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Experimental Validation of FE/BEM dynamic strain model under diffuse acoustic field loading

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Structural finite element (FE) models naturally output displacement or acceleration response data. However, they can also be used to compute stress, internal forces, and strain response. When coupled with a boundary element model (BEM) of the fluid surrounding the structure, a fully coupled analysis can be performed. Modeling a diffuse acoustic field in the BEM fluid provides an excitation like that found when the structure is placed in a reverberation chamber. Fully coupling the structural FE model to the acoustic BEM model provides a means to predict not only the acceleration response of the panel to diffuse field loading, but also the ability to predict the dynamic stress and strain response. This type of model has been available with current predictive tools, but experimental validation of the prediction of dynamic stress or strain is difficult to find. An aluminum panel was instrumented with accelerometers and strain gages and hung in a reverberation room and subjected to a diffuse acoustic field. This paper presents the comparison of the experimental and predicted results.

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1 INTRODUCTION

JPL has been using the VA-One Stress Module software[1] to predict stress induced by diffuse acoustics on flight hardware such reflector, solar panel, and other flight hardware of light weight, structurally stiff, and large surfaces. The analysis is based on an analysis method that couples structural finite element (FE) models with acoustic boundary element (FEM) models. Precise measurements of stress or strain values on such hardware are hard to come by. This is particularly true with flight hardware due to the fact that installation of strain gauges on such structures usually require re-surfacing of the hardware that would usually compromise structural integrity of the flight hardware. Therefore, no reliable comparison of test versus analysis results on stress induced on flight hardware due to diffuse acoustic excitations has been produced.

JPL undertook this project specifically to validate the prediction of stress response to diffuse acoustic field excitation on structures. The goal of this project is to demonstrate that structural FE models coupled to acoustic BEM models is a reliable approach to predict the dynamic stress response of structures that are subjected to diffuse acoustic excitations and the use of analysis software to help design flight hardware that is susceptible to diffuse acoustic excitation.

2 EXPERIMENTAL APPROACH

In this project, a simple Aluminum panel was subjected to a diffuse acoustic field. The panel was made of 0.25 inch thick Aluminum with dimensions of 41 inches by 37.5 inches. It was instrumented with 6 accelerometers and 8 strain gauges and was suspended vertically by bungee cords in the JPL Environmental Test Lab reverberant room and was excited by diffuse acoustic field of 151.4 dB overall SPL. The average sound pressure spectra measured at three room microphones is shown in Table 1. Normal accelerations and in plane principal strains were measured and compared with the predictions. The locations of the accelerometers and strain gauges are shown in Fig. 1. Pictures of the test configuration are shown in Figs 2-4.

Table 1 – Average sound pressure spectrum in the test chamber.

Frequency	SPL re 20 μPa
31.5	133.1
40	135.9
50	136.3
63	138.1
80	139.7
100	140.9
125	140.0
160	141.6
200	141.7
250	142.8
315	142.1
400	139.4
500	137.7
630	136.2
800	134.8
1000	133.0
Overall	151.4

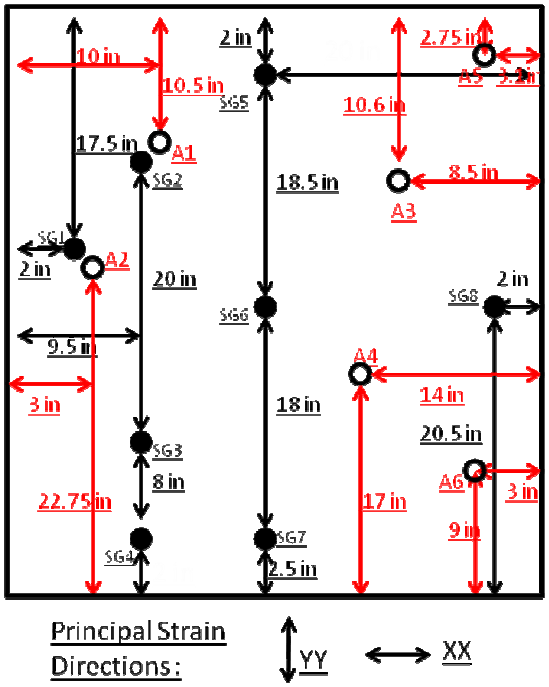

Fig. 1 – Locations of the accelerometers and strain gauges.

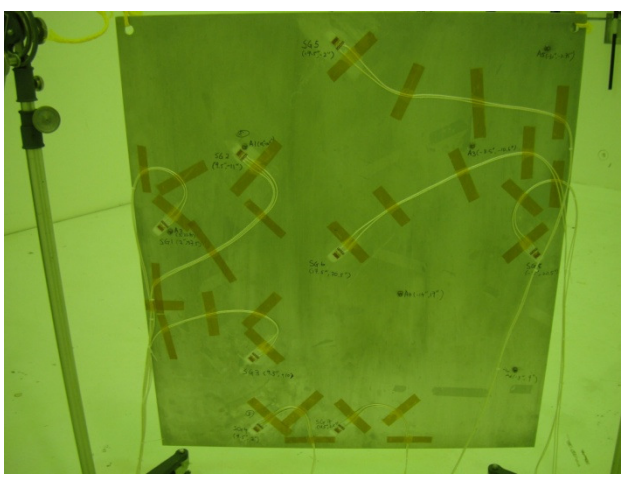

Fig. 2 – Panel with strain gauges.

