SAND2009-7349C

Preliminary Validation of a Complex Aerospace Structure

Michael Arviso, D. Gregory Tipton & Patrick S. Hunter Sandia National Laboratories[1]
P.O. Box 5800
Albuquerque, NM 87185

ABSTRACT

A series of modal tests were performed on a complex aerospace structure, consisting of a shell structure with joints and discrete payloads, in order to validate a finite element model of the structure. Modal tests have been performed on individual assemblies followed by model updating using the measured modal data. The final configuration has placed all assemblies together as a complete unit which includes a multitude of joints and interfaces. Frequency response functions (FRFs) were chosen as the validation metric.

INTRODUCTION

The purpose of this work is to ascertain the validity of a finite element model by determining if it produces an accurate representation of the dynamic characteristics of the complex aerospace structure. Model validation is performed with the use of frequency response functions (FRF's) as the independent validation metric. Test and model FRF's were compared to determine the validity of the model.

Several modal tests were performed with a variety of excitation inputs (locations, directions, and magnitude) to gather frequency response functions and mode shape information in order to update the model. These tests were performed in stages to aid in model correlation. Testing was conducted at multiple assembly levels starting with individual components and culminating in the complete structure. The final configuration includes a multitude of welds, rivets, brackets, bonds, and joints with uncertain material properties and joint stiffnesses. Data of interest ranged from 100 to 1000 Hz which enveloped the test environment for the structure.

The complex aerospace structure has been dynamically tested with concurrent model updating for a three year period. In the first year a model was developed extremely quickly using new design through analysis tools that needed experimental data to be used to perform the validation. During this phase, the major steps included correcting modeling errors such as oversimplifications and connectivity issues. Initially the basic structure without any brackets or payloads was examined and tested in order to improve correlation and to isolate modeling issues. A multitude of material parameters were calibrated during this phase. Modal test data during this phase was used to compare modal frequencies and shapes to help improve the model. These tests were extremely helpful in bringing the model to better agreement with the structure. As we know, models are susceptible to errors, oversimplifications, incorrect assumptions, and unknown parameters that may be corrected only through a series of testing and calibration.

In the second year, focus was on investigating the uncertainty in the model. There were modeling uncertainties associated with unknown parameter values as well as variability of manufacturing (part to part) parameters. Experimental uncertainty primarily included assembly variability, as only one structure is available for testing. A natural question was presented, which asks, as more uncertainty is added to the model, is it really easier to validate the model? The answer is yes, however the uncertainty used in validating the model must be carried

[1] Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

forward when performing subsequent calculations. In doing so, a model will have been created that is not as useful, in part due to the high uncertainty [5].

Through testing it was shown that uncertainty included in the model was plausible [5]. The main question was, "Is it reasonable to include uncertainty in analytical models at all?" Well, real structures do have variability; therefore any model of a real structure should also include variability.

Uncertainty investigated in the model included two material thicknesses, one adhesive modulus, and three joint stiffness properties.

MODEL

The aerospace structure consists of an exterior shell surrounding interior bracing, which supports several brackets holding payloads. Figure 1 shows a simplified illustration of the structure. The bracing is attached to the exterior shell using a combination of rivets, bonds, and welds, which are not explicitly modeled. The brackets are attached to the bracing using bolted joints, which are represented in the model using one-dimensional spring elements in each degree of freedom. The payloads are bolted to the brackets, which are also represented in the model with springs. Forces were input into the structure in directions axial, normal, and tangential to the exterior shell and at one of the mounting feet.

