ASD/CLAS Nonlinear Coupled Loads Analysis Capability

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Nonlinear Springs

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Background

- 2005: NASA Mission Critical Risk Mitigation Initiative
  - Shuttle/payloads nonlinear transient coupled loads analyses (CLA) initiated
  - Simulate/investigate the impact of complex component interfaces involving deadbands
- 2005-2006: Initial Nonlinear CLAs
  - Executed with commercially available heritage tools
  - Resulted in unrealistic response time-histories
  - Dominated what can be best described as “numerical noise/chatter”
- 2006: ASD's Nonlinear CLA Capability was Investigated
  - Rigorous verification process performed
    - Resulting nonlinear time-histories were shown to be physically realizable and free of any numerical noise/chatter
    - Solution conformed to the physical parameters and constraints defined in the analysis

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Background – Cont'd

- 2006: ASD's Nonlinear Solution Selected for Mission Specific Critical Risk Mitigation Analyses
  - 2006-2008: ASD performs all Orbiter/payloads nonlinear CLAs
    - STS-118, 122, 127
- 2009: ASD's Nonlinear CLA Capability Commercially Available
  - ASD/CLAS linear capability extended to include nonlinear capability
  - STS-129: Lockheed-Martin (Houston) completes the most complex Space Shuttle/payloads nonlinear CLA ever conducted for NASA
    - See ASD/CLAS Customer Success Story: Lockheed-Martin

ASD's nonlinear solver, selected by NASA and NASA's prime cargo integration contractor, is commercially available in ASD/CLAS.

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Executive Summary

This briefing presents a summary of the capability within ASD's Coupled Loads Analysis System (ASD/CLAS) to simulate piece-wise linear springs.

The ASD/CLAS capability of executing nonlinear deadband interfaces between components has enabled analysts community to simulate/investigate complex interfaces between components, the most obvious being interfaces with deadbands and/or snubber type interfaces (one direction open ended deadbands).

This same validated capability may be utilized to simulate piece-wise linear interface springs. This briefing illustrates that capability and should be of interest to transient analyses of the AMS payload to be delivered to the ISS.

Nonlinear Spring Capability

- With ASD/CLAS's nonlinear component interface capability, simulations involving nonlinear springs are easily accomplished
  - Some nonlinear spring examples
    - Bi-linear springs
    - Tri-linear springs
    - Stiffening springs
    - Softening springs
    - Tension only springs (straps)
    - Compression only springs (snubbers, bumpers)
    - Combinations of the above

- Graphical depiction of a tri-linear strap (tension-only) is given in the backup slides

Three Example Problems

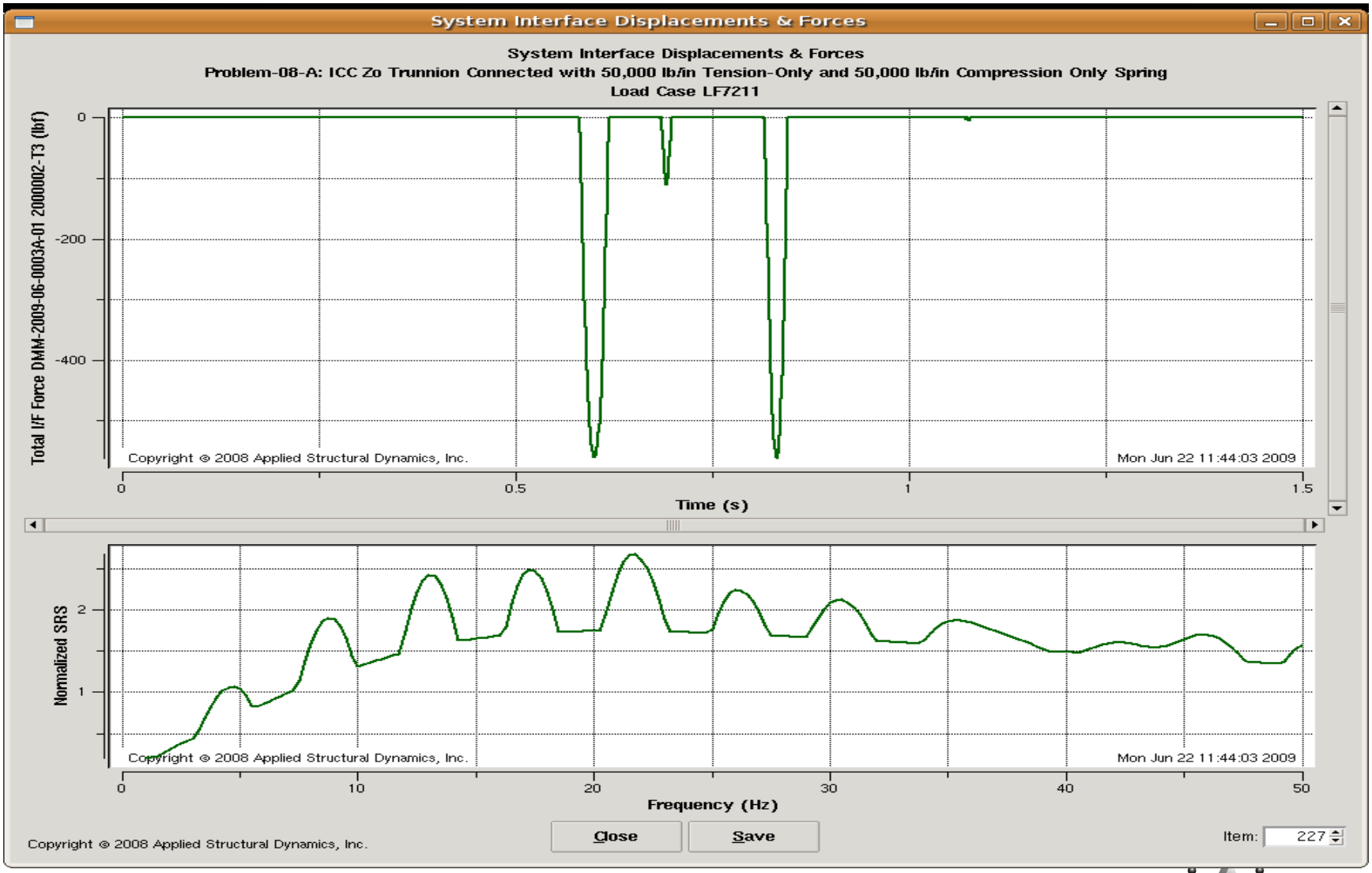
- The following Shuttle/payloads coupled loads analysis (CLA) involving nonlinear springs is presented:
  1) Equal stiffness tension/compression spring
     - Validated with linear a CLA
  2) Compression-only spring (snubber)
  3) Tri-linear stiffening compression-only spring (tri-linear snubber)

1) Equal Tension/Compression Springs

- Problem: Execute a Space Shuttle/payload CLA with one nonlinear spring interface
  - Couple one of the Space Shuttle/payload interfaces with a 50,000 lb/in “tension-only” spring and a 50,000 lb/in “compression-only” spring
  - Provide payload side interface force time-histories for each spring
  - Provide Space Shuttle side interface force time-history which should be the negative sum of the two springs forces

- Validation: Execute linear CLA with the same interface coupled with a 50,000 lb/in tension/compression spring
  - Provide Space Shuttle side interface force time-history and compare to above nonlinear solution

