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Acoustoelasticity Testing: Changing Boundary Conditions and Damping

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Acoustoelasticity Testing: Decoupling with Damping and Boundary Condition Changes

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Abstract

A series of modal tests were performed on an acoustoelastic system to explore how changes to the air and structural components affect the acoustoelastic coupling. This work is a continuation of previous experimental and analytical efforts. Here, the test method and perturbations were much more controlled than in previous tests, resulting in more refined data. Outputs of interest here are the coupled system modes as well as the resulting frequency response for various perturbations of the coupled system. Perturbations explored in this work include mass loading the structure, changing the air damping, and changing the air boundary conditions. Results of these tests indicate that simply adding damping to the air component, using foam or other absorptive material, is not sufficient to fully decouple the system. Rather, it is preferred to employ a change to the air boundary conditions, in the form of volume inclusions or scatterers, to prevent formation of the acoustic coupled mode.

TABLE OF CONTENTS

FIGURES

TABLES

1. TEST OBJECTIVES & METHODOLOGY

This section describes the objectives of this series of tests and the general test methodology used.

1.1. Test Objectives

Objectives of this testing is to re-visit the acoustoelastically-coupled hardware, known as the Schultz Acoustoelastic Demonstrator (SAD), to further explore how to decrease or eliminate the undesired effects of acoustoelastic coupling. Acoustoelastic coupling occurs when the modes of a hollow structure are similar to modes of the interior fluid volume in terms of both frequency and shape [1, 2]. This coupling introduces additional modes which appear as repeated modes when measured on the structure and can be seen in the structural frequency response function (FRF). This phenomena is qualitatively similar to the tuned vibration absorber wherein the coupling introduces a second peak and a shift in the original peak [3].

The purpose of this work is to explore how to decouple hollow structures such that the resulting modal test data is of the in vacuo structure. As modal tests are typically done to correlate or calibrate to finite element models (FEM), it is important for the test configuration to match the model. Generally, FEMs do not include internal fluid volumes, thus it is best to remove any acoustoelastic coupling from the test system to provide structural responses that most closely match the form of the FEM.

1.2. Methodology

The SAD structure is tested using typical modal test practice in terms of the instrumentation, excitation, and test boundary conditions. First, a structural modification is made to "tune in" the acoustoelastic coupling of a chosen mode. This results in very significant acoustoelastic coupling (i.e. additional or split peaks in the FRFs). Next, several different decoupling strategies are employed to various degrees. Measurements are made for each perturbation of the system and compared with baseline measurements. For ease, these comparisons are made using just one drive point FRF; full mode fits were not performed for each data set. Note that using a mode parameter extraction routine that relies on modal filtering to estimate the modal parameters will not work robustly for this type of coupled system due to the repeated structural mode shapes for the acoustoelastically-coupled modes. A simple method was used to identify the mode shape near a peak in the FRF: plotting the imaginary part of the FRF. This is an approximation of the mode shape and works well here because the modes are well-spaced.

2. TEST ARTICLE AND INSTRUMENTATION

2.1. Test Article

The SAD test article is an aluminum shell with an 8 inch outer diameter (OD), 7 inch inner diameter (ID), and 24 inch length, shown in Figure 1. It has ½ inch thick end plates bolted to the shell. One of these end plates has a two inch hole which allows for access to the cavity while testing.

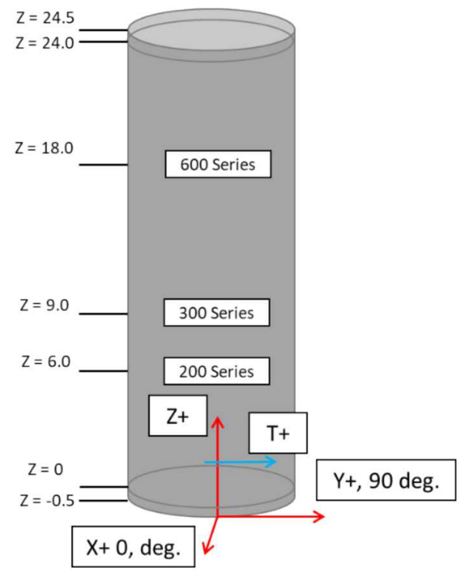

Figure 1: Left: SAD hardware, instrumented with uniaxial accelerometers. Right: Diagram of axes and gage stations.

2.2. Instrumentation

18 PCB 352A71 uniaxial accelerometers were glued to the shell with superglue. Gage locations are shown in the table and figure below. Two rings consist of six gages each (200 and 600 series) and one ring has four gages (300 series). There are also accelerometers at the two drive point locations, nodes 901 and 904. At these drive point locations, accelerometers are placed as near as possible to shaker drive pads. Load cells are mounted to these drive pads, providing measured input forces. Two seven pound modal shakers are attached and driven simultaneously, resulting in a multiple-input/multiple-output (MIMO) test.

