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Preliminary Validation of a Complex Aerospace Structure

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Introduction

- **Modal Vibration test data >> Validate FEM**
- **Uncertainty >> Validation process**
  - **Measurements**
  - **Analysis predictions**
- **Uncertainty quantification**
  - **Fabrication uncertainty**
  - **Analysis uncertainty**
    - Mesh convergence, Material modulus, Joint stiffness
- **Validation**
  - **Final Configuration**

Purpose

- **Uncertainty Investigation**
  - **Test hardware**
  - **Finite Element Model**
- **Validation of FEA Model**
  - **Includes Uncertainty**
- **Experimental Uncertainty**
  - **Manufacturing (part to part)**
  - **Assembly**
  - **Measured data**
- **Modeling Uncertainty**
  - **Part tolerances / sizes**
  - **Material properties**

Model Development / Validation Process

- Create finite element mesh*
- Calculate frequencies and mode shapes
- Calibrate model using test data
  - Test data collected from different input locations on structure than validation data
- Model verification
- Run uncertainty analysis
  - Determine properties to vary and probable ranges
  - Use Latin hypercube approach to generate multiple realizations of model
  - Run all realizations and compute model FRFs
- **Evaluate validation metrics**
- **Measure FRFs / mode shapes on final configuration**

*Steps completed previously and presented at IMAC XXVI & XXVII

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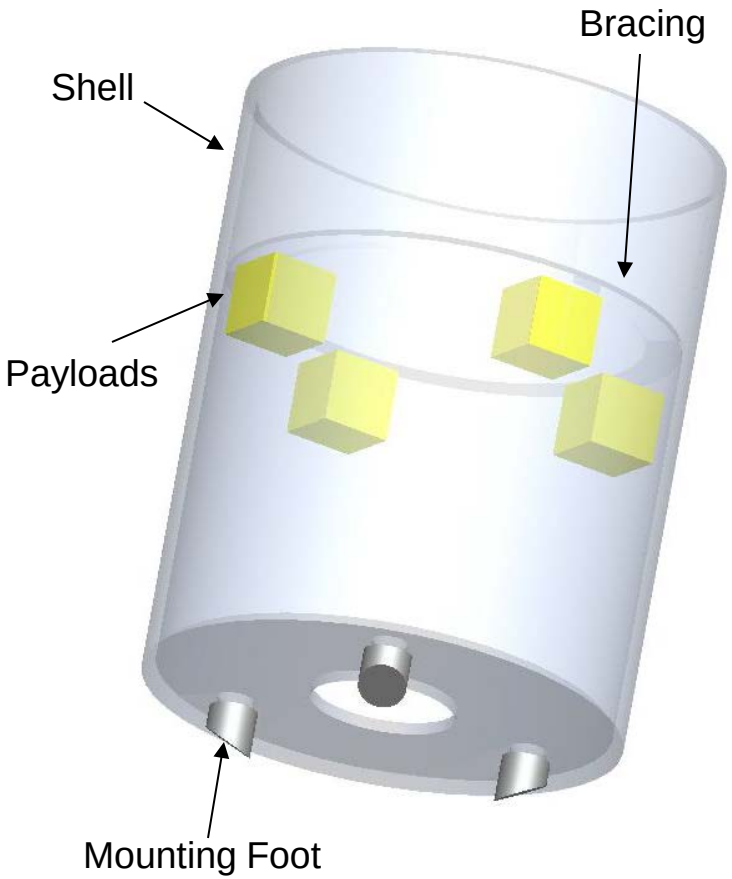
Simplified Aerospace Structure

- **Structural Elements**
  - **Outer Shell**
    - includes 3 mounting holes at base
  - **Interior Bracing**
    - riveted & welded in place
    - rivets/welds not modeled explicitly
  - **Payload Brackets**
    - bolted to bracing
    - bolts modeled with 1D springs
  - **Payloads**
    - bolted to brackets
    - bolts modeled with 1D springs
  - **Mounting Feet**
    - suspension points for free-free modal test



Analysis Model

- **Finite Element Model**
  - **400,000 2nd order elements**
  - **5.6 million degrees of freedom**
- **Computing**
  - **Model run using Salinas***
    - 5 hours on 100 processors
    - Computed modes and FRFs up to 2000 Hz