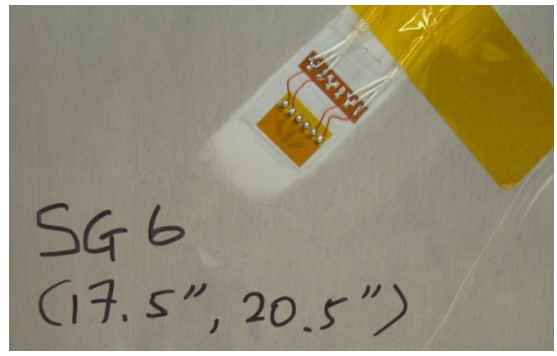

Fig. 3 -- Close up of strain gauge SG6.

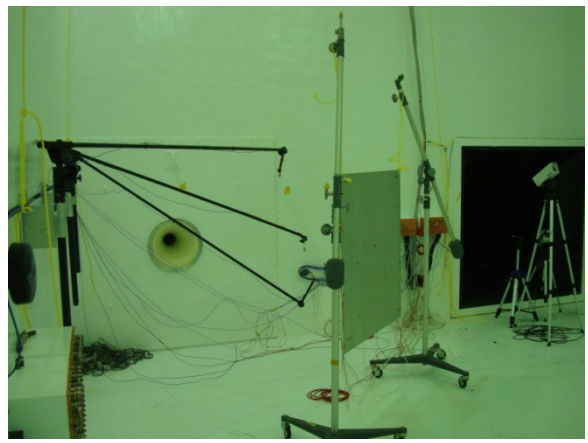

Fig. 4 – Panel hanging in the test chamber.

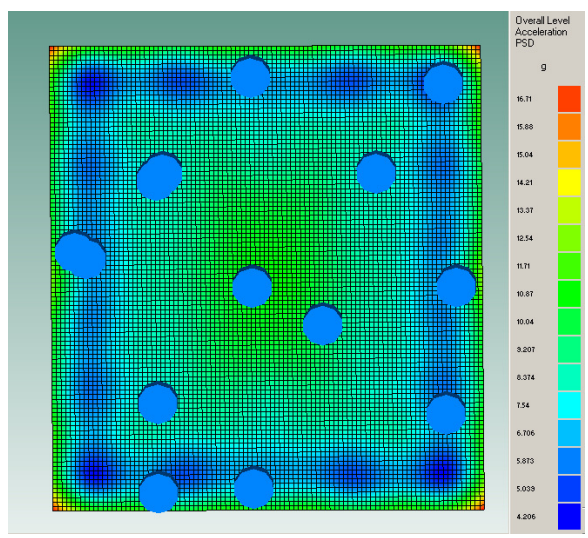

Fig. 5 – Prediction response of the plate to the acoustic field in g_{rms}. Blue circles represent transducer locations.

3 MODELING APPROACH

The model was developed with a combination of structural finite element analysis and acoustic boundary element analysis.

3.1 Structural Model

An FE model of the panel was meshed with 9880 4-node quadrilateral elements. The Aluminum was assumed to have a density of 2711 kg/m^3, a Young's modulus of 7.1e10 Pa and a Poisson's ratio of 0.31. The boundary conditions were assumed to be free-free. 58 panel modes were computed up to 800 Hz with NX Nastran. While the actual panel damping may vary with frequency, a damping loss factor of 1% was used for all frequencies in analysis. The results may be improved if more effort was spent to measure the actual panel damping.

The structural modes are typically computed in units of displacement. However, FE codes can compute the structural modes in units of stress, strain, or internal forces. Once the modal contribution factors are computed for the response, the mode shapes are then used to convert these modal contribution factors to displacement, stress, strain or internal forces. More information about the computation of dynamic stress type response can be found in Segalman[2] or Cotoni[3].

3.2 Acoustical Model

The acoustic boundary element mesh is made with the same geometry as the structural mesh, but with the elements coarsened so that the acoustic BEM mesh is smaller than the structural mesh. The acoustic mesh is typically coarsened because the acoustic wavelengths are usually significantly longer than the structural wavelengths over the frequency range where FE/BEM analysis is usually performed. In this case, the acoustic node spacing was about 7 times that of the structural model. There were only 234 nodes on the acoustic mesh surface, which was meshed with 3-node triangular elements. The fluid was assumed to be air with a density of 1.21 kg/m^3 and a speed of sound of 343 m/sec.

The diffuse field was modeled with 50 uncorrelated plane waves. These plane waves were distributed in direction with 36 degree steps in both the latitude and longitudinal directions. This method of modeling a diffuse field captures the idea that a diffuse field contains uncorrelated energy propagating in all directions. This method can be shown to exactly converge to the perfectly diffuse acoustic field as the number of plane waves approaches infinity. Fortunately, 50 planes waves are more than adequate to model a diffuse acoustic field to 500 Hz.