Nonlinear CLA: "Tension-Only" Interface Spring Force – Payload Side



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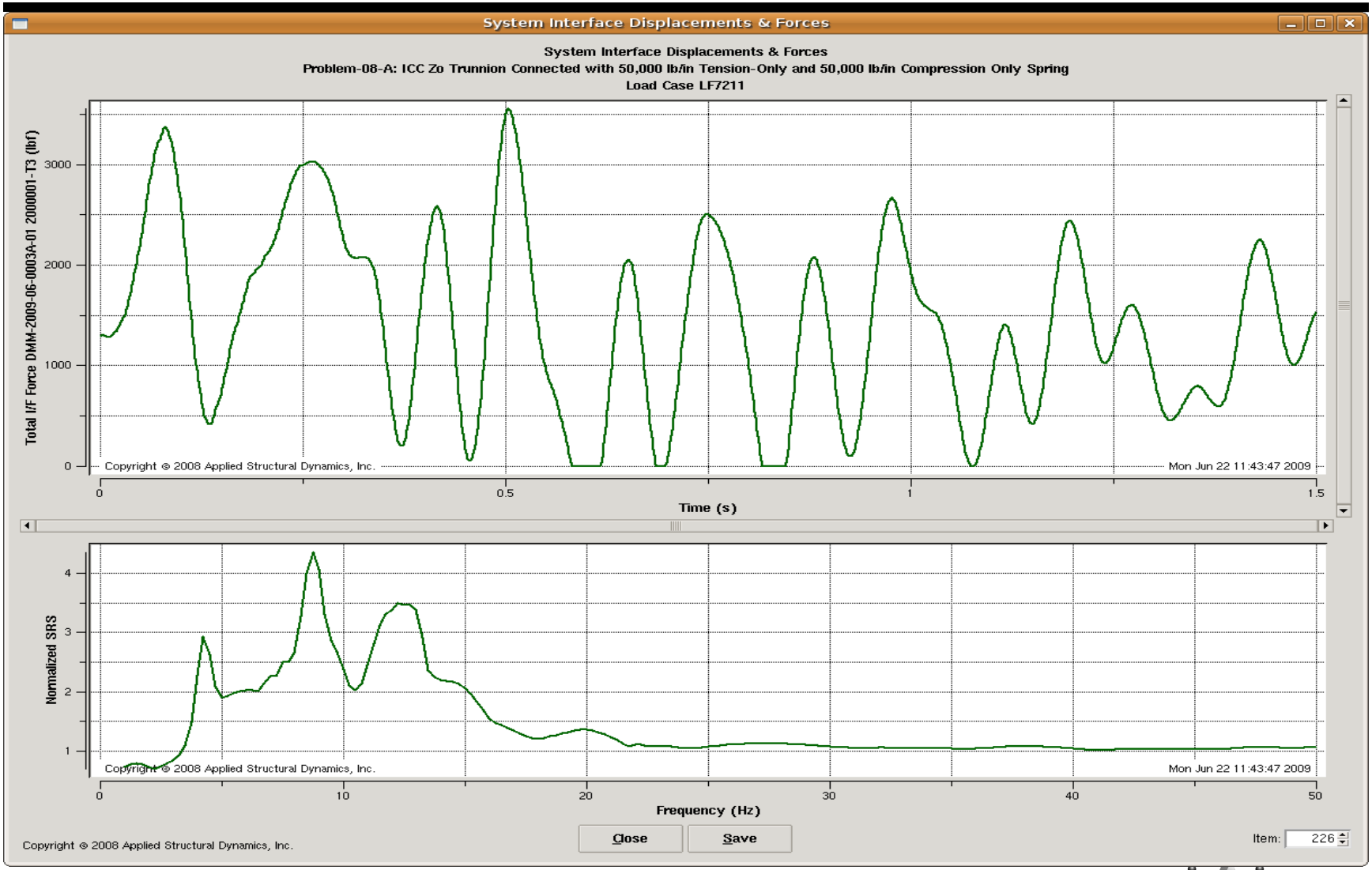
Nonlinear CLA: "Compression-Only" Interface Spring Force – Payload Side



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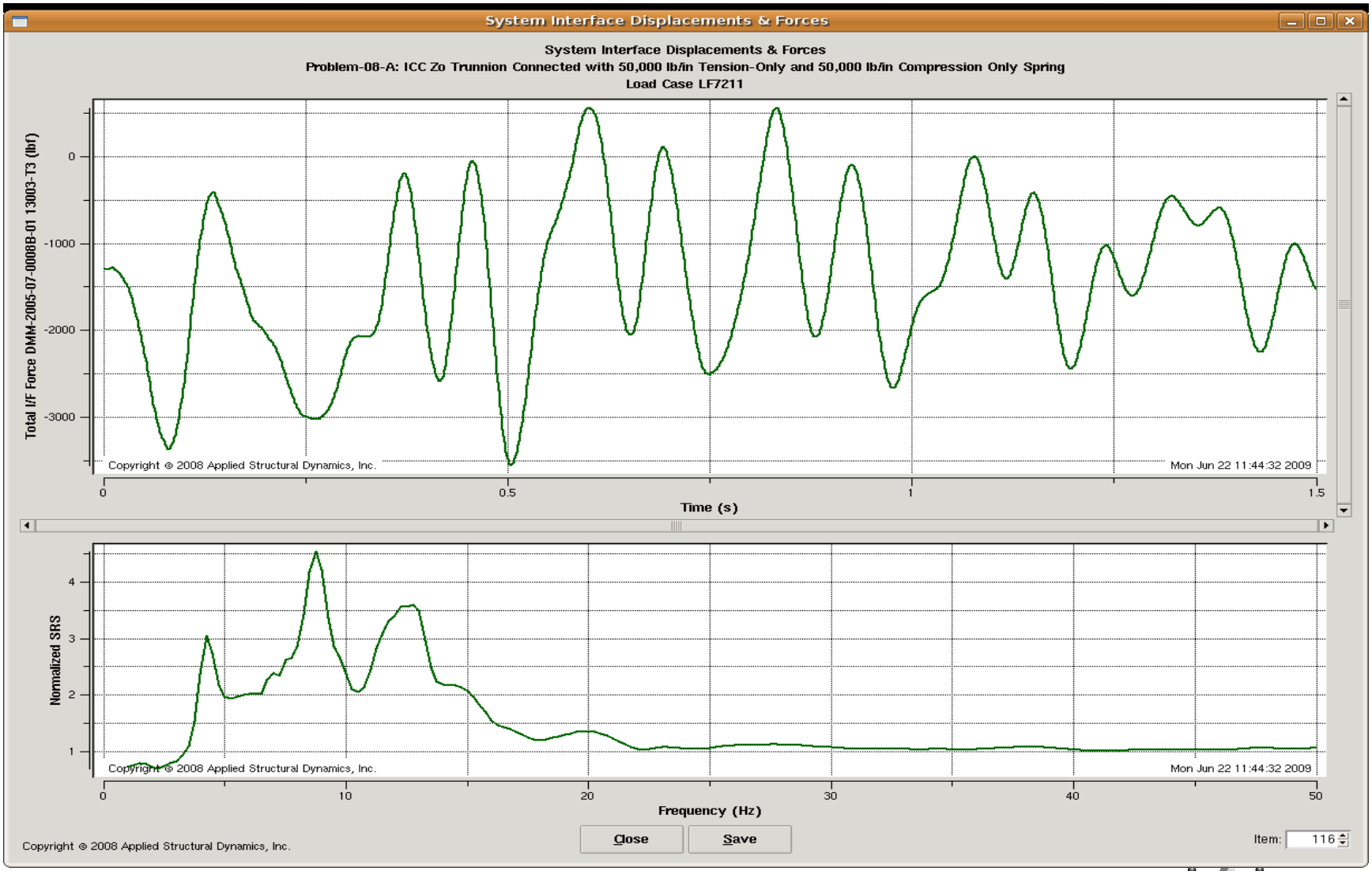
Nonlinear CLA: Total Interface Spring Force - Space Shuttle Side