*Structural dynamics code developed at Sandia National Laboratories

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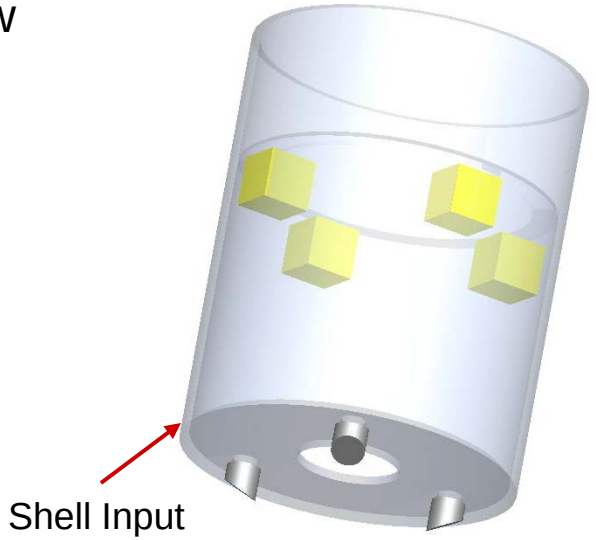
Test Program

- **Lightly damped system**
  - ½ - 1% across frequency range (100 - 1000 Hz)
- **Modal shaker used to excite system**
  - continuous random input with Hanning window
  - minimize nonlinearities
  - accurate constraint of input locations and directions
- **Input location on shell**
  - oriented input 30º from vertical
- **Modes extracted up to 1000 Hz using SMAC* algorithm**
- **Data Collected**
  - Modal frequencies
  - Mode shapes
  - FRFs
  - Modal damping



*Developed at Sandia National Laboratories

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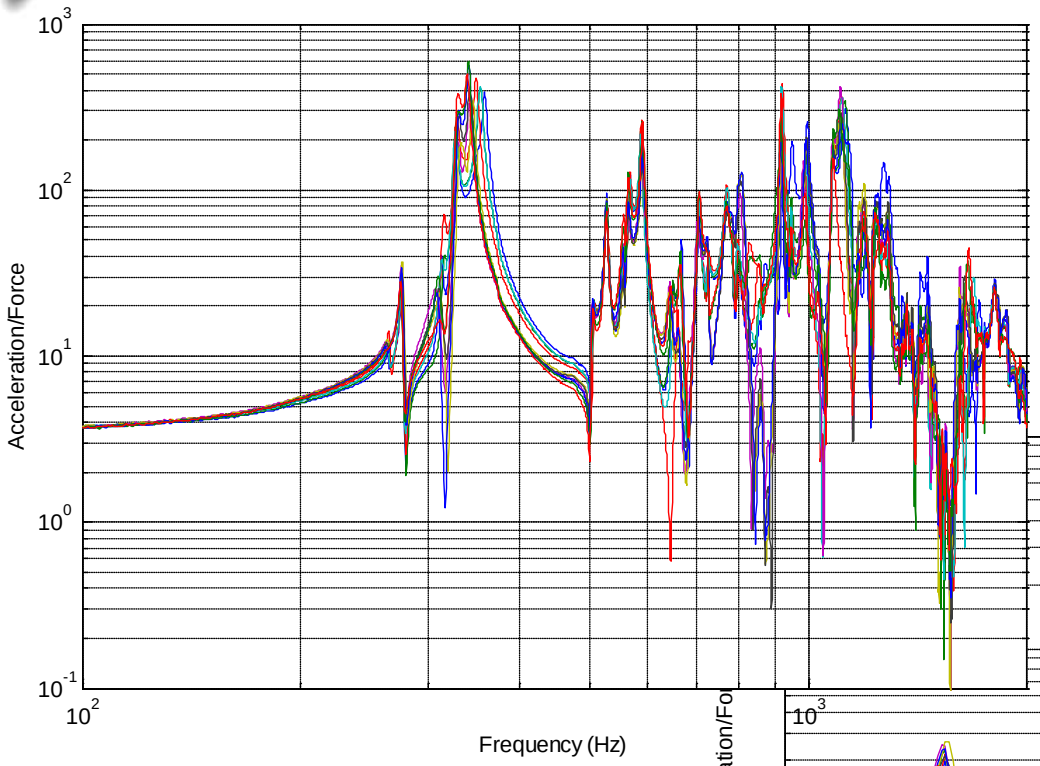
Uncertainty Quantification