3.3 Coupled Response

The modal model of the structural and the BEM model of the acoustic field are coupled by a mapping algorithm that relates the degrees of freedom on the coarse BEM mesh to the fine FE mesh. A full two-way coupling of the structural acoustic problem is enforced (the structure impacts the fluid and the fluid impacts the structure). Thus the coupled structural and acoustic equations are solved and the structural modal response spectra are found. Once the modal responses are known, it is a post processing step[2,3] to find the response, whether the displacement, stress, strain or modal force is desired.

4 RESULTS

The predicted and measured data is shown in the following figures. One thing to note, where the strain is low, much of the measurement is at the noise floor. Strain gauges SG-1xx, SG-4yy, SG-5yy, SG-7yy and SG-8xx seem to be at the lower limits of their measurement range and thus these lower strain values have significant measurement error.

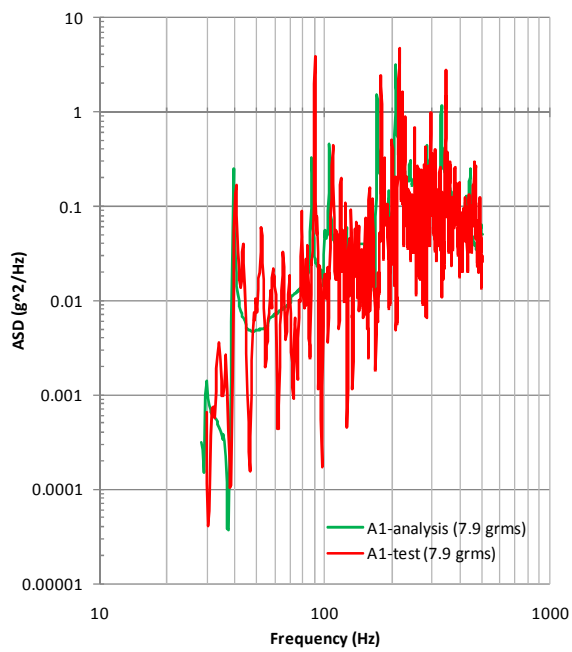

Fig. 6 – Test versus analysis acceleration spectra of accelerometer A3.

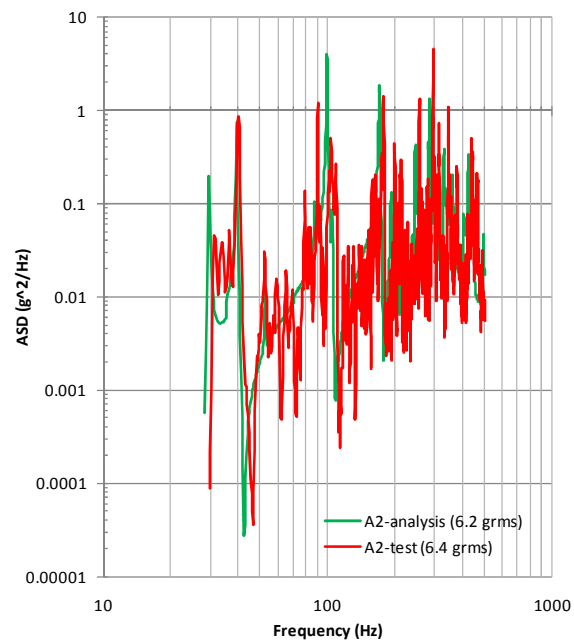

Fig. 7 -- Test versus analysis acceleration spectra of accelerometer A2.

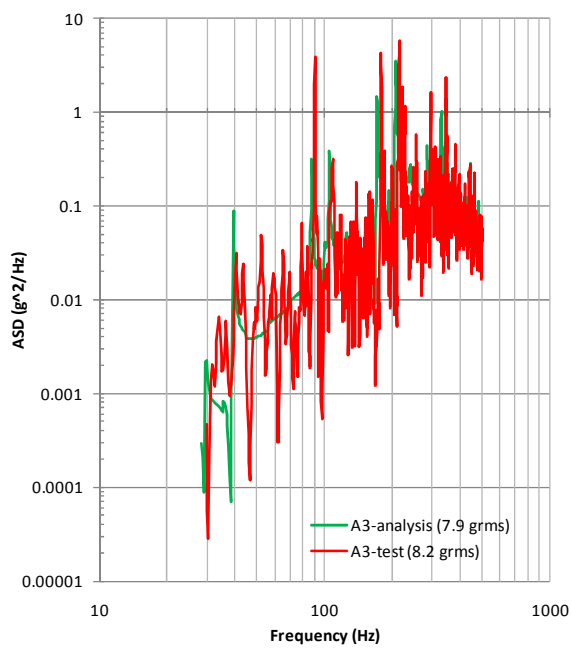

Fig. 8 -- Test versus analysis acceleration spectra of accelerometer A3.