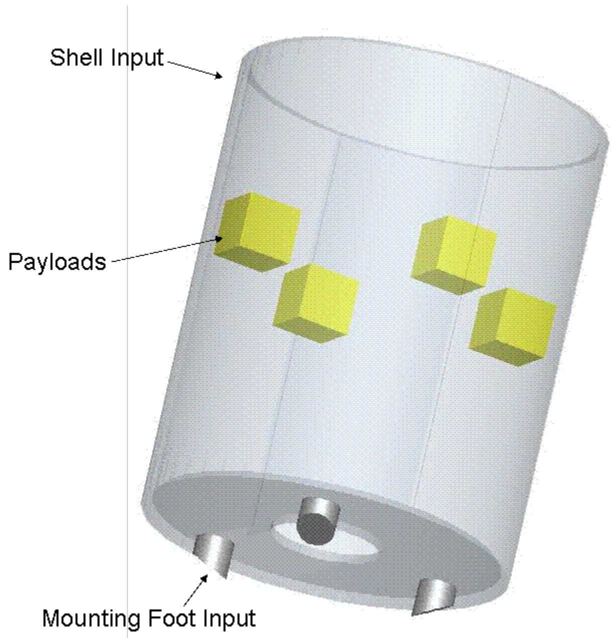

Figure 1: Simplified Illustration of Structure

The finite element model of the structure is composed of 2^{nd} order elements, a mix of hexes, quads and beams resulting in 5.6 million degrees of freedom. The modes and FRFs of the structure were calculated using Salinas, a massively parallel structural dynamics code developed at Sandia National Laboratories, [1].

TESTING

Focus of the final year of testing rests with two main configurations, one being the final configuration. The first test was conducted on a portion of the structure with its associated payload, which was used as an intermediate step leading up to the final test. The second test was performed on the full structure with all the payloads and brackets in place. FRFs were recorded for both configurations and used as calibration data for the full system model. Modal parameters, including the frequencies, damping, and shapes were extracted and compared with the model predictions.

The first test was conducted on a partial assembly of the structure using modal hammer impacts as excitation [2]. These inputs produced very clean FRF's. Varying levels of amplitude produced nearly identical FRF's; indicating that nonlinearity of the system was not present at these levels. Since the structure is basically axisymmetric, the shell ovaling modes show up as two lobed and three lobed modes. Four lobed ovaling frequencies were above the band of interest. Approximately 10 modes were extracted from the measured FRF's, up to 1000 Hz, using the SMAC algorithm [3].

The final configuration test was performed on the full structure with all the payloads and brackets in place. This test configuration used excitation inputs from both modal hammers and a single modal shaker. The modal shaker used a continuous random input with Hanning windows applied to the data. To minimize the effect of the Hanning window on the measured damping, long time blocks were utilized. The input location and direction are more accurately controlled when a modal shaker is used instead of a modal hammer. This makes the FRFs obtained using the modal shaker input more suitable for use in the validation efforts to remove input uncertainty.

Data acquisition systems were set to measure in the 0 to 2000 Hz range. Filters were used with a cutoff frequency of 3000 Hz. Hanning windows were used in conjunction with the shaker while no window was used with the modal hammer inputs.

Mode shapes were measured with a total of 204 accelerometers arranged throughout the payloads and brackets along with several rows on the shell. A total of 30 modes were extracted and the damping ratios varied between ¼ and 2 percent.

Driving point FRFs with inputs normal to the shell are overlaid and shown in Figure 2. Magnitude of the FRF is plotted from 100 to 1000 Hz, which is the frequency range of interest for this structure. As seen in the figure there are definitely two bands of modes that are present. The first band is seen in the 400 to 500 Hz region and is attributed to shell modes with some payload interaction. The second band of modes is shown in the 600 to 700 Hz region and is attributed to payloads and associated structure interacting with the shell.