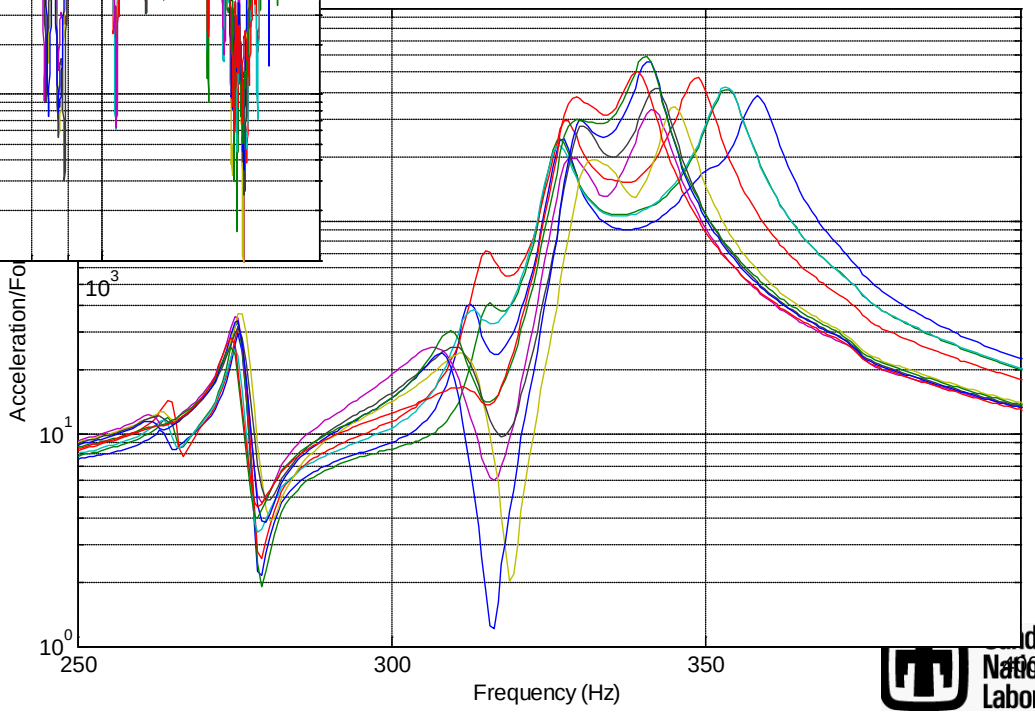
- **Areas of uncertainty**
  - **Manufacturing (part to part variation)**
  - **Assembly**
  - **Measurement**
  - **Modeling**

- **Assembly Uncertainty**
  - **Assembly - Disassembly – Reassembly**
  - **Different Individuals**
  - **Variations – Component Exchange**
  - **10 buildups**

Assembly Variability FRF's



Full Spectrum



First Lateral & Axial Modes

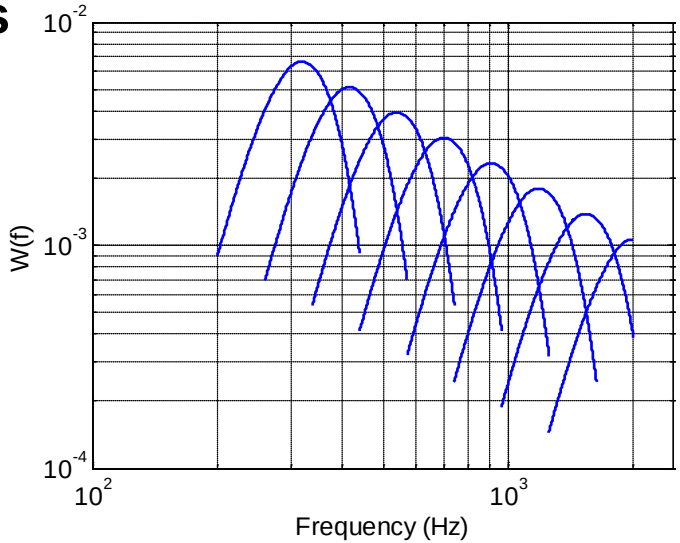
Uncertainty Quantification

- **Areas of uncertainty**
  - **Manufacturing (part to part variation)**
  - **Assembly**
  - **Measurement**
  - **Modeling**

- **Modeling Uncertainty**
  - **Material Modulus of Elasticity**
  - **Sheet Metal Thickness**
  - **Bolted Joint Stiffness**

Model Validation

- **Numerical Comparison**
  - **50 Analytical FRF's**
  - **10 Experimental FRF's**
- **Simplification**
  - **2 locations on payloads used as validation points**
  - **FRF's calculated in 3 directions**
  - **Total of 6 validation FRF's**
- **Comparison**
  - **Multiply FRFs by weighting function to compare response in frequency bands**