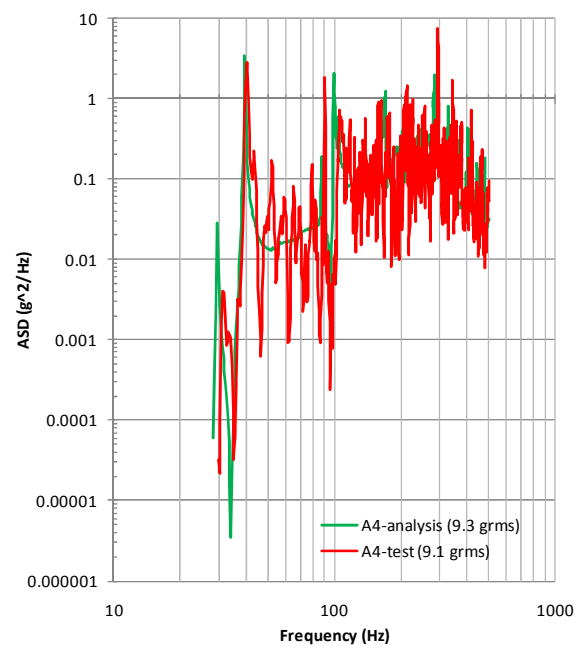

Fig. 9 – Test versus analysis acceleration spectra of accelerometer A4.

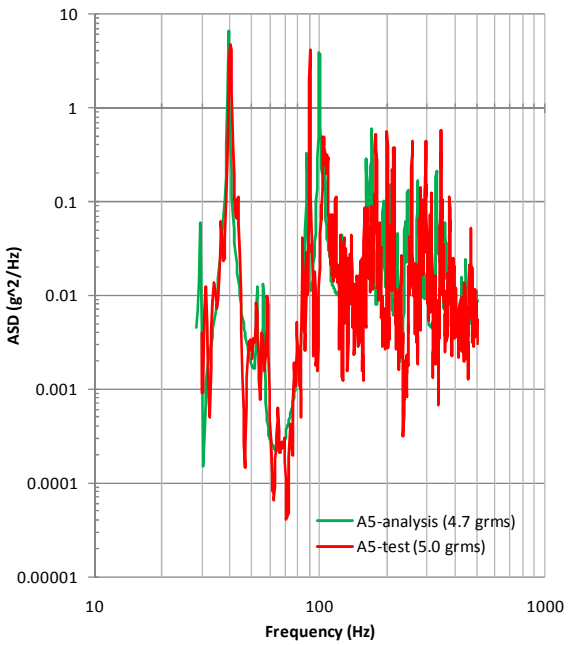

Fig. 10 -- Test versus analysis acceleration spectra of accelerometer A5.

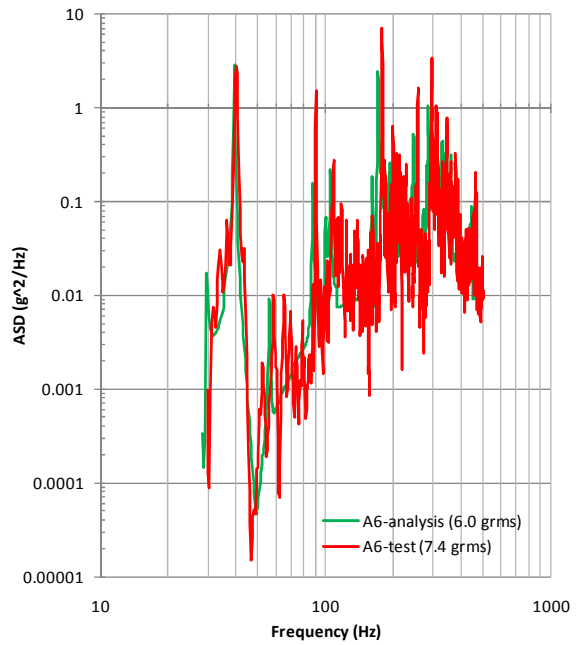

Fig. 11 -- Test versus analysis acceleration spectra of accelerometer A6.

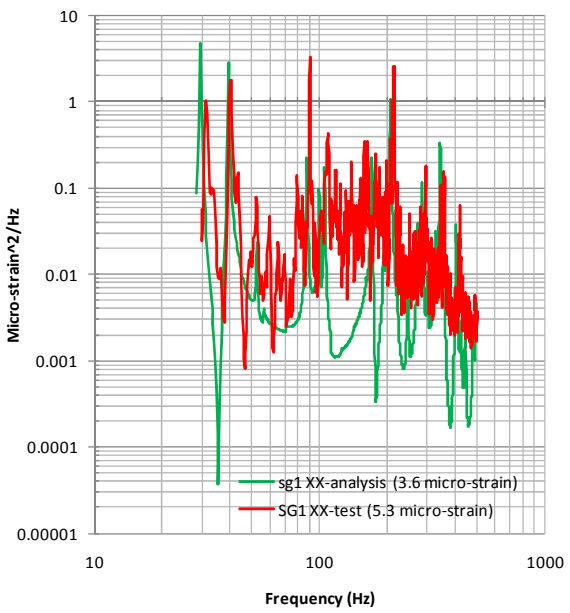

Fig. 12 – Test versus analysis strain spectral PSD at SG1 in the xx direction.