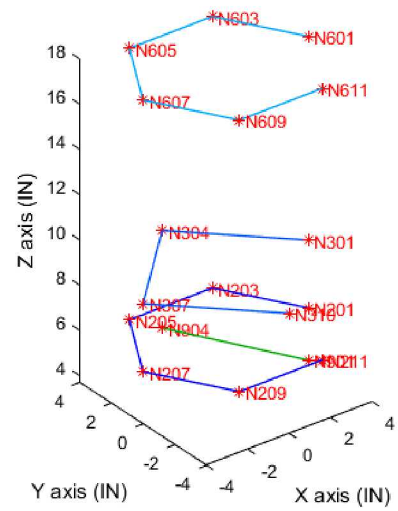

Figure 2: Accelerometer locations, indicated by the gage node IDs in 3-D space

Table 1: Accelerometer locations

Node ID	X [in]	Y [in]	Z [in]	Theta [deg.]
201	4.0000	0.0000	6.0000	0
203	2.0000	3.4641	6.0000	60
205	-2.0000	3.4641	6.0000	120
207	-4.0000	0.0000	6.0000	180
209	-2.0000	-3.4641	6.0000	240
211	2.0000	-3.4641	6.0000	300
301	4.0000	0.0000	9.0000	0
304	0.0000	4.0000	9.0000	90
307	-4.0000	0.0000	9.0000	180
310	0.0000	-4.0000	9.0000	270
601	4.0000	0.0000	18.0000	0
603	2.0000	3.4641	18.0000	60
605	-2.0000	3.4641	18.0000	120
607	-4.0000	0.0000	18.0000	180
609	-2.0000	-3.4641	18.0000	240
611	2.0000	-3.4641	18.0000	300
901	4.0000	0.0000	3.6875	0
904	0.0000	4.0000	4.6875	90
901	4.0000	0.0000	3.6875	0
904	0.0000	4.0000	4.6875	90

3. TEST SETUP

The general test setup is shown in Figure 3. For ease of setup and repeatability, the structure was set on a soft foam ring which contacts just the OD of the shell end cap. The two shakers were located at 0 and 90 degrees and connected to the structure via piano wire stingers between the shaker heads and the load cells mounted to the drive pads cemented to the structure. For inputs to the seven pound shakers, burst random signals were used. Each burst was one second long, with 50% duration, 50% off time and 30 averages were taken for each test. The voltage level of the signals was set as 0.10 volts in IDEAS and the shaker gain was set to level 1. The bandwidth of the excitation was 60 to 3200 Hz. Each time the end cap was removed to add or remove objects from the internal cavity, the end cap screws were torqued to the same value, 30 inch-pounds.

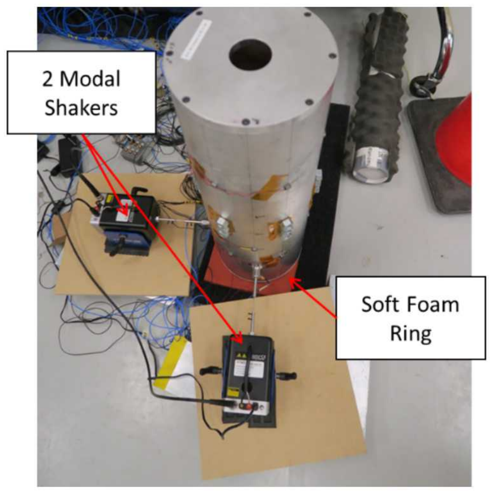

Figure 3: MIMO modal shaker test setup

4. TESTS AND RESULTS

This section presents each test configuration (perturbation) and the effects on the drive point FRFs to show how each change affects the coupling.

4.1. Structural Change: Added Mass

The first change was to tune in the structural 3,0 ovaling mode to more closely match the acoustic 3,0 mode. For this coupled pair, the structural mode was higher frequency than the acoustic mode, so adding mass to the structure can shift the structural mode down into closer frequency proximity to the acoustic mode. Mass was added by gluing large nuts at the anti-nodes of the structural 3,0 mode, at six locations around the middle of shell.

Different from the other tests shown in this report, this test was run with a hammer input and not MIMO shaker inputs. After this test was performed to tune-in the structure mode, shakers were added for subsequent tests to get more control and consistency. This test was first run with the shell empty however it became difficult to determine which peak was the structural mode and which peak was the acoustic mode. Foam was added to the cavity to add air damping and reduce the acoustic mode to make the structural mode easier to identify and track. The acoustic mode frequency is around 2600 Hz and the structural mode is around 2700 Hz. Masses were added incrementally and the frequency of the structural mode was tracked based on the peak in the FRF and peak in the complex mode indicator function (CMIF). It was found that using three nuts at each of the six locations shifted the structural mode by the correct amount, very near 2600 Hz. Note that the 3,0 mode is shifted more dramatically than the other modes; this is because the weights were specifically added to the anti-nodes of the 3,0 mode.