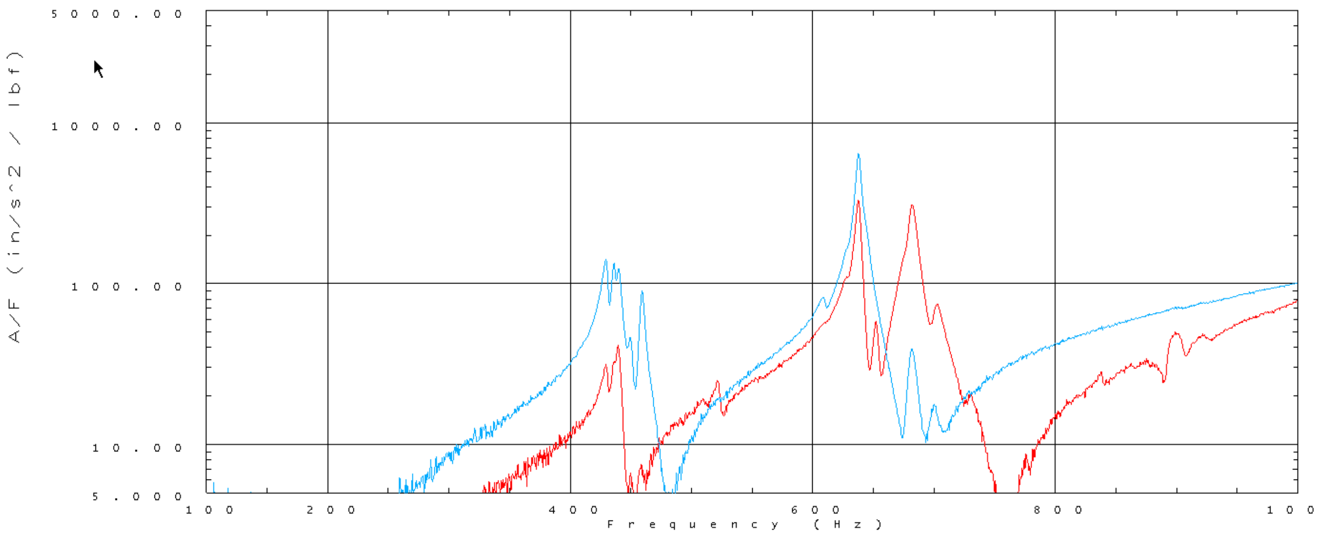

Figure 2: Driving point FRF for inputs normal to shell in two different locations

Driving point FRFs with inputs axial to the shell are overlaid and shown in Figure 3. As seen in the figure, there is only one band of modes that are present. This band is seen in the 400 to 500 Hz region and is attributed to shell modes with some payload interaction. The second band of modes that was presented before is not excited with the input axial to the shell.

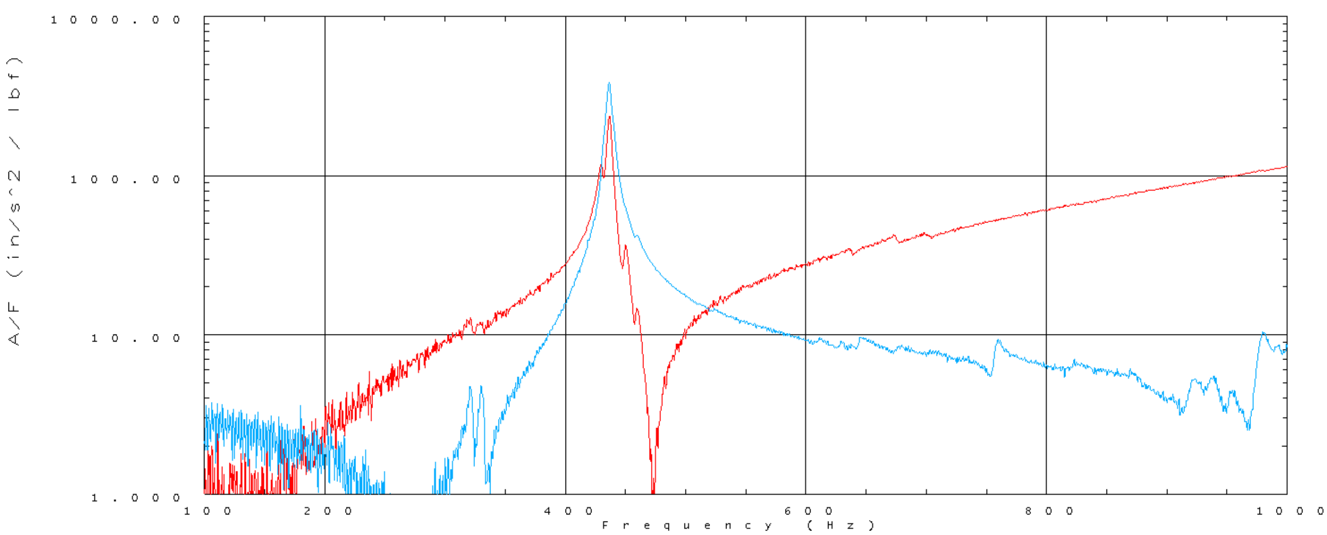

Figure 3: Driving point FRF for inputs axial to shell in two different locations

Driving point FRFs with inputs tangential to the shell are overlaid and shown in Figure 4. As seen in the figure there is definitely two bands of modes that are present once again as in Figure 2. The first band is seen in the 400 to 500 Hz region and is attributed to shell modes with some payload interaction. The second band of modes is shown in the 600 to 700 Hz region and is attributed to payloads and associated structure interacting with the shell.