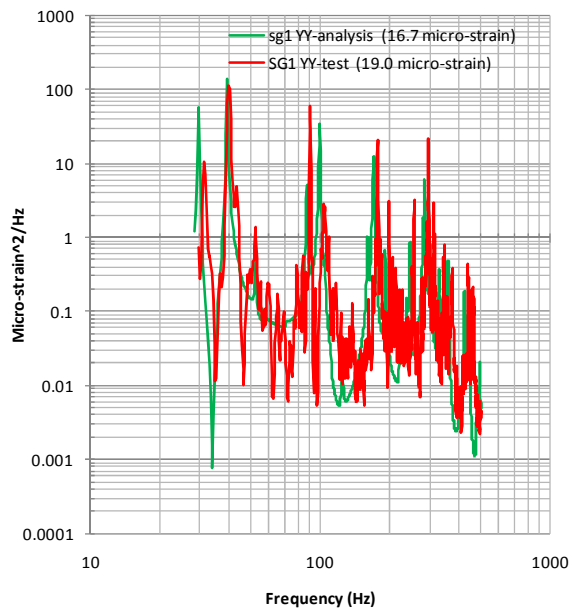

Fig. 13 -- Test versus analysis strain spectral PSD at SG1 in the yy direction.

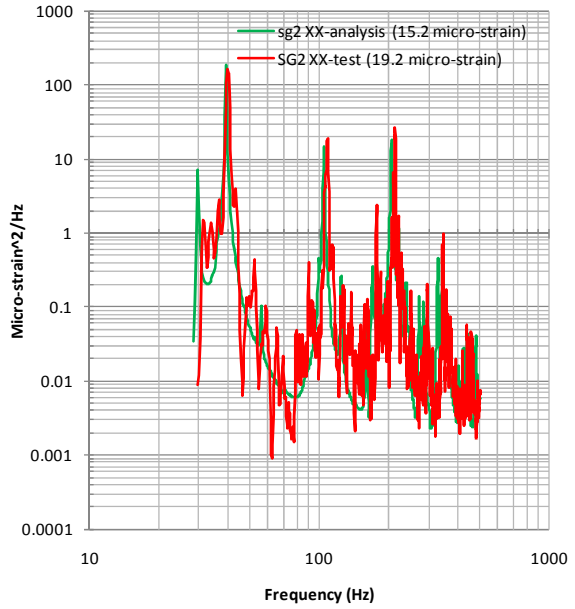

Fig. 14 -- Test versus analysis strain spectral PSD at SG2 in the xx direction.

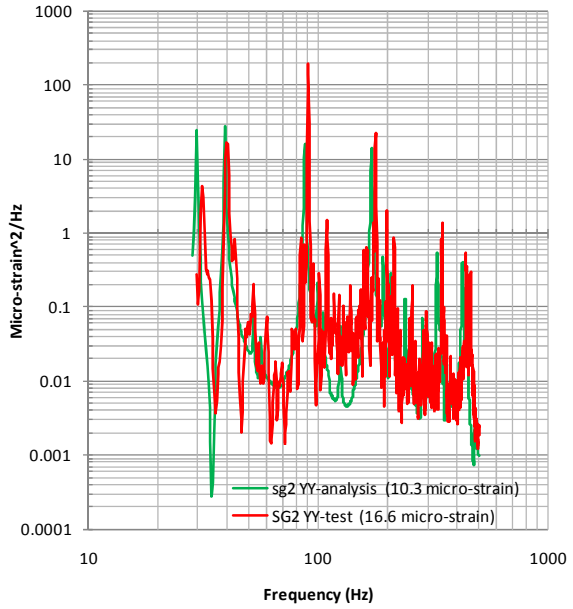

Fig. 15 -- Test versus analysis strain spectral PSD at SG2 in the yy direction.

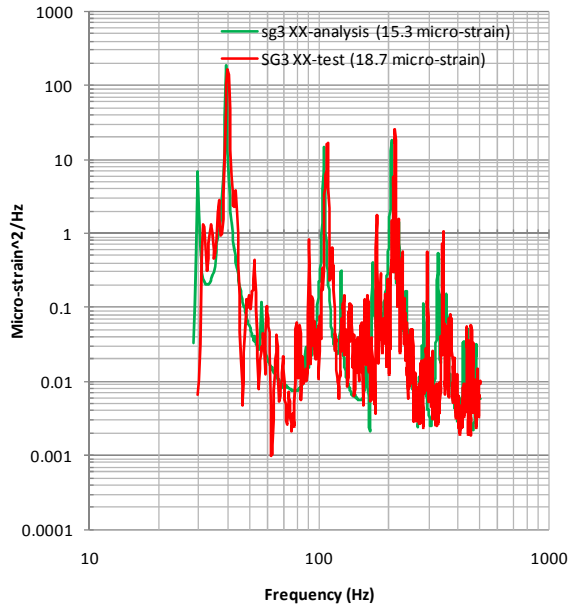

Fig. 16 -- Test versus analysis strain spectral PSD at SG3 in the xx direction.