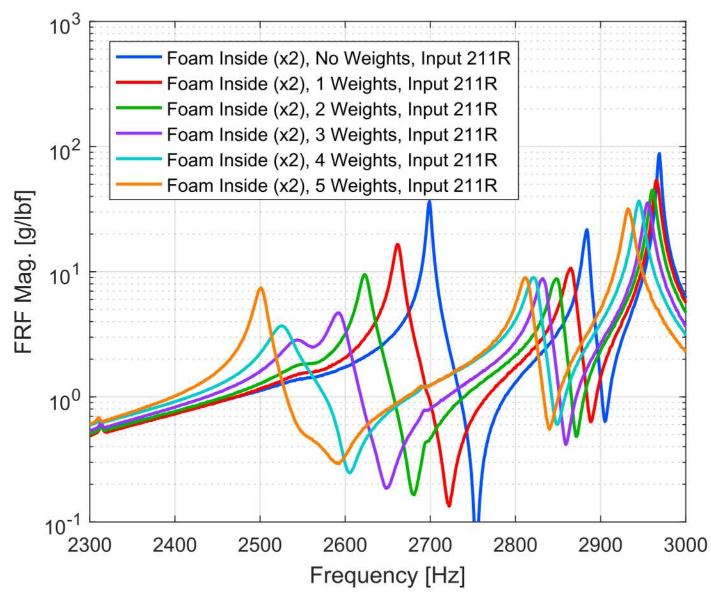

Figure 4: Drive point FRF with masses added to the anti-nodes of the 3,0 ovaling mode of the shell

4.2. Acoustic Change: Added Air Damping

Increasing the damping of the air component has been the method employed to-date to decouple these acoustoelastic systems [4] [3]. This is in part because adding absorptive material (e.g. open-cell foam) to the air cavity causes the coupled acoustic-dominant peak to disappear, leaving just one, structure-dominant peak. This is also because it is easy to implement; just put some foam in the cavity and run the test. However, consistent with previous tests, it is observed here that the peak amplitude and frequency of the FRF will change with the amount of foam added. Additionally, analytical modeling suggests that increasing the air component damping changes the measured response because the air and structure components remain coupled.

In this test, air damping was implemented by hanging open-cell, absorptive foam blocks from strings in the cavity, shown in Figure 5. These blocks were spatially distributed as evenly as possible. Up to 36 foam blocks were added, and this amount essentially filled the entire cavity. Hanging by strings allowed the foam to not contact the shell walls in any significant way, minimizing the effects of added mass or stiffness on the shell.

When just a few blocks of foam are added to the cavity, there is a clear trend where the two peaks in FRF amplitude reduce, Figure 6. As more foam is added, the two peaks blend into just one observable peak. The amplitude and also the frequency of that remaining peak continues to change with additional air damping, Figure 7.

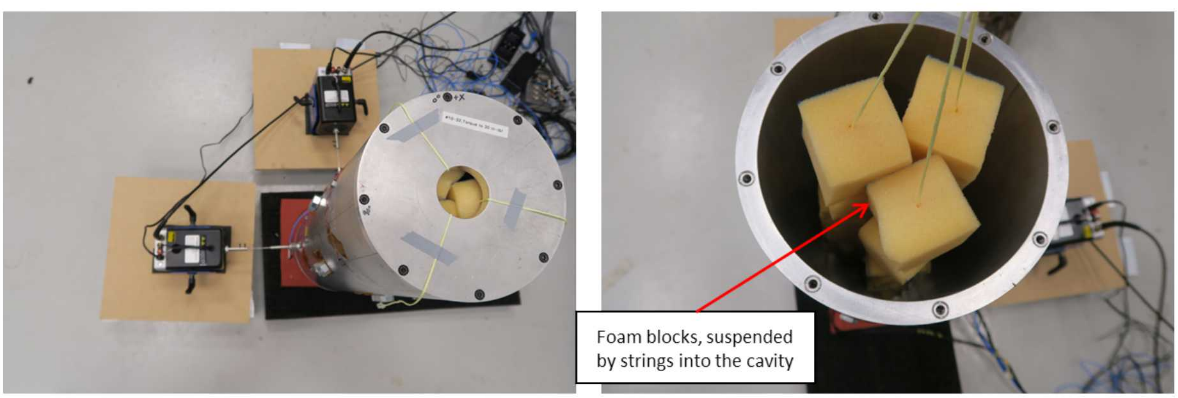

Figure 5: Left: Test setup with strings of absorptive foam blocks suspended in the cavity by strings hung through the opening in the Z+ end cap. Right: Detail of the foam blocks on the strings.