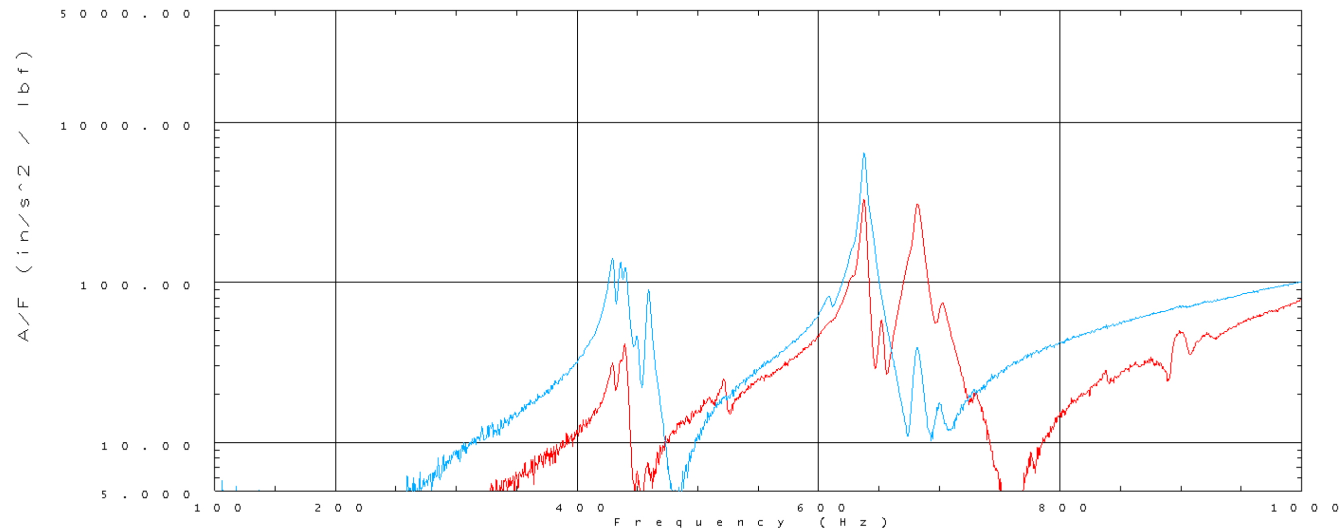

Figure 4: Driving point FRF for inputs tangential to shell in two different locations

Driving point FRF with shaker input near one of the mounting feet are overlaid and shown in Figure 5 from two different load levels produced by the shaker. Again, magnitude of the FRF is plotted from 100 to 1000 Hz, which is the frequency range of interest for this structure. In this figure the two distinct bands of modes are not present as seen in the previous figures. The close match between these two data sets shows that nonlinearity is negligible, at least at these levels.

