



A Structural Dynamics Model Validation Example with Actual Hardware

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Model Validation and Uncertainty Quantification Tutorial

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Model Validation History in Structural Dynamics

In the 80's

Validation = Correlation = Updating = Refinement
= “better match” between analysis and test data

In the 90's the definition of validation began to be refined.

One often-referenced definition that has emerged is:

“Model validation is the process of determining the degree to which a computer model is an accurate representation of the real world from the perspective of the intended model application.” [1]

Here we take the approach that the model will make a blind prediction that will be compared to test results. Pre-determined bounds are set to determine if the model is valid or invalid.

Different hardware is used for correlation and calibration than for the validation.



Steps to Model Validation [2]

- Preliminary Steps
 - Specify model use/purpose (what decision is to be made)
 - Specify response measures (what the model predicts)
 - Specify validation features and metrics and comparison domain
 - Specify calibration experiments
 - Specify validation experiments
 - Specify adequacy criteria
- Perform calibration experiments/Calibrate model parameters
- Validation
 - Perform experiment
 - Make predictions
 - Calculate metrics/compare with adequacy criterion
- Subsequent Action
 - Not valid – Reformulate model/Additional calibration
 - Valid – Make Predictions

We expand the step highlighted in blue to include correlation and calibration.



Model Validation Team

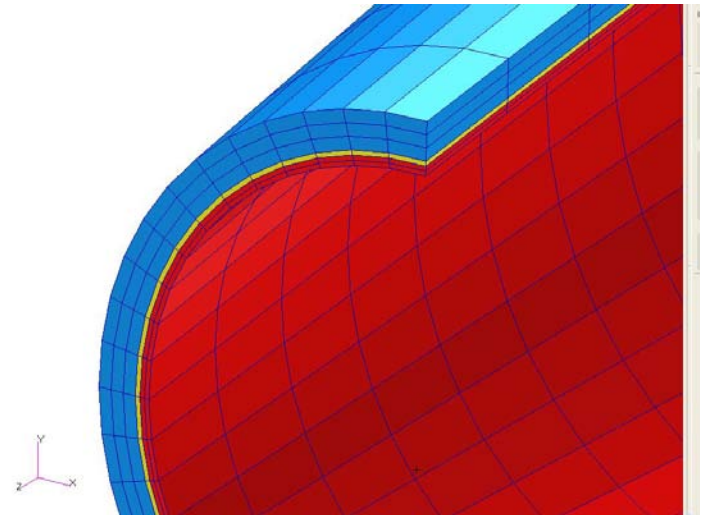
- Analysts – 4
- UQ expert – 1
- Experimentalist – 1
- Customer – 1
- Argued our way through to an eventual validation plan in advance of all predictions
 - requirements
 - response measures
 - adequacy criteria
 - calibration experiments
 - correlation experiments
 - validation experiment

Example problem

A conical shell structure with three material layers is modeled with finite elements. The outer layer is a layered carbon fiber cloth in a resin matrix. The thin middle layer is basically a glue made of a filled rubber. The inner layer is aluminum. All three layers are modeled with isotropic material properties, parameterized with modulus of elasticity and Poisson's ratio. 20 node hex finite elements are utilized.

- 3 elements through the outer layer
- 1 element through the mid layer
- 2 elements through the inner layer

We wish to validate this modeling approach for future acceleration predictions of certain components in specific environments for full system analyses.



Hardware

- Validation – Closed conical shell 

- Correlation – Conical frustum shell 

- Calibration – Glue between discs





Model Purpose / Requirements

- “Intended application” is the purpose of the model
- From this purpose, the requirements of the model must be generated, and these will later be related to response features through adequacy criteria
- The purpose of the shell is to transmit forces and motion to certain components in a complete system for certain known environments.
- The requirements are to properly represent dynamic axial motion, longitudinal bending, low order circumferential shell bending and circumferential shell extension, which are the pertinent physics for the known environments.



Response Features

- The response features of the closed conical shell were chosen to be free-free modal frequencies associated with modes that exercised the pertinent required physics. Since the FE mass was very close to the measured weight, the frequencies provide a stiffness comparison.



Physics	Mode Description
Axial Motion	First Axial
Longitudinal Bending	First Bending
Circumferential Shear Mid Layer	2,0 Ovaling
Circumferential Extension	0,0 Breathing

Adequacy Criteria – What is Unacceptable?