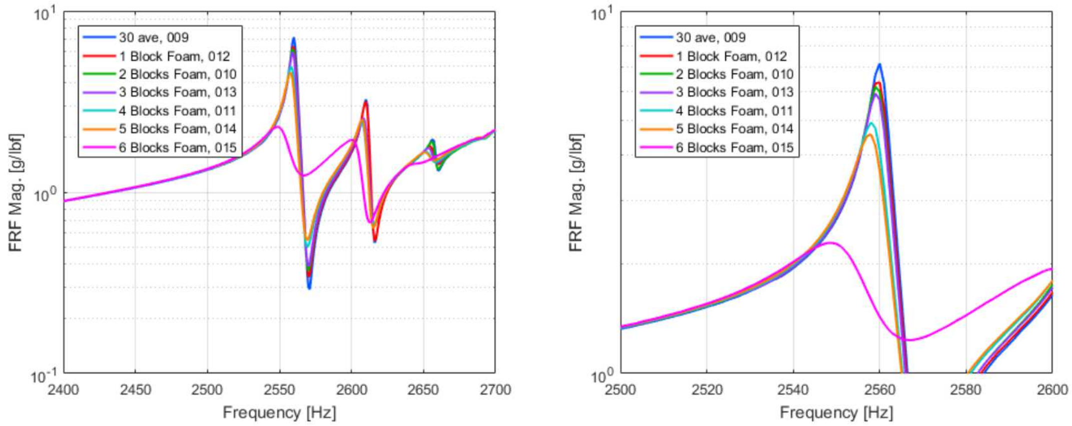

Figure 6: Left: Changes in the drive point FRF when adding small amounts of absorptive foam to add damping to the air component. Right: Zoomed in at the main peak.

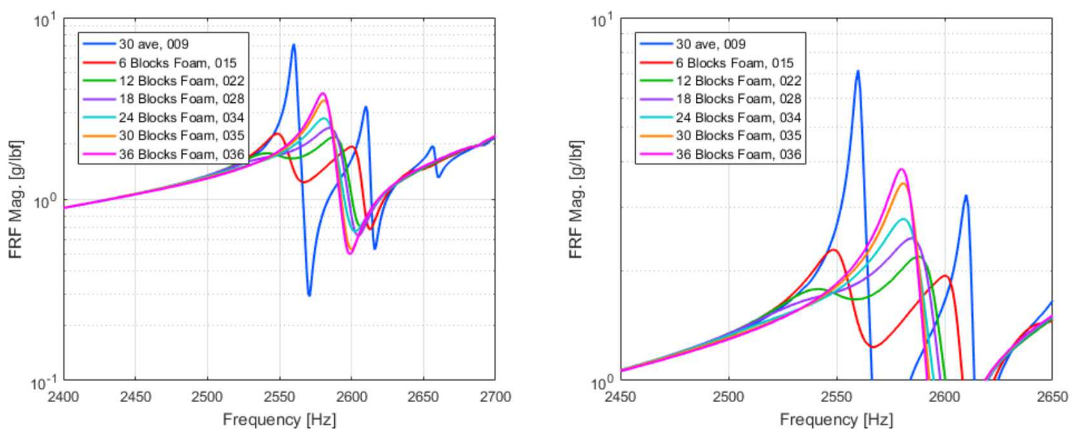

Figure 7: Left: Changes in the drive point FRF when adding large amounts of absorptive foam to add damping to the air component. Right: Zoomed in at the main peak.

4.3. Acoustic Change: Boundary Condition Change with Volume Inclusion

Here, the acoustic component is modified by changing the boundary conditions by inserting a 3 inch diameter PVC pipe, Figure 8. The pipe has end caps and is stuffed with foam, meaning it should act to the acoustic cavity like a solid cylindrical chunk inside the cavity. This turns the air cavity from a cylinder into an annulus. Interestingly, the ovaling modes of a fluid annulus are lower than the modes of a corresponding fluid cylinder. Thus, by changing the cavity into an annulus, the acoustic mode shape is largely maintained but the frequency will be shifted down.

Test results largely agree with the expectation, showing evidence of a coupled peak near 2450 Hz and a dramatic change in the original coupled, split peaks, Figure 9. A single, large peak remains at what is the structural mode frequency. This remaining peak is higher in amplitude and has apparently lower damping than the remaining peak for the absorptive foam case.