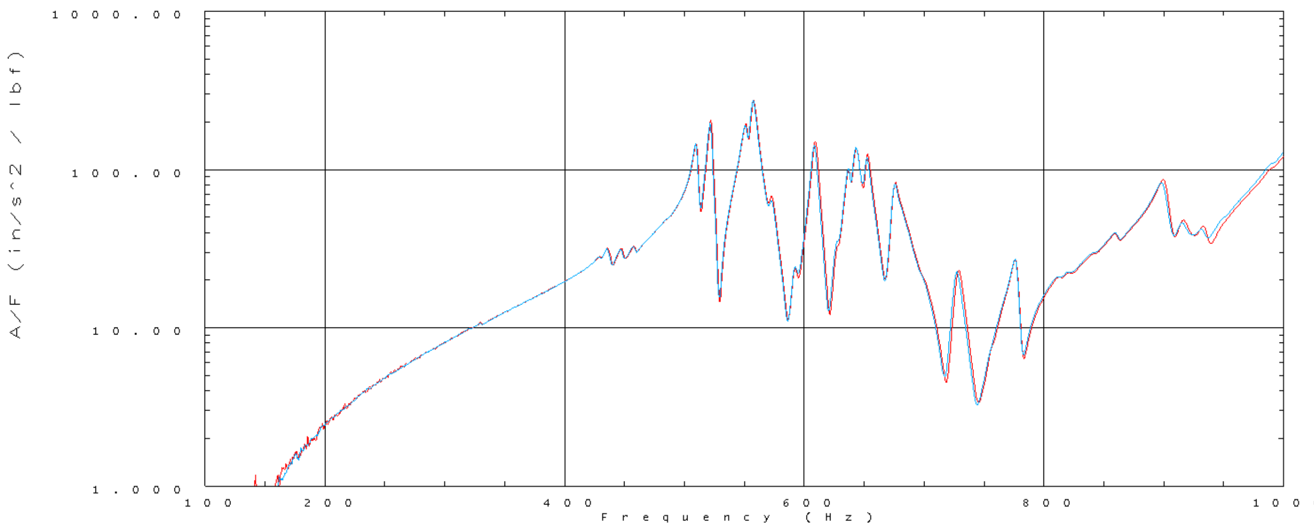

Figure 5: Driving point FRF for inputs near one of the mounting feet with shaker at two different amplitude levels

MODEL UPDATING

A preliminary finite element model would be free of errors in the ideal world; however this is not the case. In order to resolve errors, there must be some sort of test or test data available to compare against in order to update the model.

In our previous work, there have been ongoing efforts and a number of separate procedures used to update the model in the following areas: material properties, material thicknesses, meshing, structural omissions, mass verifications, connectivity issues, mode verification, and animation to verify or calibrate the model. Efforts in early tests have shown all of the previously mentioned issues that were investigated led to greater insight into the test structure thus producing a more refined model of the aerospace structure. It is known that models are prone to have uncertainties in all these areas that may only be corrected through testing and model calibration as shown in Table 1 with the before and after analysis frequencies and test modes [4]. Note the largest error goes from 35% to 3.5% after calibration. The next step is evaluation of the calibrated model to ascertain the model's validity.

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%

Table 1: Analysis Mode Updating – Subassembly of Main Structure

Uncertainty quantification can be applied in modeling and testing. Model verification including solution verification, uncertainty quantification, and two validation steps were used to compare the experimental and model results. Level of uncertainty does affect how the model is validated, but it also affects how the uncertainty is carried forward in subsequent predictions. The model was validated in both the full frequency range enveloped by the test parameters as well as the operational frequency range of interest [5].

Figure 6 depicts FRFs from a chosen validation point on the structure with experimental (blue) overlaid upon the analytical (red) FRFs with associated analytical uncertainty. Analytical FRF's were generated for a variety of material thicknesses, adhesive modulus, and bolt stiffness parameters. Adding additional uncertainty, such as changing the material thicknesses, adhesive modulus, or bolt stiffnesses, to the analytical model only serves to remove the distinct peaks at the higher frequencies making it difficult to depict any modes at the higher end while the lower peak around 350 Hz is quite apparent. Experimental data showed variability in the 5.5% range while the variability of the analytical data approached the 10 to 15% range. The experimental variability only included assembly uncertainty, since only one structure is available for testing.