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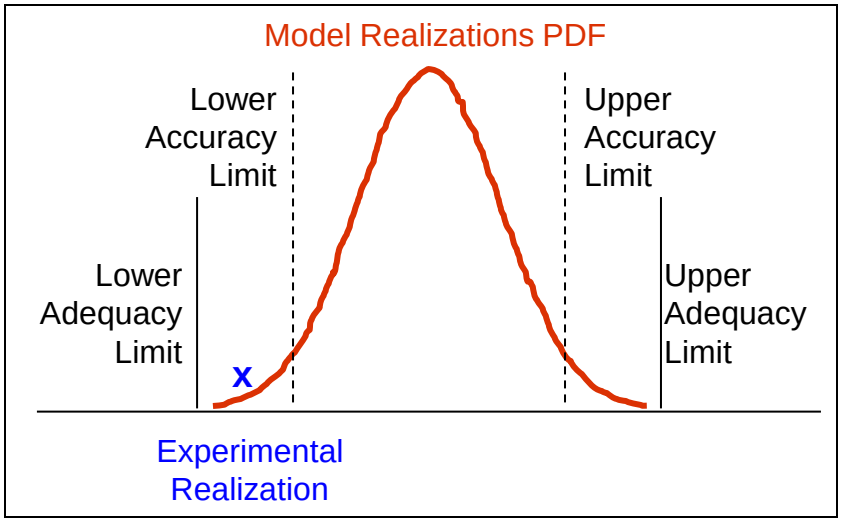
Validation Process

- **At each validation point and each frequency window**
  - **50 model realizations and 10 experimental realizations**
  - **FRF is multiplied by weighting function and integrated**
  - **Probability density function (PDF) created from model realizations**
  - **Each experimental realization is compared to model PDF**
    - **Accuracy assessment** – falls within 90% probability window
    - **Adequacy assessment** – “good enough” model (often ±6 dB)



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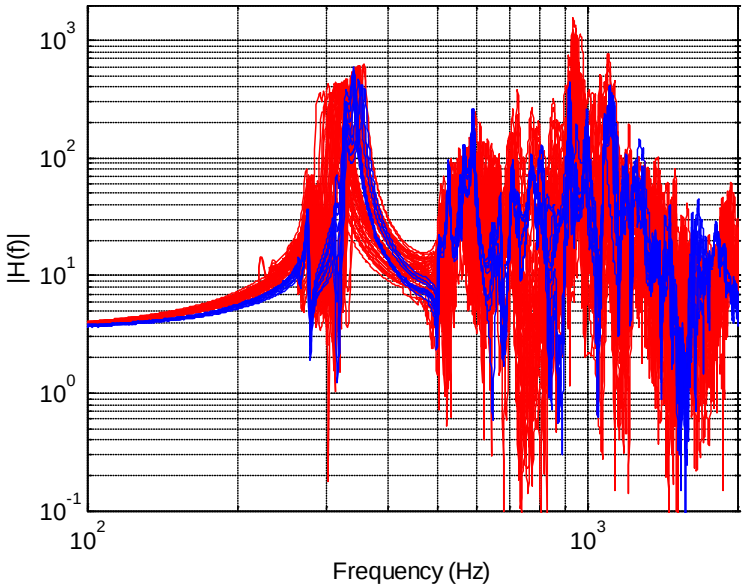
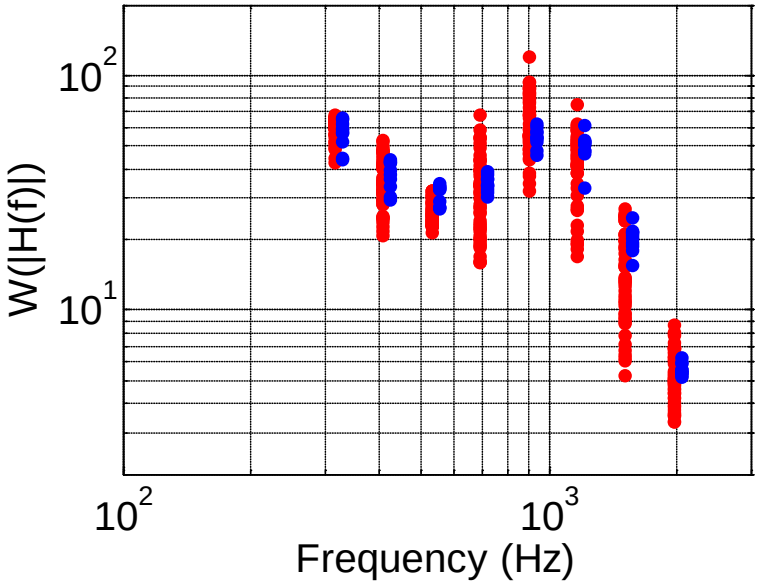
Validation Point 1 – Payload 1, Axial



Experimental FRFs (blue) and Model FRFs (red)