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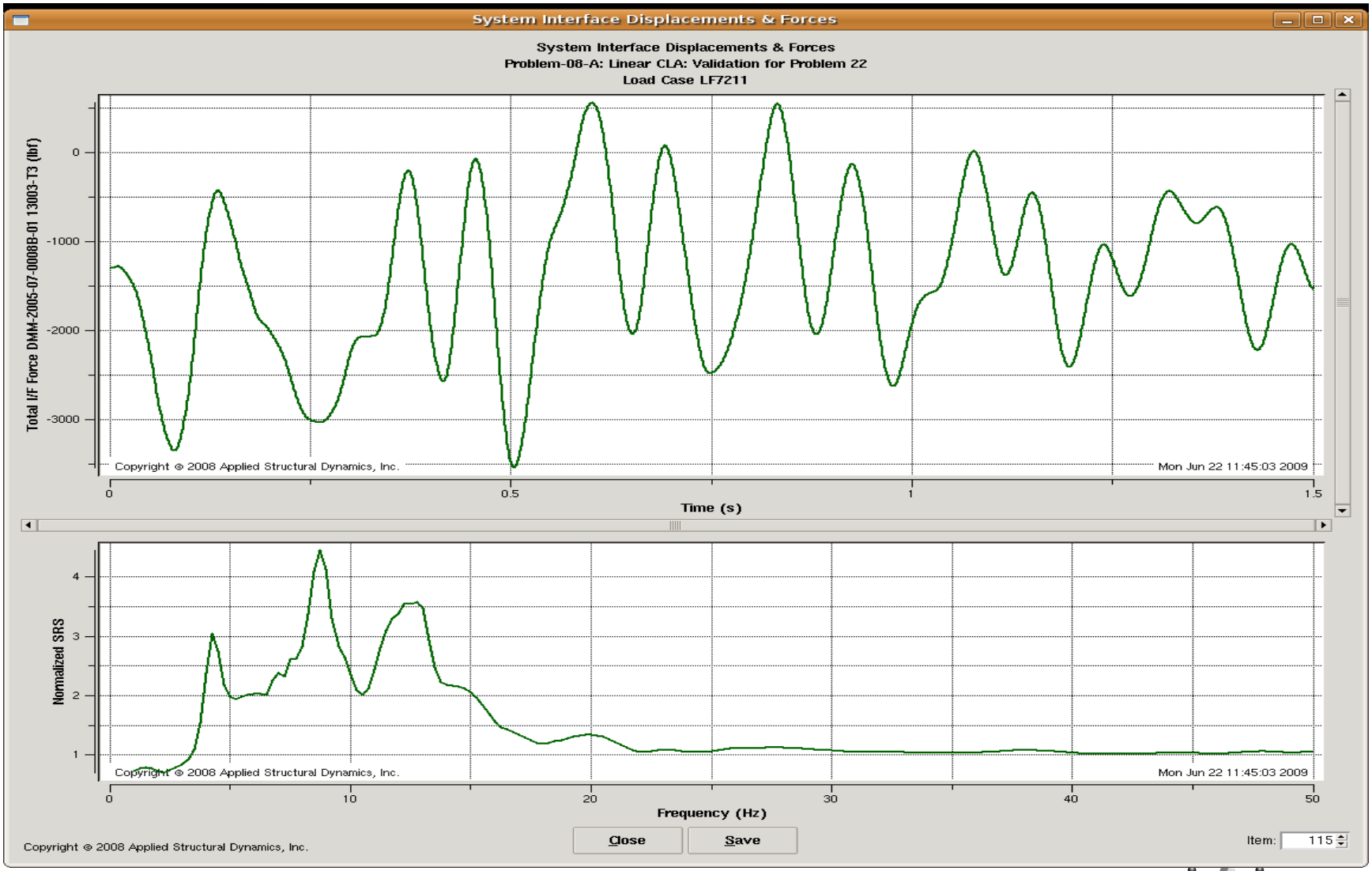
Linear CLA: Interface Spring Force - Space Shuttle Side



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1) Equal Tension/Compression Springs Validation

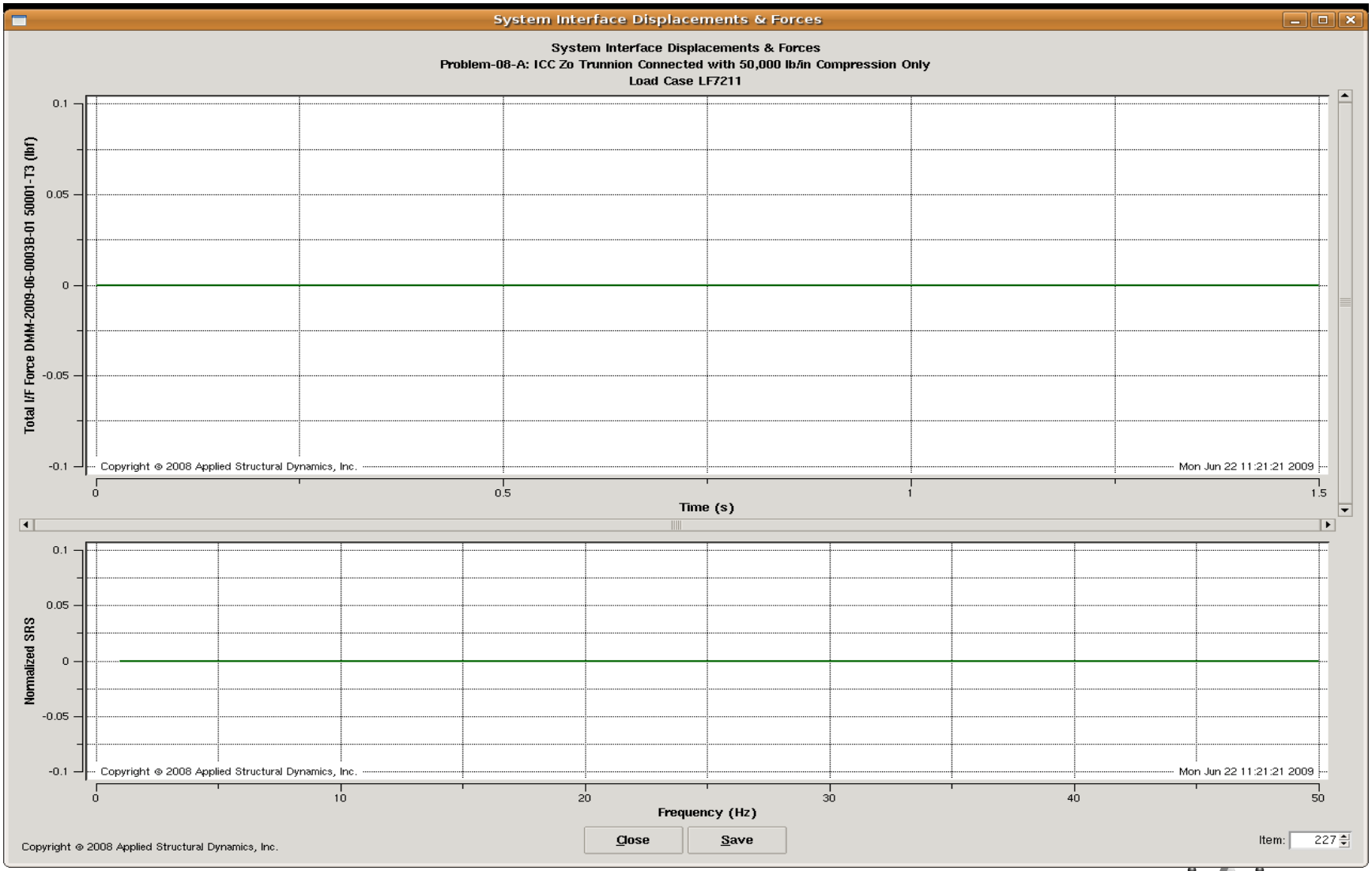
- Comparison of linear and nonlinear CLA Space Shuttle side interface force time-histories is in exact agreement
  - The Shuttle side interface force is exactly equal to the negative summation of the “tension-only” and “compression-only” payload side interface forces
  - The results verify that the nonlinear CLA accurately transitions between the compression and tension spring

