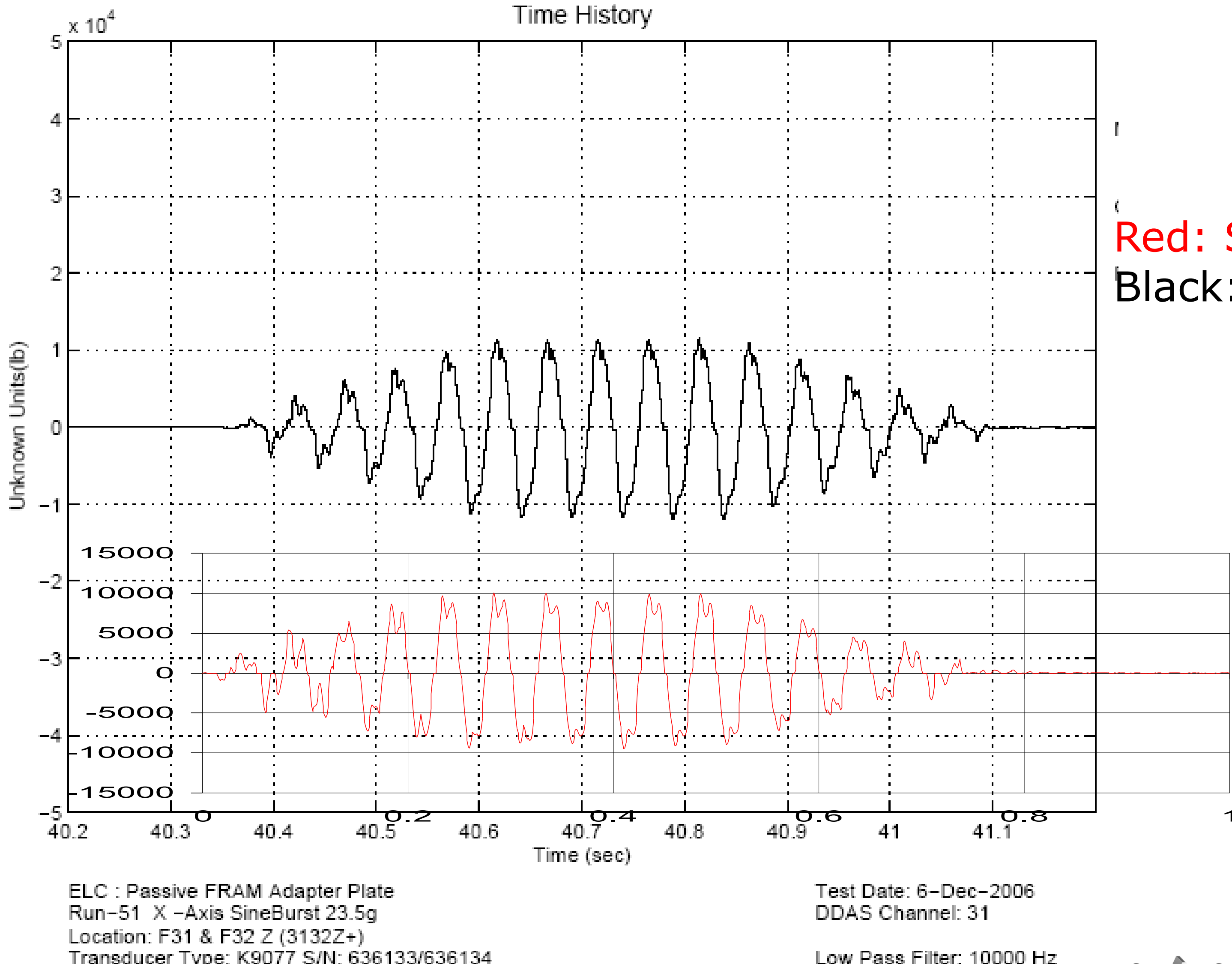
Test Date: 6−Dec−2006
DDAS Channel: 32

Low Pass Filter: 10000 Hz

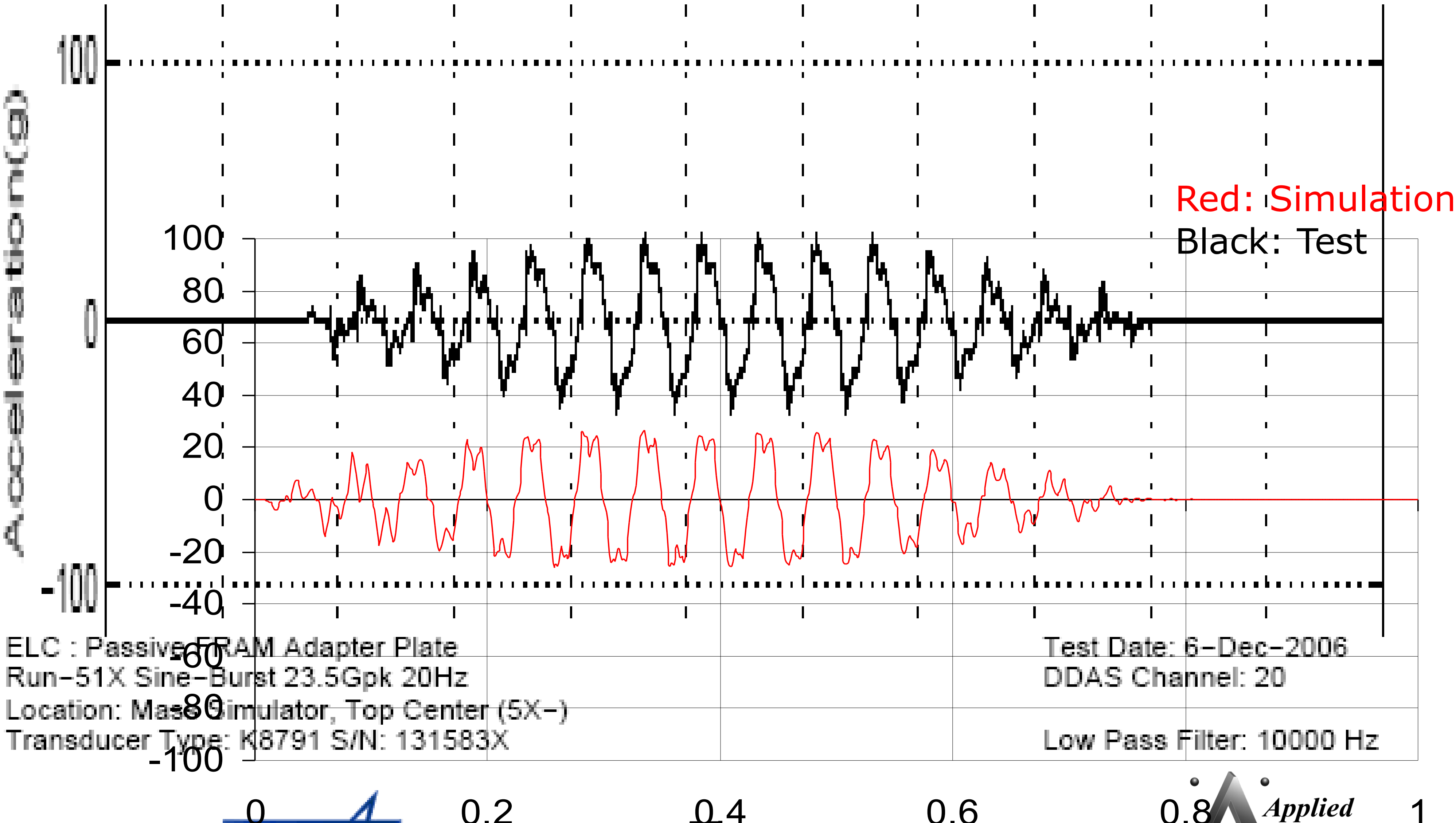
Run-51X: X Force Summation



Run-51X: F3 Z Force



Run-51X: Top Mass X Acceleration

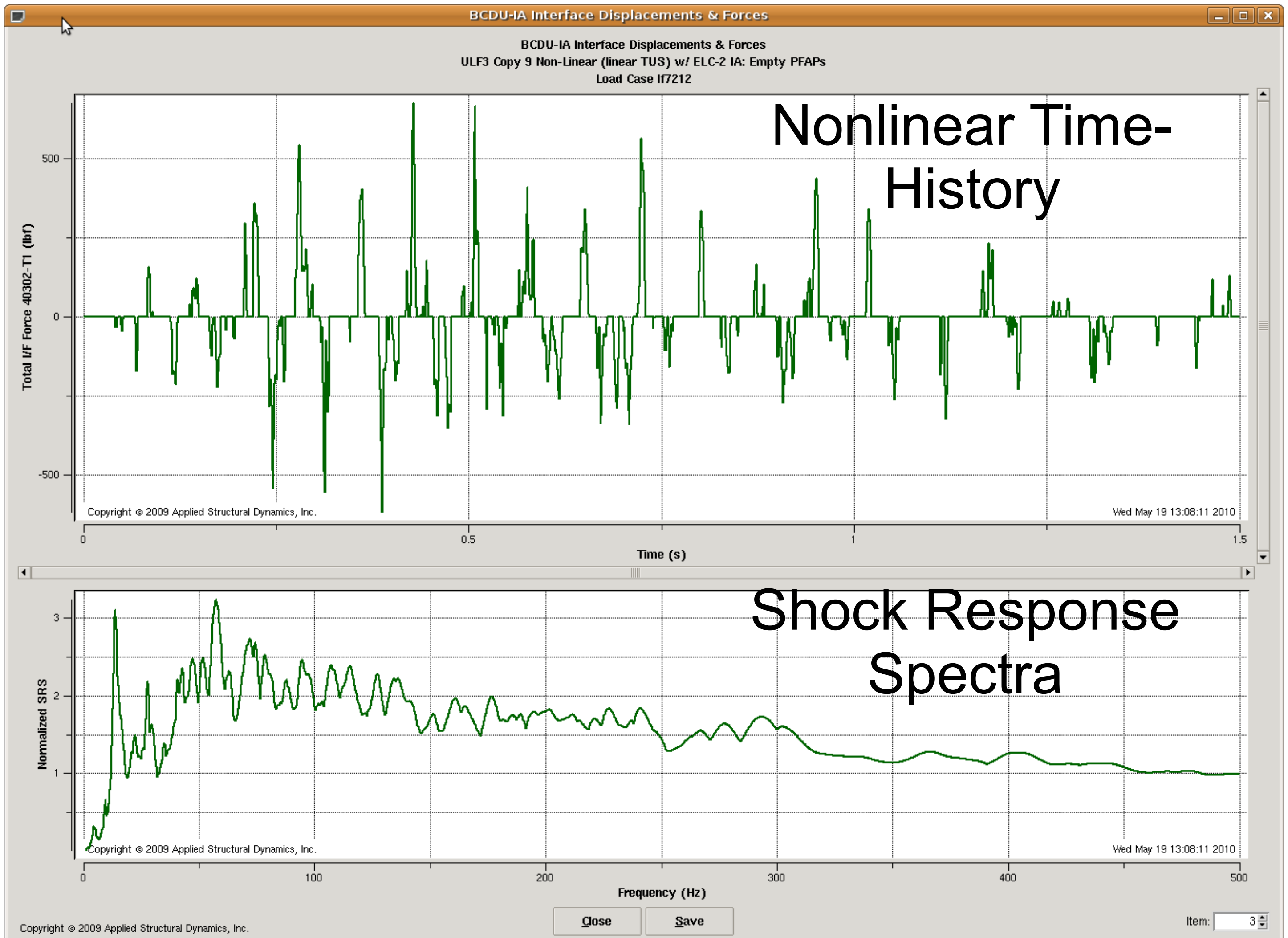


Space Shuttle Mission ULF-3

- A “massive” nonlinear CLA conducted by Lockheed Martin
  - 40 components with nonlinear interfaces
    - Components with deadbands on both sides of the interface
  - 453 deadbands
  - Included TUSRA with deadbands at <u>four</u> separate interfaces
- Solved with a 0.001 second time-step with ASD/CLAS software
  - Zero numerical noise/chatter in any component recoveries

Component Interface Force

40 Nonlinear Components/453 Deadbands



Screenshot from ASD/CLAS Software

Shuttle Mission ULF3 CLA: Landing

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Summary

- In 2005, NASA Space Shuttle Program (SSP) initiated an investigation to assess the impact of the component interface deadbands on transient environments
- Nonlinear CLAs with heritage tools resulted in “unrealistic” time-histories
- In 2006, NASA and Lockheed Martin investigated, verified, and selected ASD's nonlinear CLA capability
  - Later, anchored to test

Summary – Cont'd

- Since 2006, 21 Space Shuttle/payloads nonlinear transient CLAs have been conducted for the NASA to design and certify payloads
  - First 4 by ASD
  - Next 17 by Lockheed Martin utilizing the ASD/CLAS software
  - Nonlinear CLAs in the SSP are continuing to this day

Concluding Remarks

- Impact of small deadbands on component transient environments can be significant
- Accuracy of the nonlinear CLA solution is paramount!
  - The analytical problem is extremely complex
  - Filtering unrealistic nonlinear solutions for a better answer is highly discouraged
- Future launch services (COTS, …) to utilize the same flight hardware for cargo deliveries to the ISS