Experimental and Model Validation Metrics

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Validation Statistics

Validation Point	Location	Direction	Validated Data Points		
			Adequate ± 6dB	Adequate ± 3dB	Accurate
1	Payload 1	Axial	100%	100%	90%
2	Payload 1	Lateral	100%	89%	**26%**
3	Payload 1	Lateral	100%	**74%**	**41%**
4	Payload 2	Axial	100%	100%	**75%**
5	Payload 2	Lateral	100%	85%	**30%**
6	Payload 2	Lateral	100%	94%	**25%**

84% of assessments must meet criteria for model to be validated

Final Configuration Testing

- **Excitation**
  - **Modal Hammer**
  - **Shaker**
- **Instrumentation**
  - **204 Accelerometers**
- **Data Acquisition**
  - **0 to 2000 Hz**
- **Data**
  - **30 modes**
  - **Damping ¼% to 2%**

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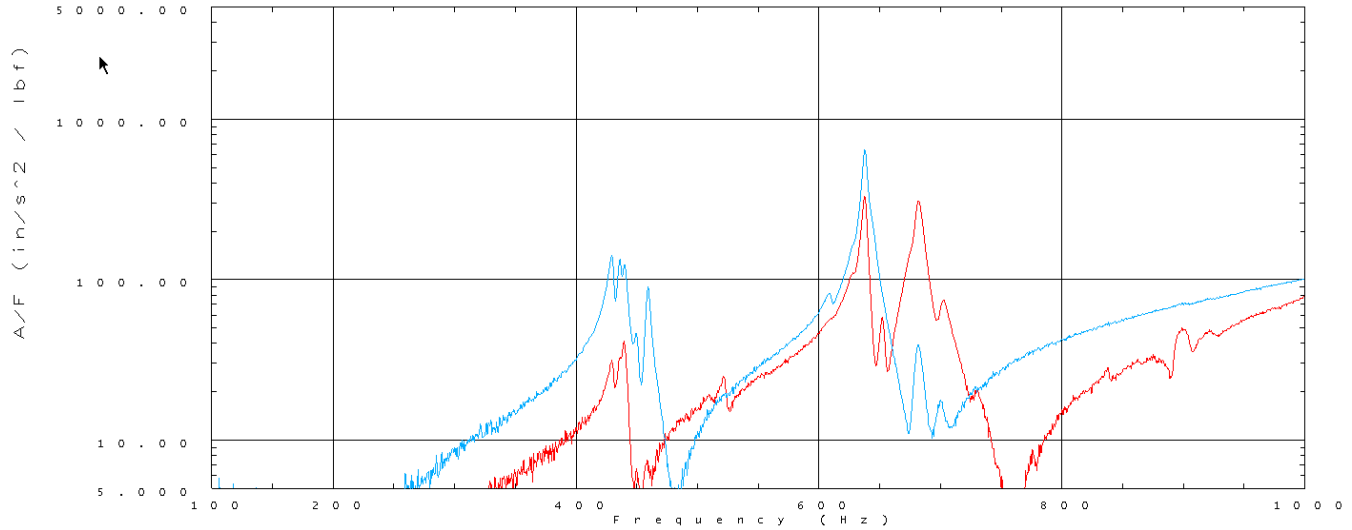
Driving point FRF for inputs normal to shell



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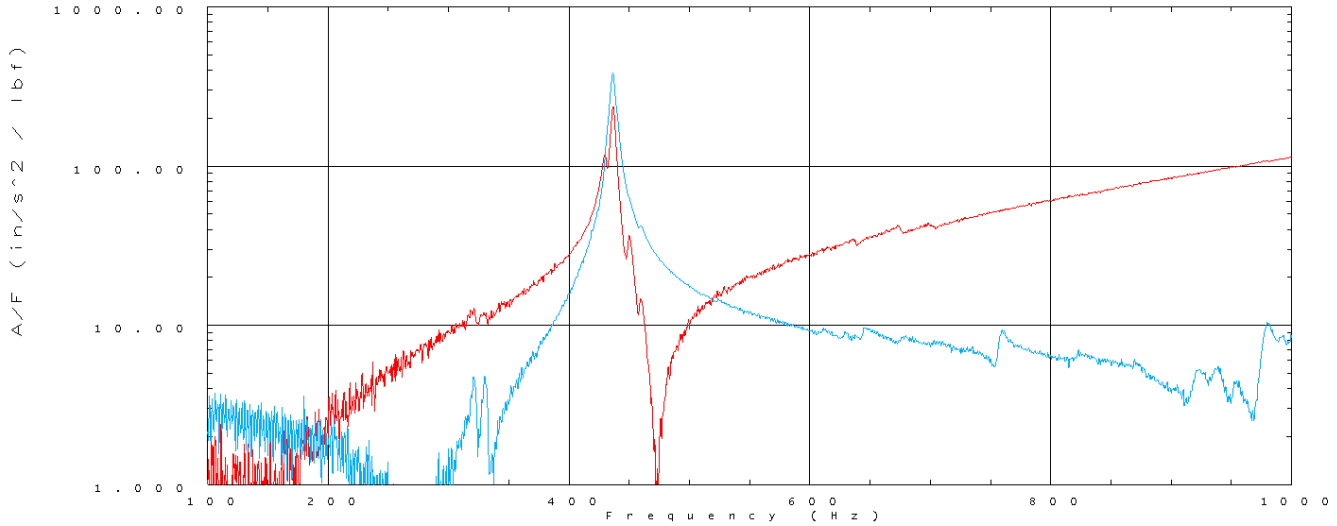
Driving point FRF for inputs axial to shell