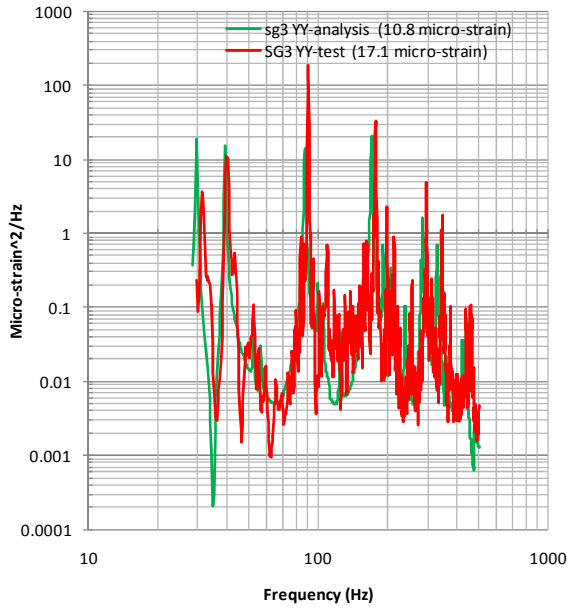

Fig. 17 -- Test versus analysis strain spectral PSD at SG3 in the yy direction.

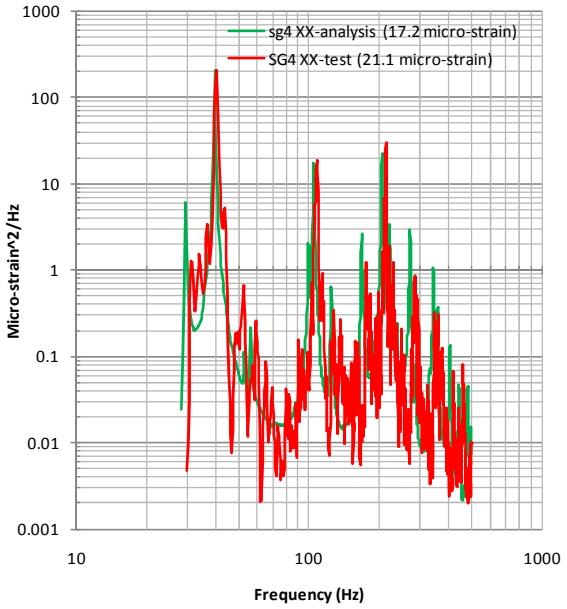

Fig. 18 -- Test versus analysis strain spectral PSD at SG4 in the xx direction.

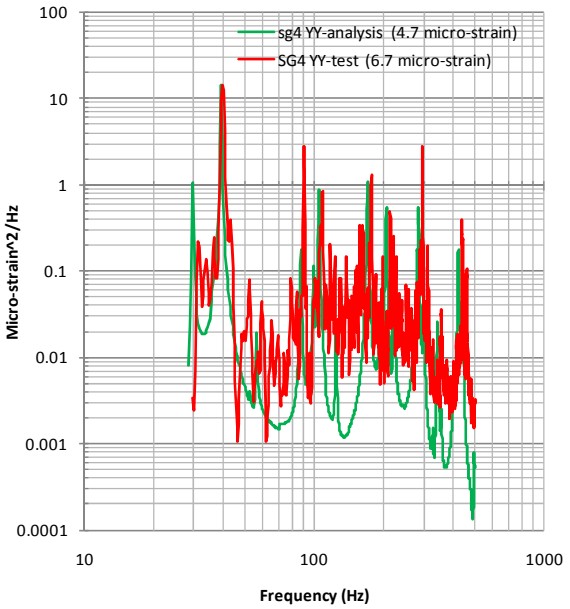

Fig. 19 -- Test versus analysis strain spectral PSD at SG4 in the yy direction.

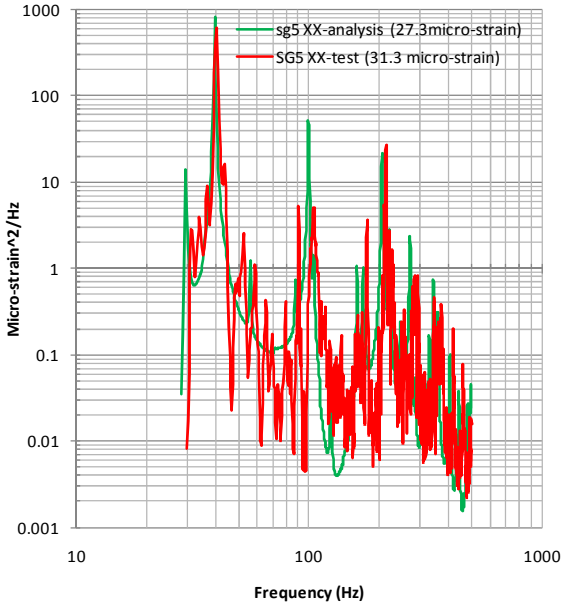

Fig. 20 -- Test versus analysis strain spectral PSD at SG5 in the xx direction.