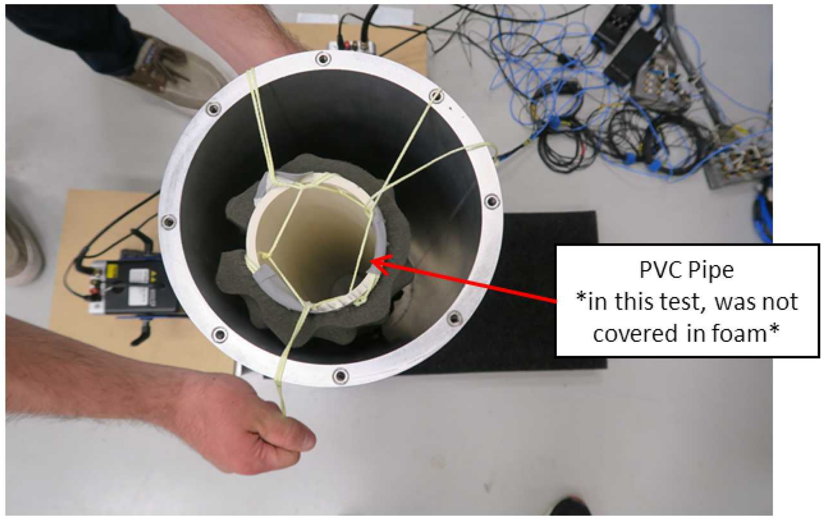

Figure 8: PVC pipe in the cavity, with the end cap removed for clarity. In the actual test, the PVC was filled and capped, and suspended from the Z+ end cap.

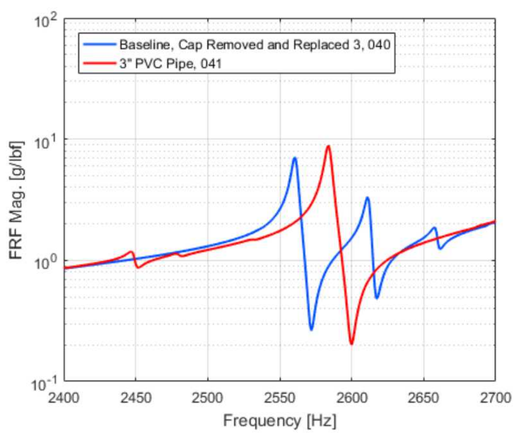

Figure 9: Change in the FRF when placing 3” filled PVC pipe in the cavity

4.4. Acoustic Change: Scattering to Remove the 3,0 Mode Shape

With the changes to air damping and the change from a cylinder to an annulus, we see that the acoustic mode is still present in the 3,0 form, just shifted in frequency. This shift in frequency reduces the dramatic split peak but still introduces an additional, albeit small, peak in the structural FRF.

Therefore, it may be better to change the acoustic component in ways which prohibit the undesirable mode, i.e. alter the air boundary conditions such that the 3,0 mode will not exist. This could be accomplished by adding rigid partitions or large, irregular solid chunks. A simple first attempt was to simply add many irregularly-placed scattering panels. This was easily implemented with folded cardboard, cardstock or paper, as shown in Figure 10.

An obvious question is how could something light and flimsy like paper be effective? The answer is impedance. At low frequency, yes the paper would likely have no effect. However, at high enough frequency, the paper has sufficient inertia to present non-trivial impedance to the air. This impedance mismatch causes reflections which, in turn, alter the boundary conditions of the acoustic cavity and reduce the 3,0 mode. This is a fundamentally different change from adding damping.

Adding the cardboard scatterers is effective in removing the additional coupled peaks and results in a remaining single peak which is sharper and higher in amplitude than was observed with the foam tests, Figure 11. Scatterers were also added in different amounts, ¼, ½ and full, and these each yielded different results. This indicates that the simple addition of some scattering panel in the cavity is not sufficient. Rather, many are needed and/or they need to be spatially distributed.

Different types of scatterers were also implemented. In addition to cardboard, folded card stock and crumpled copy paper were used to disrupt the acoustic boundary conditions. Results of these tests are shown in Figure 12. Card stock and paper behave similarly to cardboard, with some slight change in the peak amplitudes. Addition of the scatterers results in a single peak of similar amplitude to the peak obtained with the PVC inclusion, which was sharper and higher amplitude than the peak obtained with absorptive foam.