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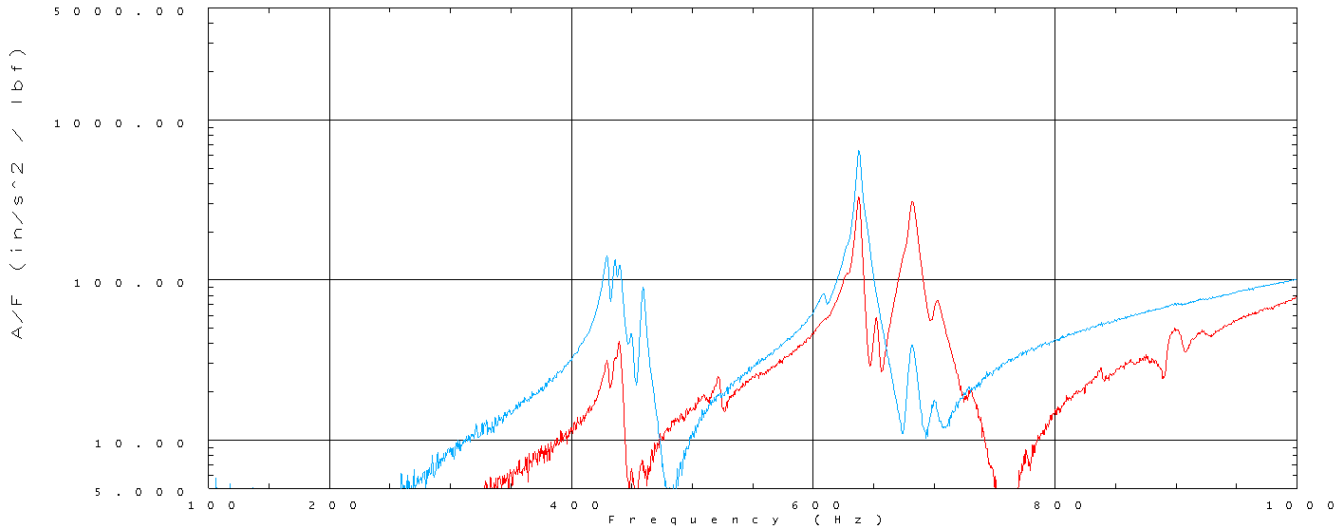
Driving point FRF for inputs tangential to shell



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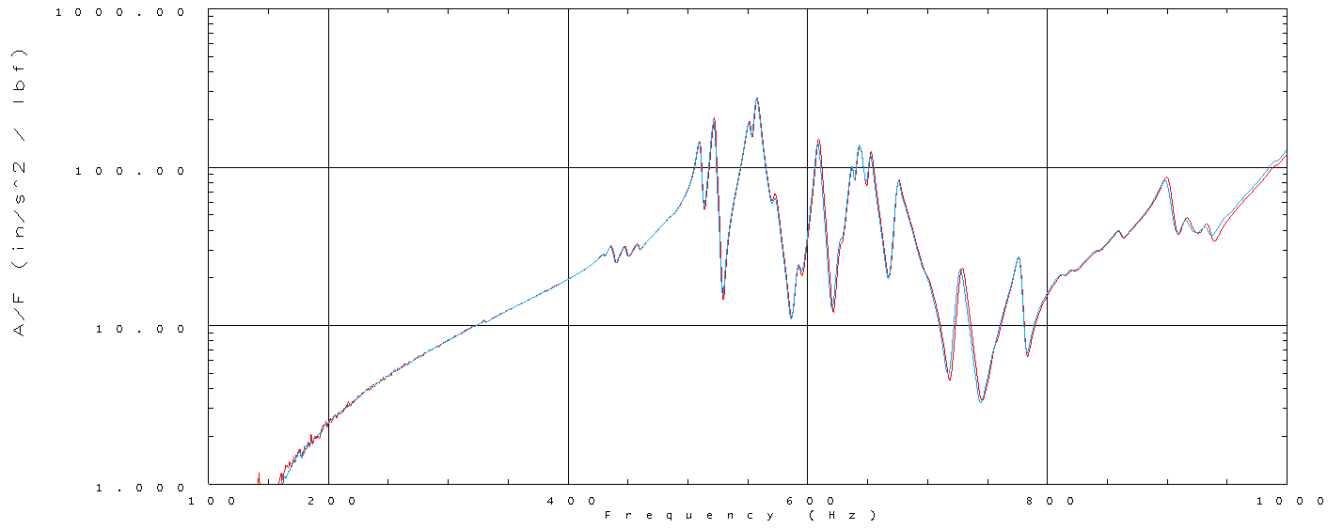
Driving point FRF with shaker input