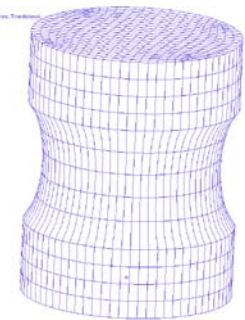
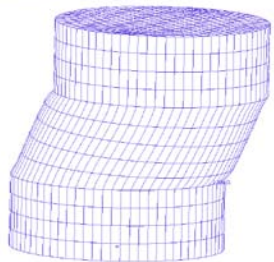
- A small stiffness error of X% would indicate a global stiffness error of 2X%, for each particular mode
- The team agreed on adequacy criteria for each mode that the model should predict within $\pm(10^2 + U_m^2)^{1/2}\%$ of the test frequency. U_m is uncertainty due to known variability investigated with the model.
- An additional check was that the lowest 4 lobed ovaling mode would be within 15% of the test frequency.

Physics	Mode Description
Axial Motion	First Axial
Longitudinal Bending	First Bending
Circumferential Shear Mid Layer	2,0 Ovaling
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Separate Calibration Experiment

- Calibration was performed on the **highly uncertain** glue material in the middle layer. The filled rubber like material was used to attach two steel discs.
- The shear mode and the axial mode were extracted from 5 samples with ½” thick glue between the steel discs as shown in the center of the picture.

Test Shear Frequency (Hz)	Test Axial Frequency (Hz)	Model Shear Frequency (Hz)	Model Axial Frequency (Hz)	Modulus (psi)	Poisson's Ratio
1750	2210	1749	2209	9235	0.465
1800	2275	1799	2272	9770	0.465
1787	2240	1788	2240	9630	0.46
1762	2215	1762	2214	9362	0.462
1750	2230	1750	2227	9235	0.47

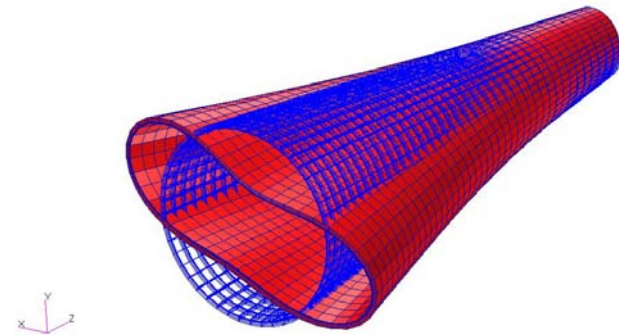


Separate Correlation Experiment

SMAC code was used to extract modes from 8 impact references. There were triax accelerometers at each 90 degrees around the circumference at 6 axial stations.

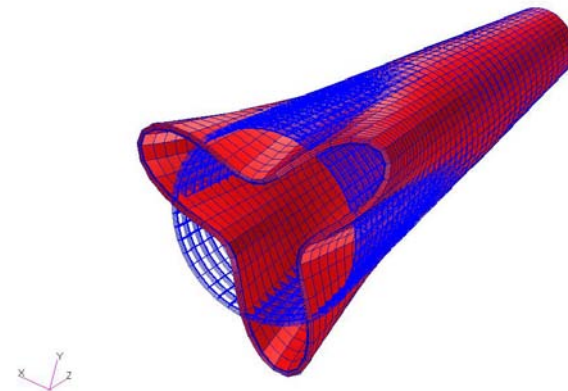
Mode #	Frequency (Hz)	Description
1	198.8	2,1 Node Forward
2	208.2	2,1 Node Forward
3	284.7	2,1 Node Aft
4	292.8	2,1 Node Aft
5	510.4	Aft 3 lobe
6	520.8	2,2
7	529.7	2,2
8	561.5	Aft 3 lobe
9	619.4	Mid 3 lobe
10	625.6	Mid 3 lobe
11	799.2	3,2
12	807.8	3,2
13	921.0	Aft 4 lobe
14	943.1	Aft 4 lobe
*	979.7	First bend Y
*	1007.8	First bend Z

MSC.Patran 2005 (2 06-Oct-08 13:13:17)
Deform: Default, Mode 7 Freq=124.25, Eigenvectors, Translational



default_Deformation :
Max: 5.71e+000 @Nd 616

MSC.Patran 2005 (2 06-Oct-08 13:14:21)
Deform: Default, Mode 11 Freq=277.3, Eigenvectors, Translational

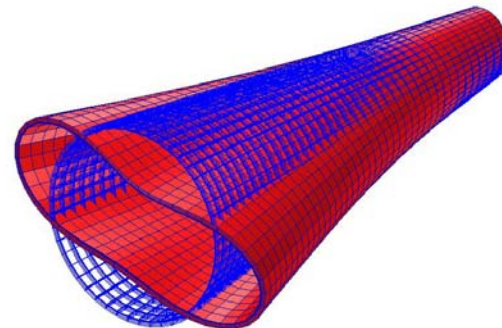


default_Deformation :
Max: 7.59e+000 @Nd 1477

Correlation UQ Analyses

- Several correlation exercises were performed predicting the frustum shell response, and these were **critical** to the success of the validation.
- Model based uncertainty quantification from eigenvalue analyses
 - Minimum and maximum manufacturing tolerances changed modal frequencies of interest less than 1 %
 - Zero and maximum allowable bond voids caused less than 1 % change in modal frequencies
 - Orthotropic vs. Isotropic formulations of the composite outer layer caused less than ½ % difference in first ten modal frequencies
 - Code to code comparison between NASTRAN and SALINAS had less than 0.03 % difference for the first ten modal frequencies