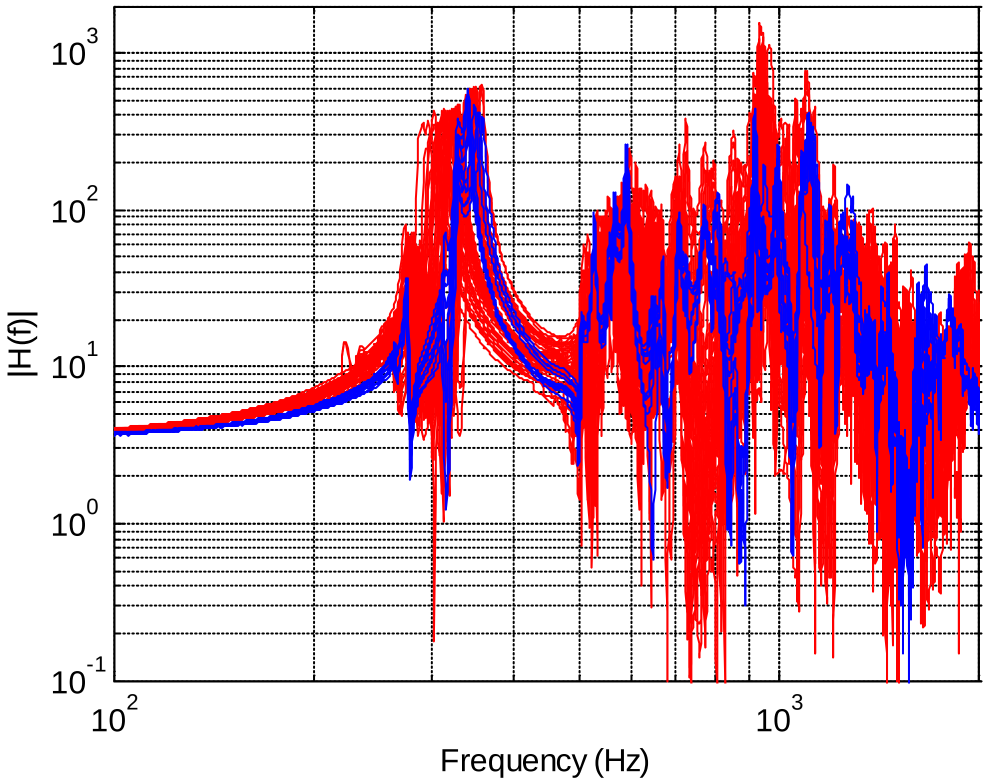

Figure 6: Validation Point 1, All Model Results (red) and Experimental Results (blue)

Shown below in Figure 7 is the comparison of the mean calibrated analytical model enveloped with the experimental results. Again, we are only analyzing data from one structure, so is the model valid? With only one structure, there is no means to find true variability of the structure. Because there is unit to unit variability, uncertainty must be included in the model. Even though the mean value realization is a good match to our experimental data, we cannot use this realization for all future analyses because the model was validated with uncertainty. In order to use the mean model realization, this one model would have to be validated to the experimental data, and as stated before, this is only one copy of the structure.

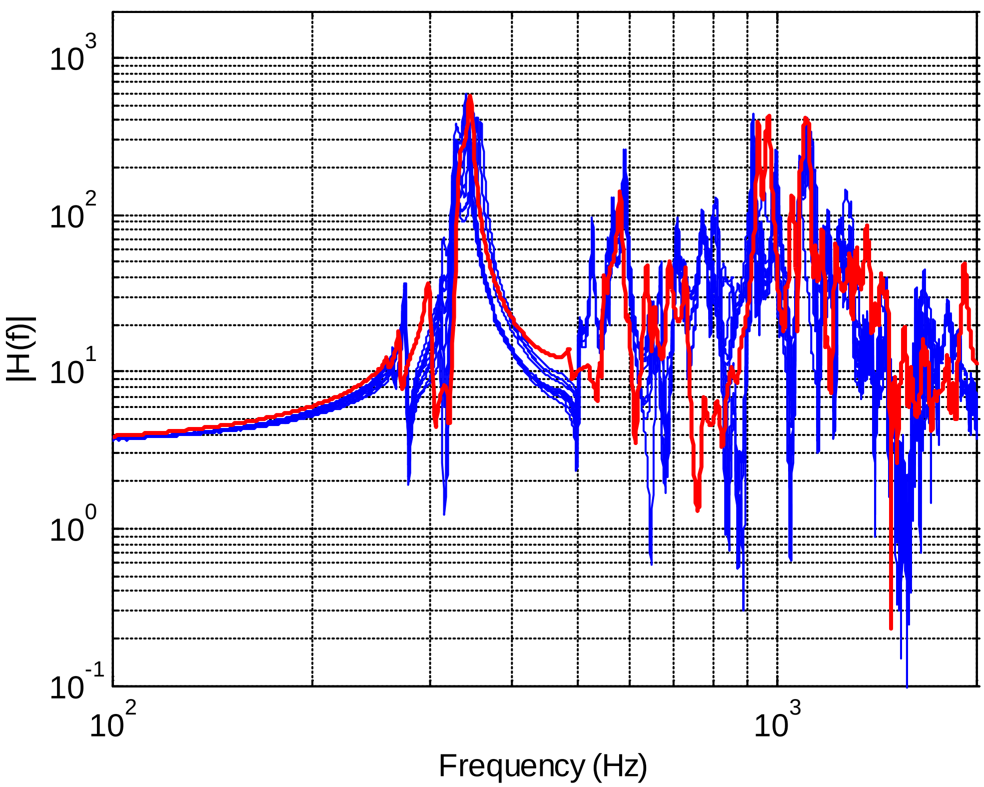

Figure 7: Validation Point 1, Calibrated Model Results (red) and Experimental Results (blue)