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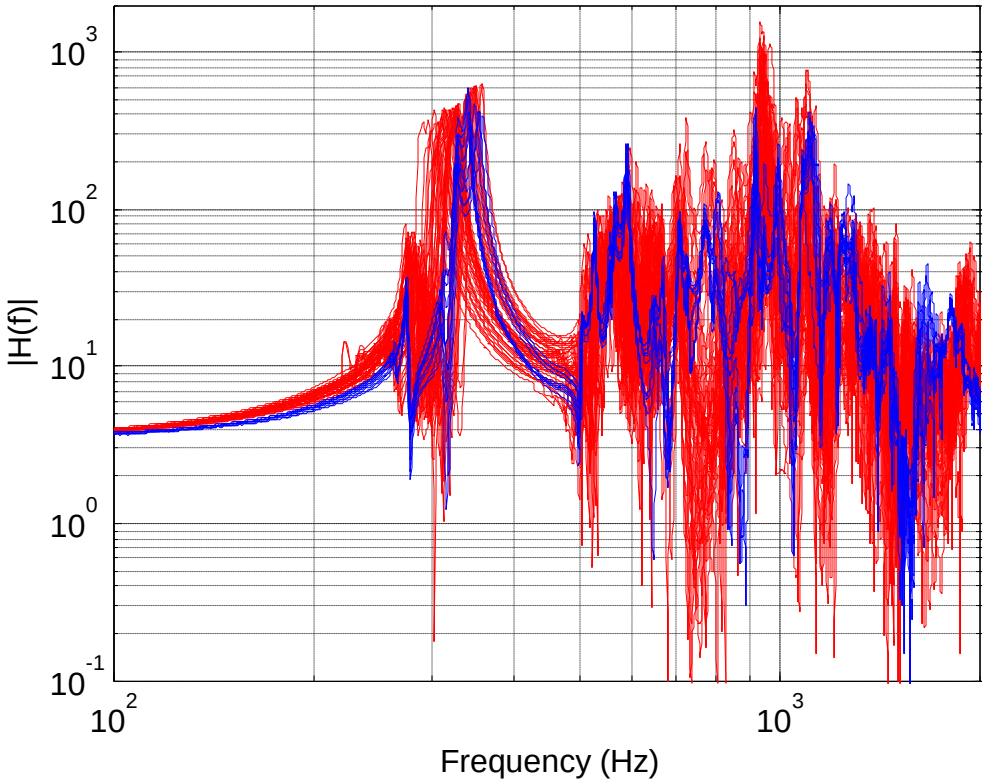
Analysis Mode Updating – Subassembly of Main Structure

Mode Description	Test Frequency (Hz)	Analysis Frequency Before (Hz)	Error Before	Analysis Frequency After (Hz)	Error After
2,0 Ovaling / Payloads In Phase with Shell	259	173	-33%	261	0.7%
2,0 Ovaling / Payloads In Phase with Shell	271	175	-35%	273	0.6%
2,0 Ovaling / Payloads Out of Phase with Shell	299	257	-14%	301	0.6%
2,0 Ovaling / Payloads Out of Phase with Shell	321	280	-13%	322	0.4%
Payloads Axial	348	236	-32%	356	2.2%
One Payload Rocking	527	406	-23%	535	1.5%
3,0 Ovaling / All Payloads Out of Phase with Shell	644	618	-4%	644	0.0%
3,0 Ovaling / 2 Payloads Out of Phase with Shell	678	634	-6%	672	-0.9%
3,0 Ovaling / 2 Payloads Out of Phase with Shell	696	657	-6%	694	-0.3%
3,0 Ovaling / 2 Payloads Out of Phase with Shell	702	698	-1%	678	-3.5%
3,0 Ovaling / 2 Payloads Out of Phase with Shell	722	717	-1%	739	2.3%

Validation Point 1, All Model Results (red) and Experimental Results (blue)