2) Compression-Only Spring

- Problem: Execute a Space Shuttle/payload CLA with nonlinear spring interface
  - Couple one of the Space Shuttle/payload interfaces with a 50,000 lb/in “compression-only” spring
  - Provide payload side interface force time-histories for each spring
  - Provide Shuttle side interface force time-history which should be the negative sum of the two springs forces

- Note: Since the spring is now “compression-only”, loss of contact is a possibility

Nonlinear CLA: "Tension-Only Spring" Interface Spring Force – Payload Side



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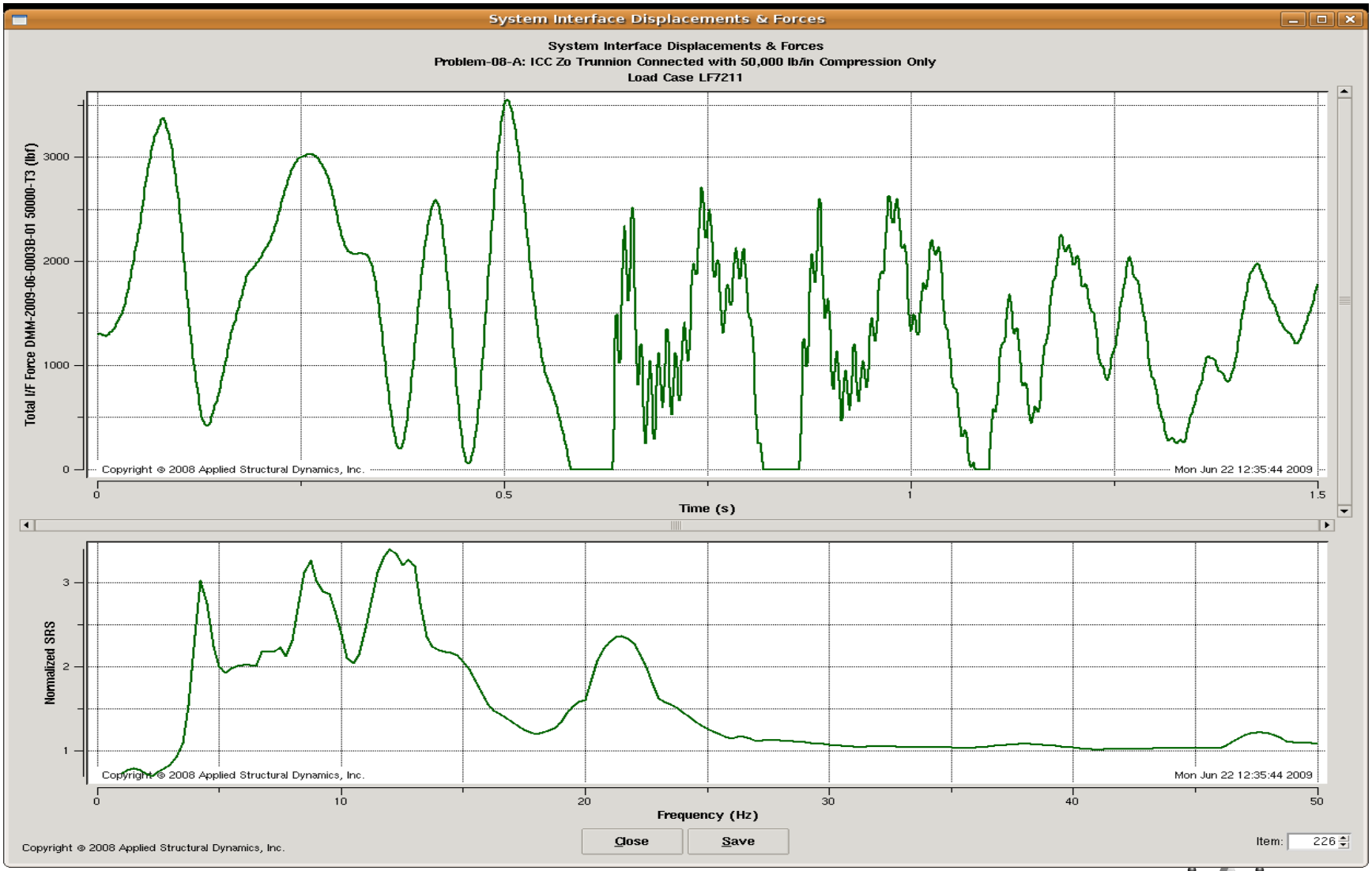
Nonlinear CLA: “Compression-Only Spring” Interface Spring Force – Payload Side