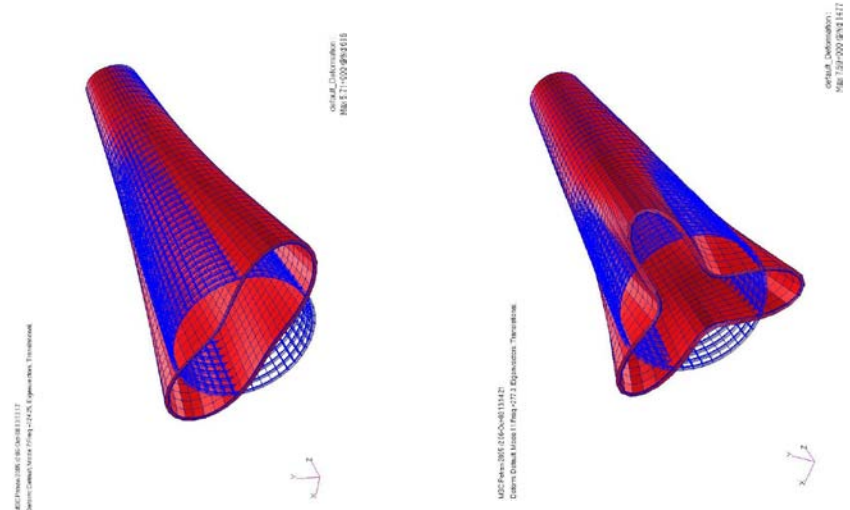
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Correlation Hardware Predictions

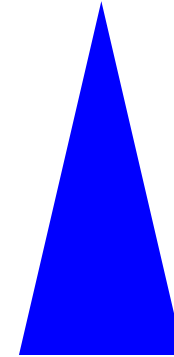
- Initial frequency comparisons showed several prediction errors >10%
- Adjusting modulus of the outer layer required -50% change (unreasonable) indicating that the problem was elsewhere
- Errors uncovered! – Reduced to less than 5%!
 - Reinvestigated disc calibration and found that dimension of the disc was the radius instead of the diameter! E dropped from 13,000 to 9,500 psi. Nu went up by factor of nearly 3
 - Detailed investigations of defeaturing in internal flanges found that certain internal slots had been neglected. These were then included and had significant impact.

Mode #	Test Frequency (Hz)	Initial Model Frequency (Hz)	Description
1	198.8	222.4	2,1 Node Forward
2	208.2	233.2	2,1 Node Forward
5	510.4	592.0	Aft 3 lobe
8	561.5	639.4	Aft 3 lobe



Validation Predictions

- Table shows the blind prediction of the 250,000 node SALINAS closed conical shell model
- All predictions well within 10%
- Experimental uncertainty less than 1 %
- Breathing mode was not identified in test
- Declared shell meshing approach valid



Mode Description	Model Frequency (Hz)	Test Frequency (Hz)	% difference
Ovaling N 2-0	589	581	1.38%
Ovaling N 2-0	589	588	0.17%
First Bending	1627.6	1647	-1.18%
First Bending	1627.6	1647	-1.18%
Ovaling N 4-0	2344.1	2372	-1.18%
First Axial	3139.7	3128	0.37%



Conclusions

- A validation team was formed that agreed on a validation requirements in advance
- Separate experiments were performed for correlation and calibration
- The calibration was very specific and removed uncertainty from very uncertain parameters
- The correlation exercises showed which properties were important and revealed defeaturing over-simplifications and an error in the calibration parameters
- Modeling is “understanding”, and much was learned in the validation process as well as gaining confidence in the specific modeling approach



References

1. AIAA (American Institute of Aeronautics and Astronautics), (1998), *Guide for the Verification and Validation of Computational Fluid Dynamics Simulations*, AIAA-G-077-1998, Reston, VA, American Institute of Aeronautics and Astronautics
2. Urbina, A., Paez, T.L., Rutherford, B., O’Gorman, C., Hinnerichs, T., Hunter, P., “Validation of Mathematical Models: An Overview of the Process”, Proceedings of the 2005 SEM Conference and Exposition on Experimental and Applied Mechanics, Paper 210, June 2005