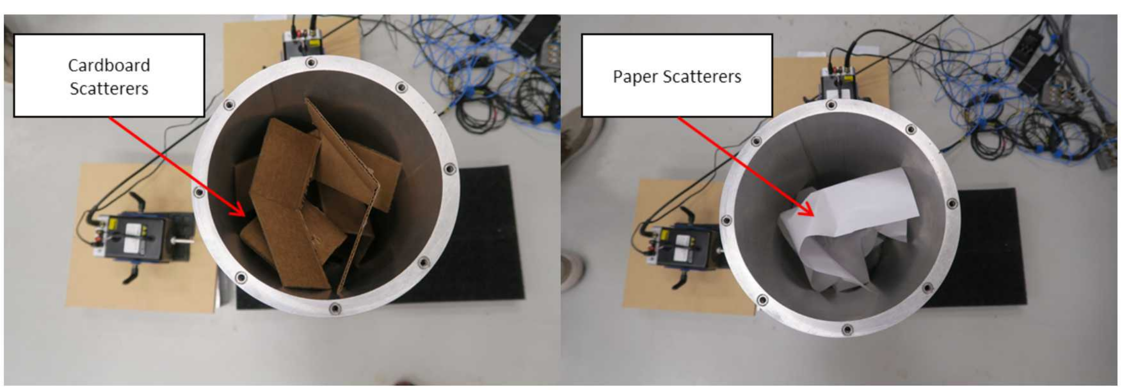

Figure 10: Left: Cavity full of folded cardboard scatterers. Right: Cavity full of crumpled paper scatterers.

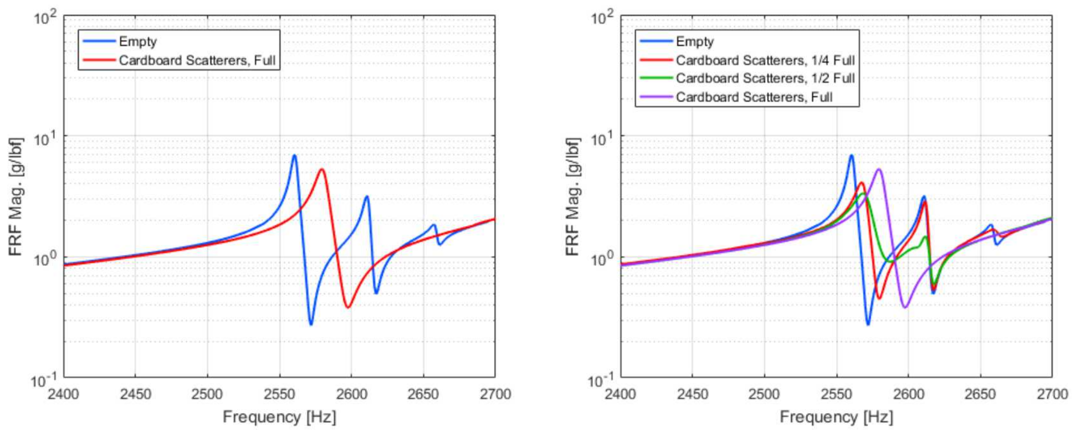

Figure 11: Left: Change in the FRF when adding folded cardboard scatterers in the cavity. Right: Comparison of the effect of the amount of cardboard scatterers.

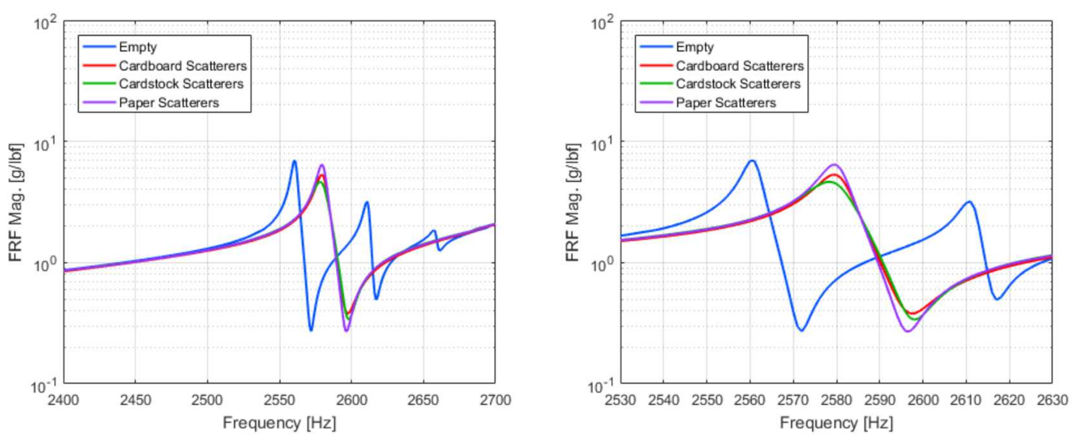

Figure 12: Left: Comparison of the different scatterers. Right: Zoomed.