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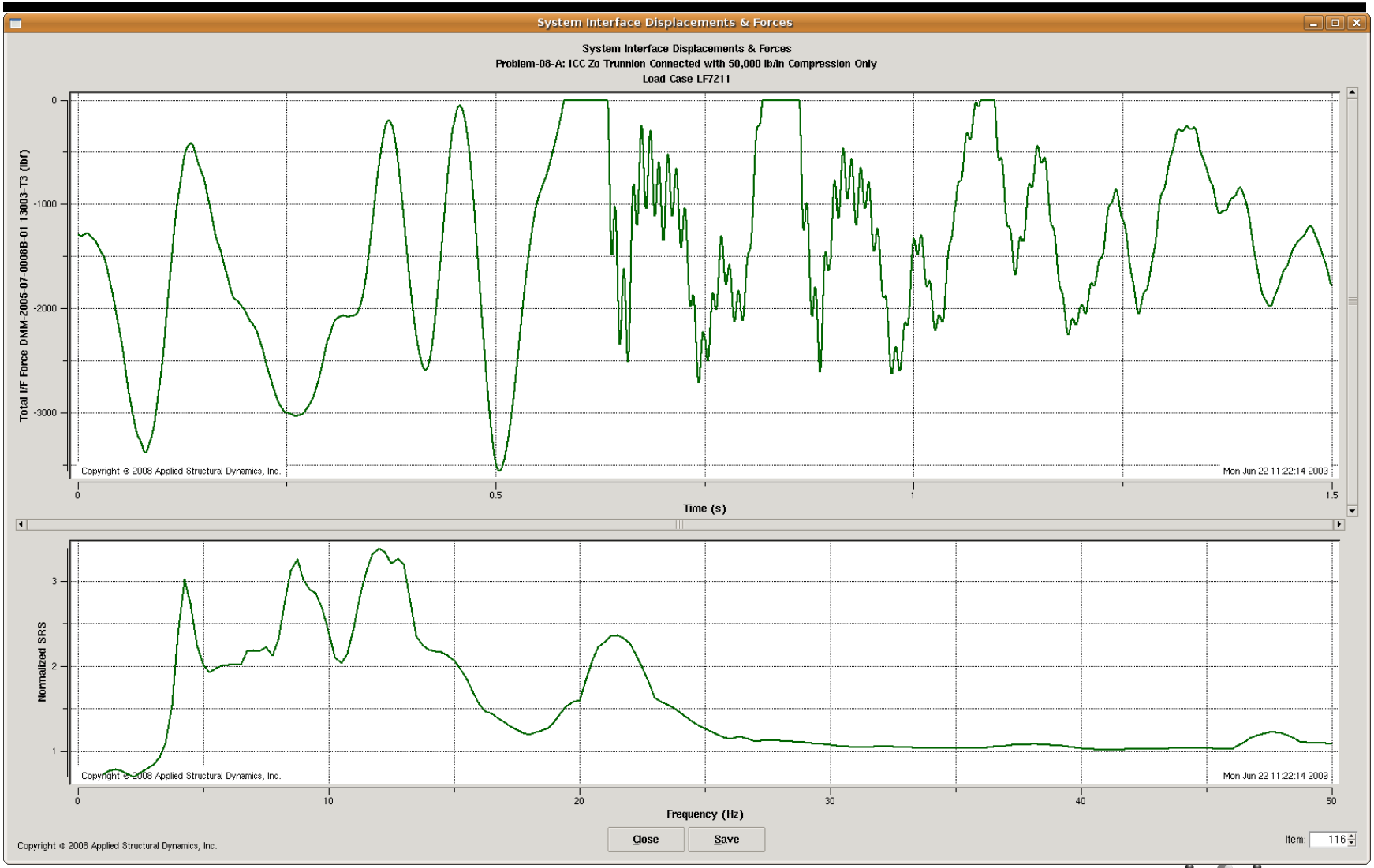
Nonlinear CLA: Total Interface Spring Force - Space Shuttle Side



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2) Compression-Only Spring Discussion

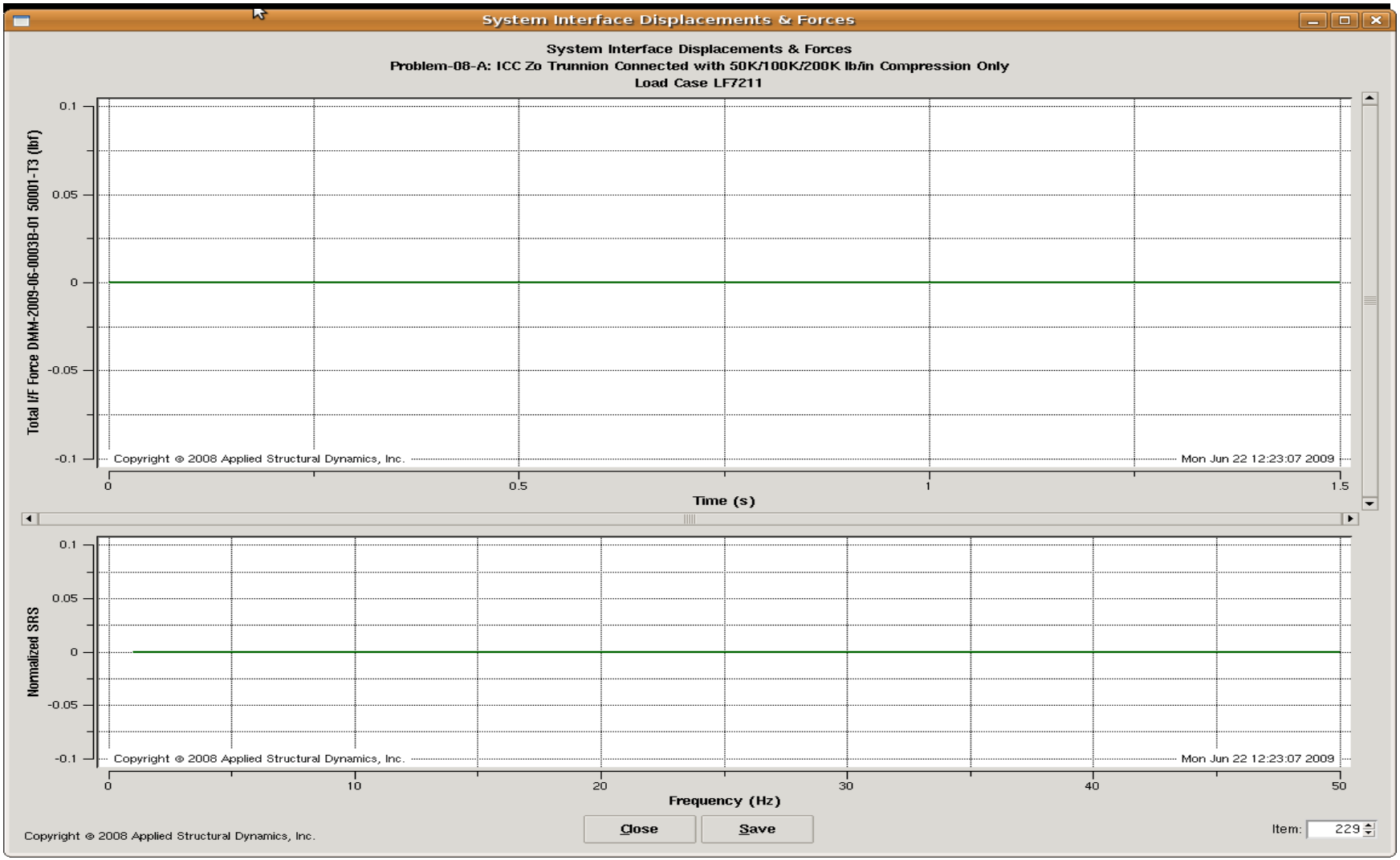
- The results illustrate the loss of contact and re-contact that is afforded by the ASD/CLAS capabilities
  - Note: Re-contact after loss of contact excites higher frequency responses
    - Zero force segments in the Space Shuttle time histories define the loss of contact