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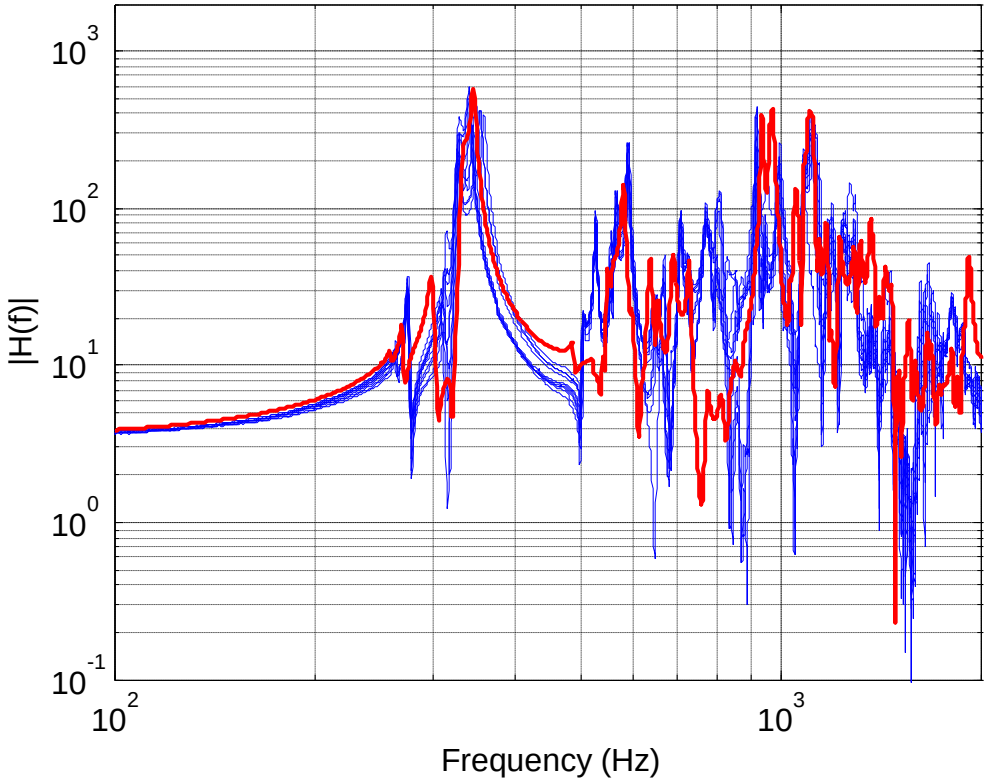
Validation Point 1, Calibrated Model Results (red) and Experimental Results (blue)



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Preliminary Analysis vs. Test Frequencies

Mode Description	Test Frequency (Hz)	Preliminary Analysis Frequency (Hz)	Error
Payloads axial Out of Phase	322	323	-0.3%
Main Payload top rocking; Payloads axial In Phase	438	325	-25.8%
Payloads axial In Phase	331	326	-1.5%
Main Payload top rocking	459	327	-28.8%
Axial – Main top & bottom Payloads Out of Phase	448	415	-7.4%
Bending – Main bottom Payload rocking	430	462	7.4%
Bending – Main bottom Payload rocking	436	467	7.1%
2,1 Ovaling – Payloads Lateral Out of Phase	510	533	4.5%
Payload & Bottom bracing Axial	609	550	-9.7%
2,1 Ovaling – Payloads Lateral In Phase	551	561	1.8%
Payloads Lateral In Phase	558	578	3.6%
Payload 1 Lateral – Small Payload Axial	771	599	-22.3%
Torsion	638	618	-3.1%
2,2 Ovaling – Payload Lateral Out of Phase	522	625	19.7%
2,2 Ovaling – Payload 1 Lateral – Small Payload Axial	643	642	0.2%
2,2 Ovaling – Payload 1 Axial	675	674	-0.1%
2,3 Ovaling – Small Payload Axial	700	675	-3.6%
2,3 Ovaling	891	697	-21.8%
Top bracing rocking	728	767	5.4%

Discussion

- **Modeling uncertainty**
- **Uncertainties in this model reasonable?**
  - **Look at variation of mode at 350 Hz**
    - 10-15% variation in model
    - 5.5% variation in experiments
- **Is it possible to add too much uncertainty?**
  - **Yes, but it is impossible to completely eliminate it**
  - **Real parts & assemblies have variability**
- **Final configuration is single representation**

Conclusions

- **Model Validation**
  - **Solution Verification**
  - **Uncertainty Quantification**
  - **Validation – Numerical comparison of experimental and model results**
- **Test Data vs. Model Data**
  - **Model correlation**
  - **Additional testing**
  - **Final Validation test**