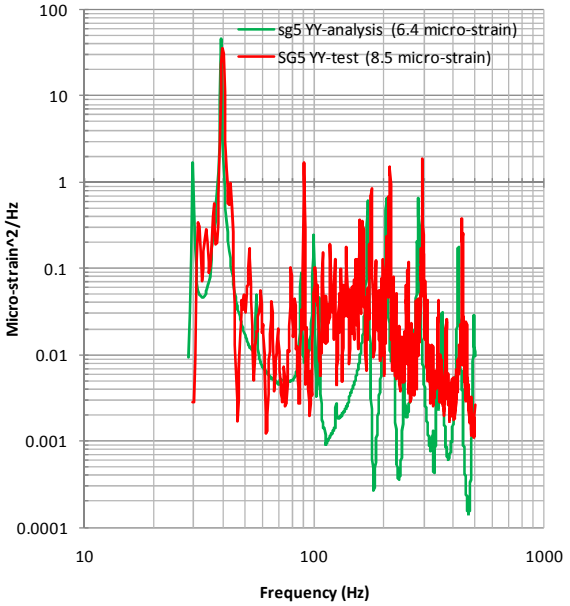

Fig. 21 -- Test versus analysis strain spectral PSD at SG5 in the yy direction.

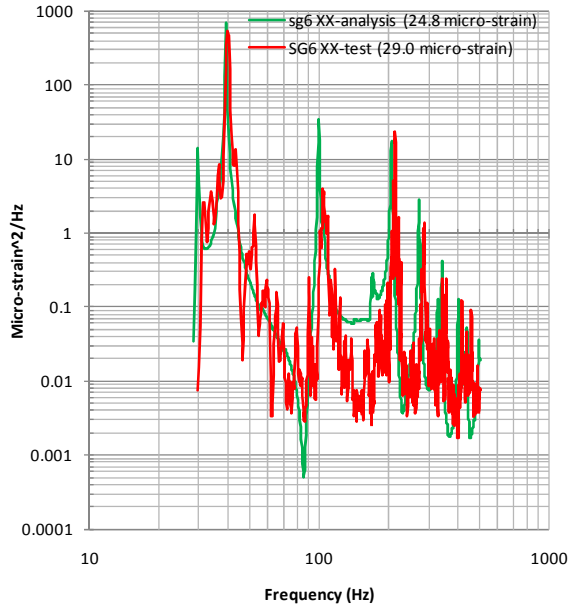

Fig. 22 -- Test versus analysis strain spectral PSD at SG6 in the xx direction.

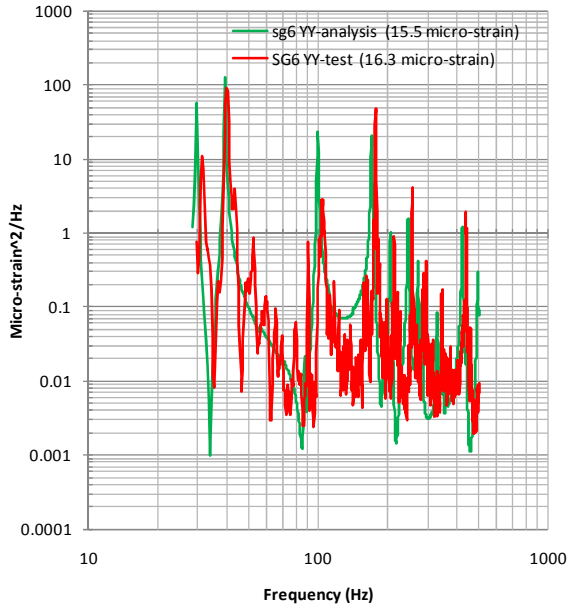

Fig. 23 -- Test versus analysis strain spectral PSD at SG6 in the yy direction.

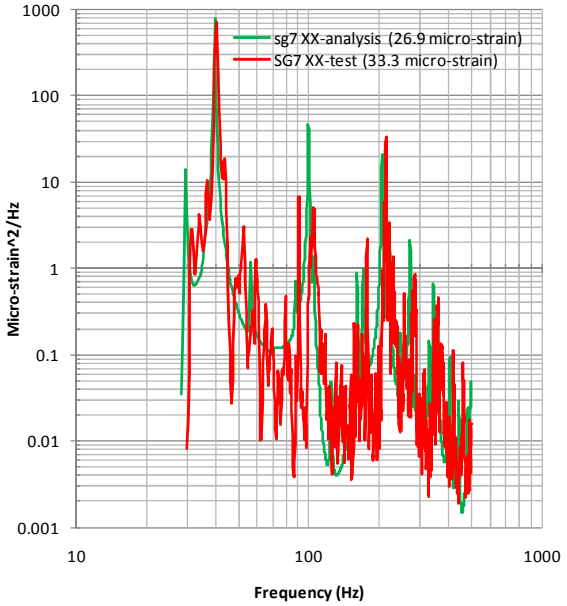

Fig. 24 -- Test versus analysis strain spectral PSD at SG7 in the xx direction.