3) Tri-Linear Compression-Only Spring

- Problem: Execute a Space Shuttle/payload CLA with nonlinear spring interface
  - Couple one of the Space Shuttle/payload interfaces with the following characteristics:
    - K = 0 for delta <= 0”
    - K_1 = 50,000 lb/in for 0”<delta<=0.05”
    - K_2 = 150,000 lb/in for 0.05”<delta<=0.075”
    - K_3 = 350,000 lb/in for delta >0.075”
  - Provide payload side interface force time-histories for each spring
  - Provide Space Shuttle side interface force time-history which should be the negative sum of the three springs forces

- Note: Since the spring is now “compression-only”, loss of contact is a possibility

Nonlinear CLA: “Tension-Only Spring” Interface Spring Force – Payload Side



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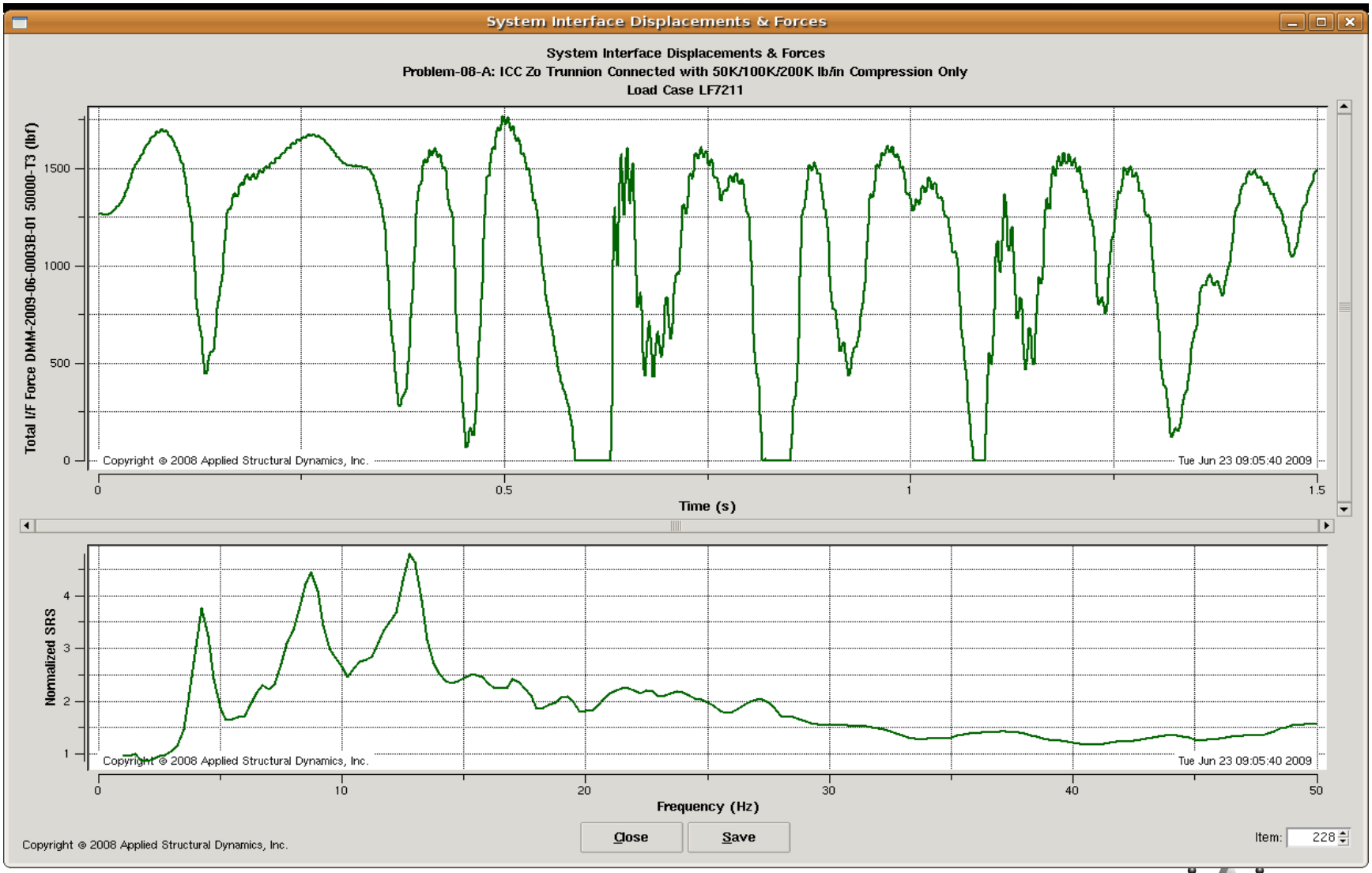
Nonlinear CLA: “Compression-Only Spring 1” Interface Spring Force – Payload Side



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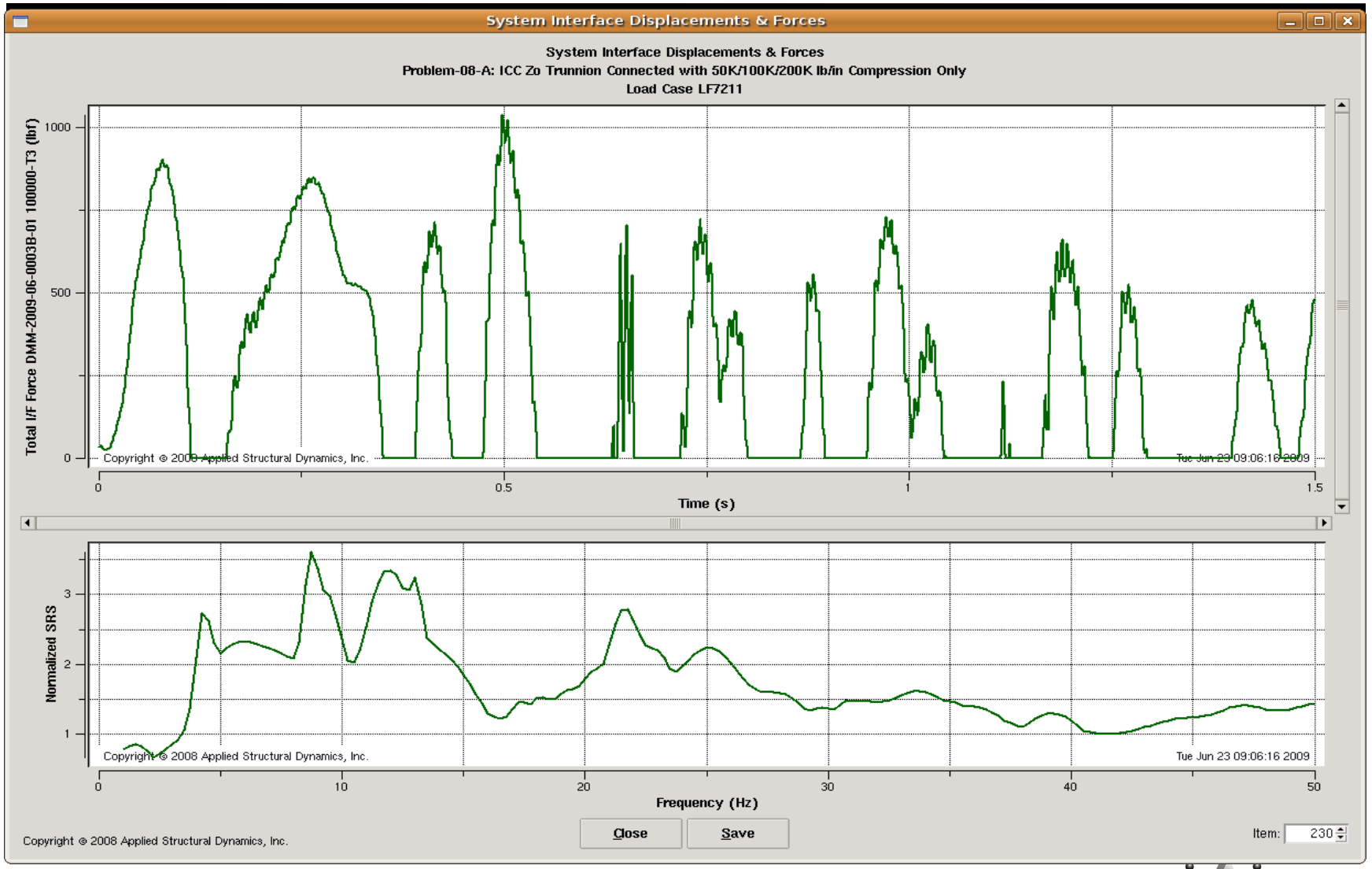
Nonlinear CLA: “Compression-Only Spring 2” Interface Spring Force – Payload Side