In addition to cardboard, card stock and paper for scattering, other thin, flexible materials were considered. A heavy plastic bag was also tested, shown in Figure 13. Here, there is less flexibility than with the cardboard or even paper scatterers but the bag has similar mass per unit area and therefore similar mass-law acoustical impedance. The plastic bag was crumpled into the cavity, providing many irregular surfaces for scattering the internal waves.

Interestingly, both paper and plastic were able to decouple the modes, and the resulting FRFs are very similar, Figure 14. Thus it may be concluded that the decoupling mechanism is similar for both paper and plastic (mass-law impedance). A heavier plastic film may provide even better performance, particularly at lower frequencies.

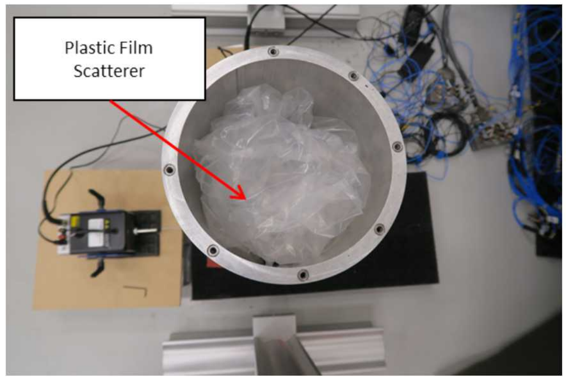

Figure 13: Cavity filled with crumpled plastic bag.

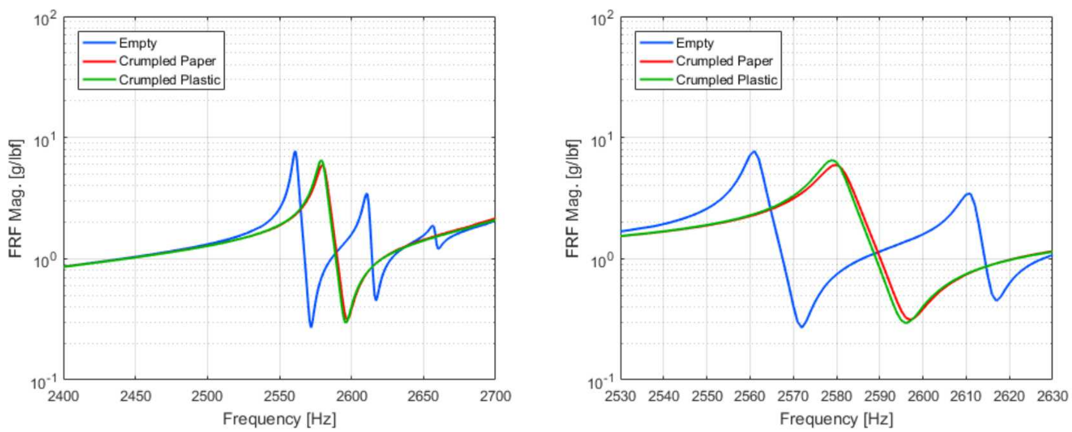

Figure 14: Left: FRFs for the plastic vs. paper. Right: Zoomed.

4.5. Acoustic Change: Rigid Foam for Scattering and Inclusions

Rigid foam was cut in irregularly-shaped chunks and suspended in the cavity. Figure 15 shows the cavity full of these chunks. It can be seen the chunks fill most of the volume and should cause different response as compared to the PVC pipe as the irregular shape should disrupt the pure 3,0 shape of the fluid annulus. These foam chunks present a change to the acoustic boundary condition, causing scattering of the internal waves. The foam chunks also take up volume. This foam is closed-cell but is still somewhat compliant which indicates it could be slightly acoustically absorptive. Ideally, it would be perfectly rigid but such a foam was not on hand.

A comparison of the test results with these foam chunks against the PVC and absorptive foam is shown in Figure 16. Interestingly, the rigid foam response is between the PVC and the absorptive foam.

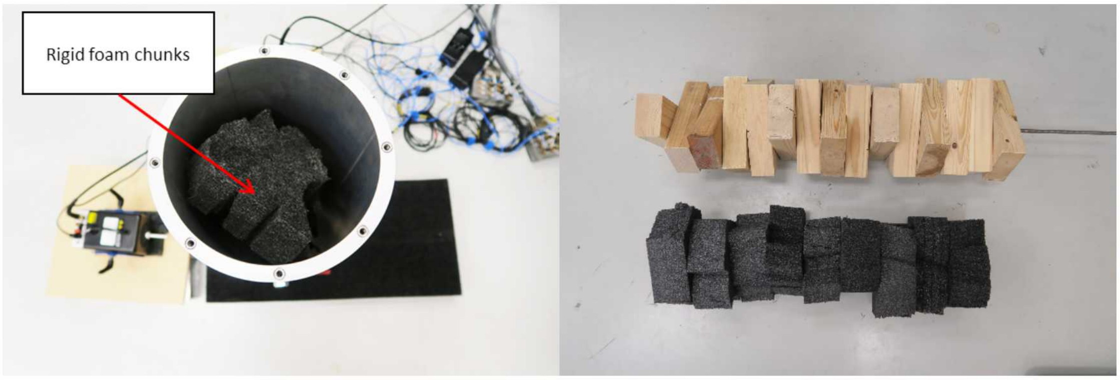

Figure 15: Left: Cavity filled with rigid foam scatterers. In the test, these were suspended from a metal rod and hung in the cavity so as to not contact the shell walls. Right: Wooden blocks (top) and rigid foam (bottom).