The final year of the project has placed the complex aerospace structure into the final assembly configuration for testing. As both the experimental and the analytical team move forward to the final assembly there are a multitude of joints, brackets, and payloads that must be instrumented to determine what interaction all the assemblies will have as a complete unit. Preliminary modes and descriptions as predicted by the analytical team will be presented in Table 2. As can be seen, a great deal of work needs to be performed in updating the final configuration in an effort to validate the finite element model. There are several modes that were not excited during the testing. Continuing efforts will be focused on updating the model and several additional tests are in order to perform the validation series on this structure.

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%
Small Payload & Bottom bracing Axial	609	550	-9.7%
2,1 Ovaling – Payloads Lateral In Phase	551	561	1.8%
Payloads and Small Payload 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%

Table 2: Preliminary Analysis Frequencies vs. Test Frequencies– Complete Assembly

DISCUSSION

The third year focused on combining all the individual assemblies into a final configuration that may be used as a single representation of a field of identically produced complex aerospace structures. The final configuration serves as a means to collect experimental data which may be used to verify or calibrate the analytical model that will be separate from a test that is used to acquire validation data to rate or verify the finite element model.

Data collected in the final year still resides as preliminary data that is to be used in the validation efforts. Validation metrics are still being considered and defined to ascertain the validity of the latest finite element model.

Validation of a complex aerospace structure is by no means a finished project. There are still many ideas or approaches that may be considered to perform additional verification and validation experiments. Additionally, the focus of this series of experiments is to consider the range from 100 to 1000 Hz. As the model and structure move forward in areas of study, other areas of interest may arise.

Some emphasis must be given to the testing circumstances in which only one test unit is available and is to serve as a representation of the entire field of complex aerospace structures. With this in mind, it is understood that there exists unit to unit variability as well as fabrication uncertainty.

CONCLUSION

Performing the instrumentation, data acquisition, testing, and analysis for both final configurations was by no means an easy task. The FRFs were collected and used as calibration data for the full system model. Modal parameters, including the frequencies, damping, and shapes were extracted and compared with the model predictions.

A great deal of work exists in order to correlate the model to the experimental data as seen in Table 2, and the next step would be to agree to the type of test that needs to be performed to serve as the final validation test, which may be used to ascertain the validity of the model.

There also exists the assumption of linearity that is used for modal analysis. While inputs are being driven at low levels this assumption is quite valid, but as inputs begin to approach higher levels the assumptions are no longer valid. Real environmental loads may drive nonlinearities that are not captured by this analysis. With this said, there still exists a large area of uncertainty which was not captured by this analysis.

REFERENCES

[1] Bhardwaj, Manoj; Pierson, Kendall; Reese, Garth; Walsh, Tim; Day, David; Alvin, Ken; Peery, James; Farhat, Charbel and Lesoinne, Michel, "Salinas: A Scalable Software for High-Performance Structural and Solid Mechanics Simulations", Supercomputing 2002. Baltimore, MD. Nov 2002.
[2] Carne, T.G. and Stasiunas, E.C., “Lessons Learned in Modal Testing-Part 3: Transient Excitation for Modal Testing, More than just Hammer Impacts,” Experimental Techniques, vol.30, No.3, May/June 2006, pp 69-79.
[3] Hensley, D.P., and Mayes, R.L., “Extending SMAC to Multiple References,” Proceedings of the 24th International Modal Analysis Conference, pp.220-230, February 2006.
[4] Rice, A. E., Carne, T. G., Kelton, D. W., "Model Validation of a Complex Aerospace Structure," Proceedings of IMAC XXVI Conference, SEM, Orlando FL, 2008
[5] Rice, A. E., Arviso, M., Paez, T. L., Carne, T. G., Hunter, P. S., "Uncertainty Quantification in Model Validation of a Complex Aerospace Structure," Proceedings of IMAC XXVII Conference, SEM, Orlando FL, 2009