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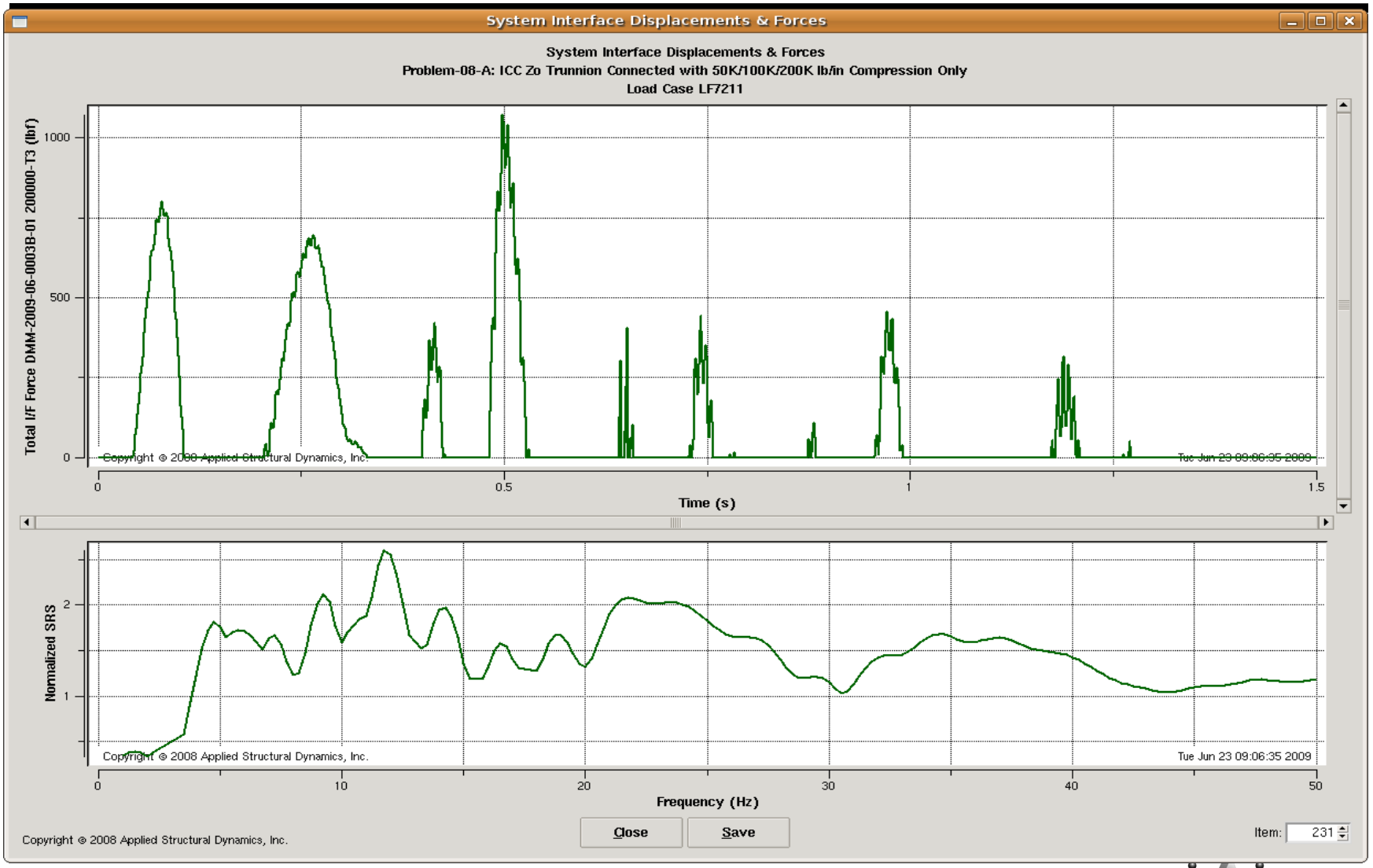
Nonlinear CLA: “Compression-Only Spring 3” Interface Spring Force – Payload Side