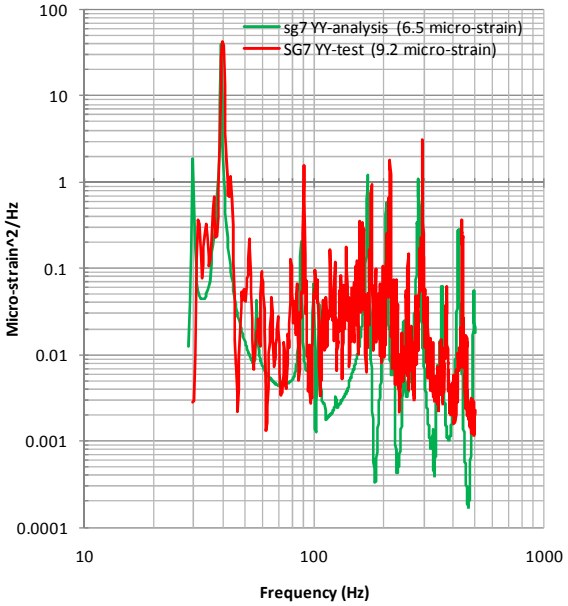

Fig. 25 -- Test versus analysis strain spectral PSD at SG7 in the yy direction.

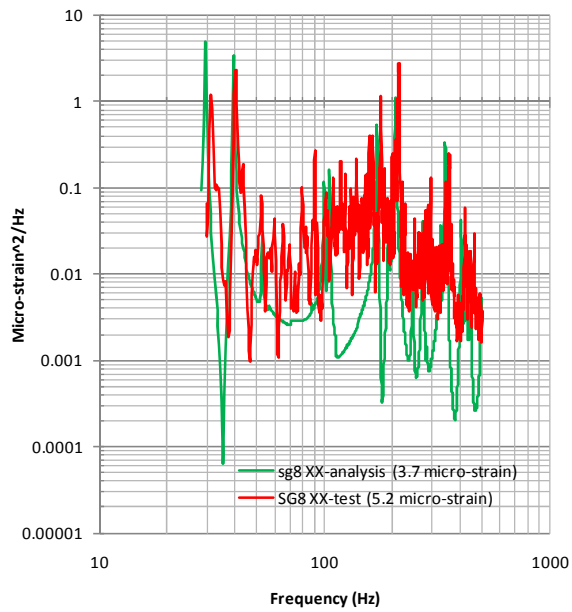

Fig. 26 -- Test versus analysis strain spectral PSD at SG8 in the xx direction.

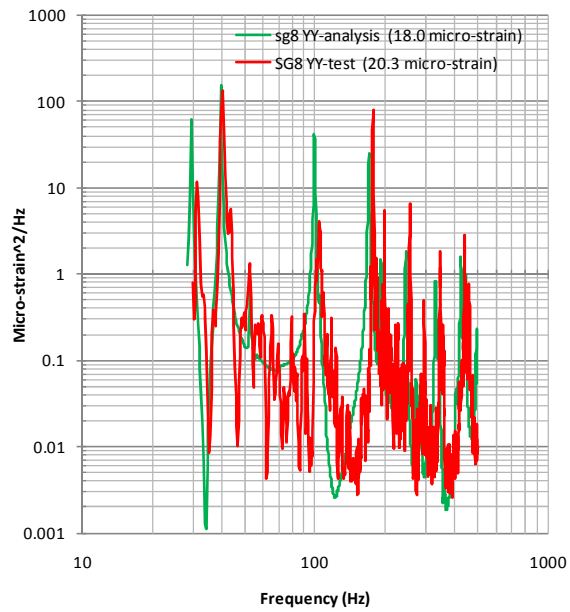

Fig. 27 -- Test versus analysis strain spectral PSD at SG8 in the yy direction.

5 CONCLUSIONS

Excellent test versus analysis comparisons at **all** accelerometer and strain gauge locations were obtained. This is particularly true when the strain data was at higher levels and not obscured in the noise floor. These results support the use of a FE/BEM modeling approach by validating both the ability to model the diffuse sound field and the ability to predict secondary dynamic results quantities such as strain, stress or internal forces. The results could probably have been improved with better knowledge of the panel damping. It is also likely that the acoustic field was not perfectly diffuse at frequencies below 60-80 Hz in the test chamber. A more detailed analysis of the room acoustics could investigate room dependant effects on the dynamic response.

These results provide tangible evidence that the physics of the dynamic response of a structure driven by a diffuse acoustic field can be computed. In addition, these results can be used to design structures by providing reliable dynamic stress, strain and internal force predictions.

6 ACKNOWLEDGEMENTS

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3. Cotoni, V., *VA One Stress Recovery Module: User's Guide, Theory & QA*, ESI Group, San Diego (2009).