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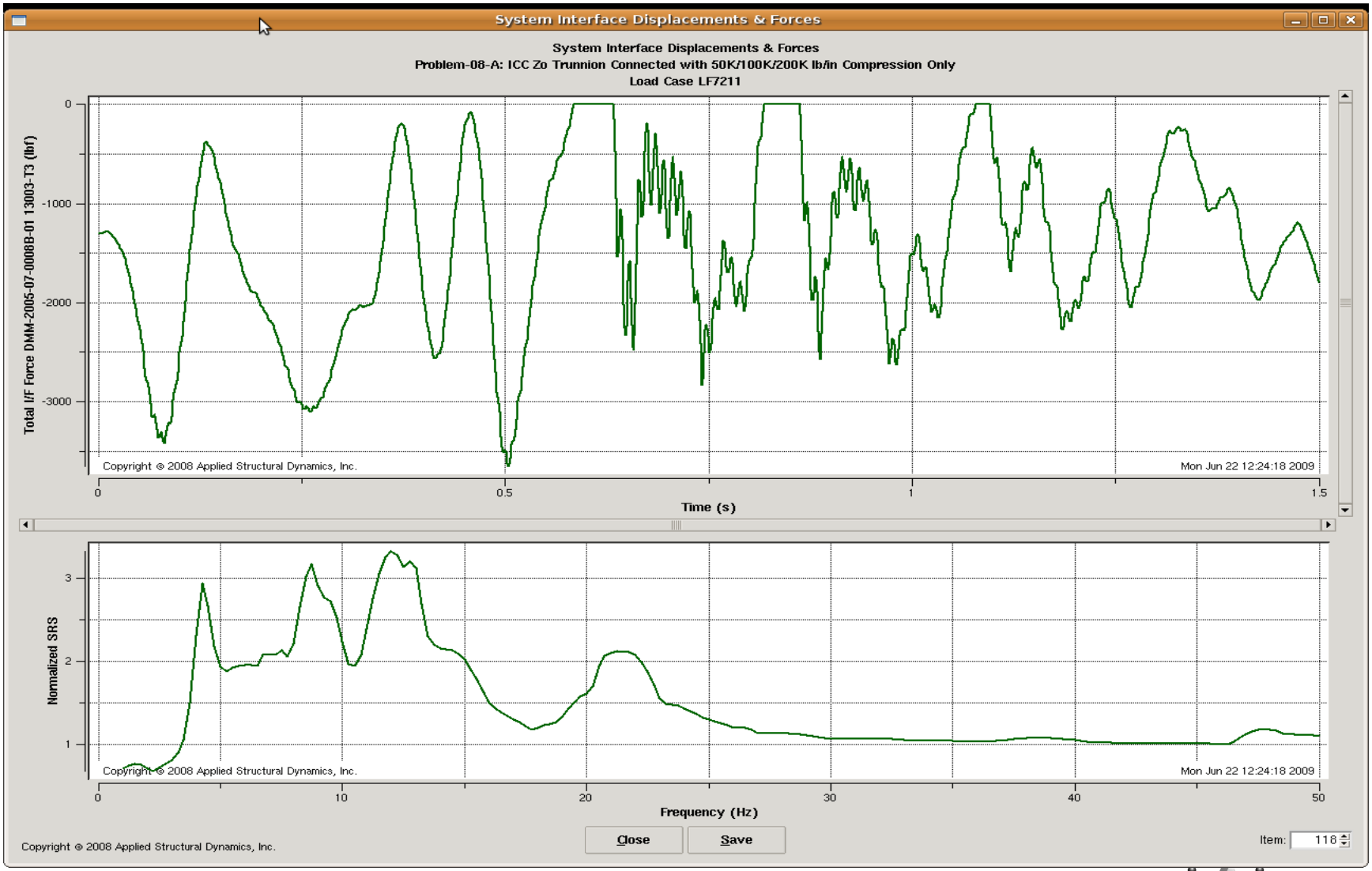
Nonlinear CLA: Total Interface Spring Force - Space Shuttle Side



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3) Tri-Linear Compression-Only Spring Discussion

- The results illustrate ASD/CLAS's capability of simulation multi-linear springs
  - Note: Spring 2 is active during a subset of time that spring 1 is active
  - Note: Spring 3 is active during a subset of time that spring 2 is active
  - Note: Re-contact after loss of contact excites higher frequency responses
    - Zero force segments in the Space Shuttle time histories define the loss of contact

Summary

- ASD/CLAS has the capability of simulating transient analyses with piece-wise linear component interface springs
  - Multiple interface springs are contained in one component's Dynamic Math Model (DMM)
    - One Degree of Freedom (DoF) for each of the springs
  - Multiple constraints, at the single interface, are defined in the ASD/CLAS constraint definition table
  - Tailored deadband limits are also defined to yield the desired spring force versus relative displacement relation
    - Tension only simulation is easily defined
      - AMS type strap restraint
    - Compression only simulation is easily defined
      - Multi spring snubber type contact

- ASD/CLAS can currently support the transient loads analyses required for integration of the AMS onto the Space Shuttle launch system

Concluding Remarks

- With ASD/CLAS, any nonlinear spring construction, tailored to the actual spring force-displacement relation, via a piece-wise linear approximation, is possible and is executed with unprecedented accuracy

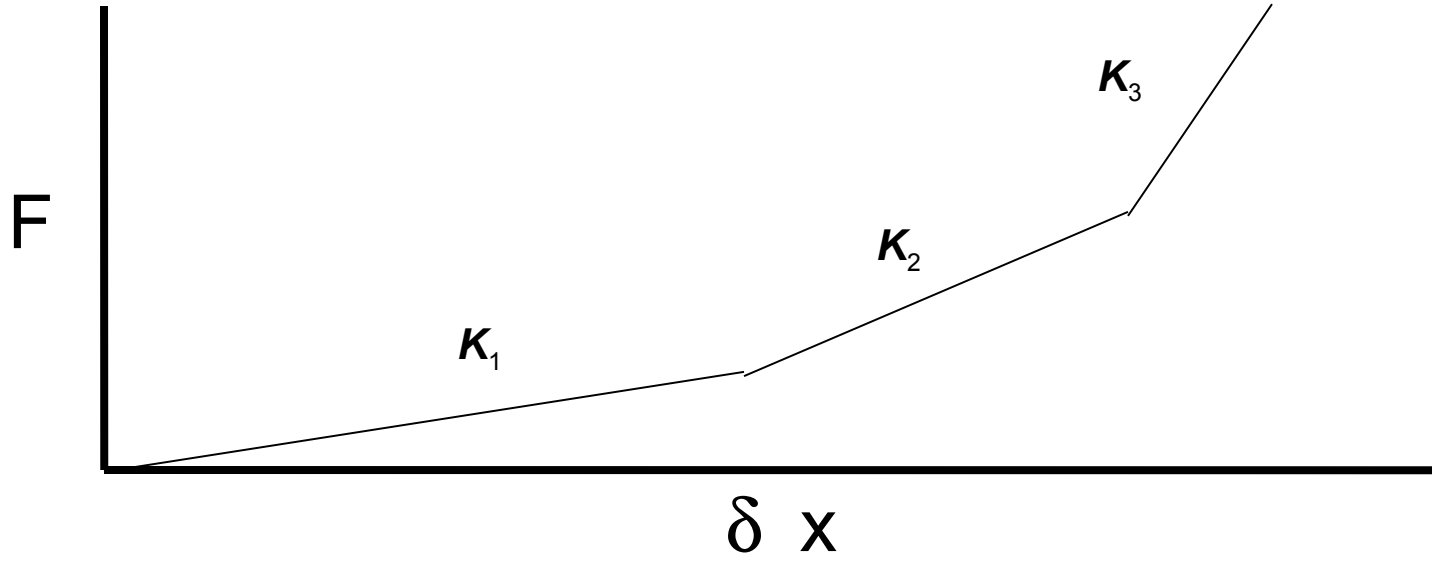
- ASD/CLAS - A significant value added tool for our technical community
  - Significantly reduce risk, schedule, and cost
  - Visit www.appliedstructuraldynamics.com for more information on ASD/CLAS and licensing

Backup Slides

Discussion/Graphical Depiction of ASD/CLAS
Construction of Nonlinear Spring Interfaces

Multi Linear Spring Interfaces

- Multi linear (piece-wise linear) interface springs can be easily be simulated via multiple interfacing springs within one of the component's DMM
  - The spring constants are tailored to yield the desired stiffness properties
  - The deadband limits are tailored to yield the desired transitions between the various stiffness levels



Multi Linear Spring Interfaces (cont'd)

- The spring constants on the previous slide are generated by tailoring the individual interface spring constants in one component's DMM
  - $\boldsymbol{K}_1 = k_1$
  - $\boldsymbol{K}_2 = k_1 + k_2$
  - $\boldsymbol{K}_3 = k_1 + k_2 + k_3$

- Again, the deadband limits are tailored to yield the desired transitions between the various stiffness levels

Multi Linear Spring Interfaces (cont'd)

- The illustrated example depicts a tri-linear tension-only interface spring between components 1 and 2