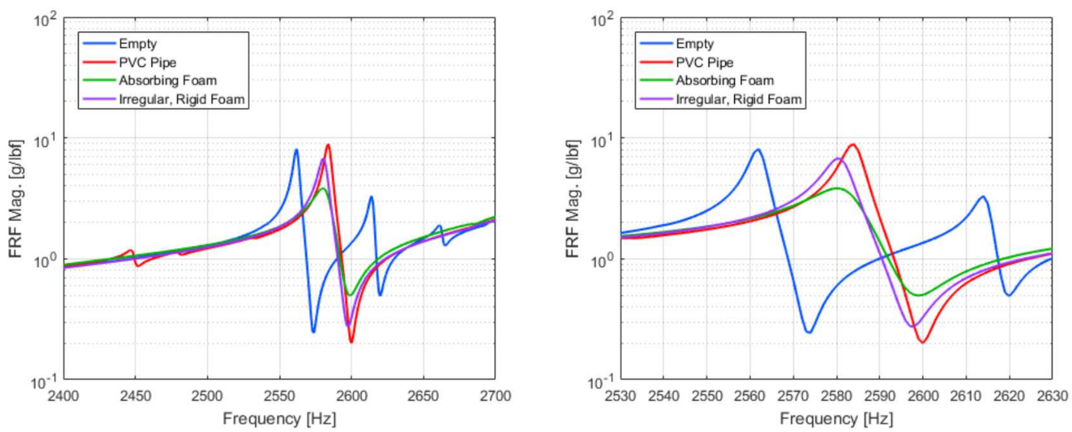

Figure 16: Left: Comparison of rigid foam against PVC and absorbing foam. Right: Zoomed.

4.6. Acoustic Change: Wood Blocks for Scattering & Volume Change

Similar to the rigid foam, wood blocks provide a change in the volume and geometry of the internal cavity. Using 15 blocks, shown in Figure 17, most of the internal cavity is filled. The remaining volume is quite different from a cylinder or an annulus and therefor the 3,0 acoustic mode should not exist or not be significant. To avoid mass or stiffness loading of the shell, the blocks were skewered on a rod and suspended away from the end caps and walls of the shell. To show how the number of blocks affects results, five and ten blocks were also tested. In those two tests, the blocks were spaced apart so there were blocks distributed throughout the volume.

Results of this test indicate that using a rigid volume inclusion (i.e. wood blocks) is effective at decoupling as long as there is enough of a change in the shape or volume. With too few blocks (five), the acoustic mode still couples.

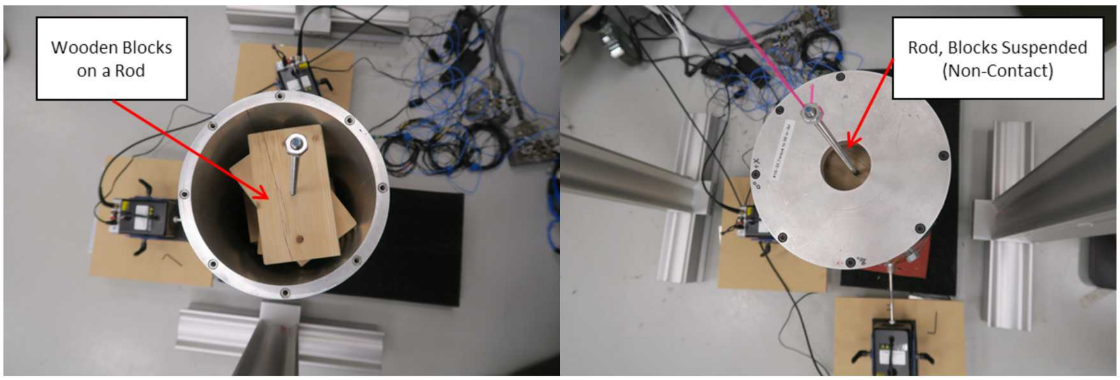

Figure 17: Left: Wooden blocks in the cavity. Right: Suspended via a string so that the blocks do not contact the shell.

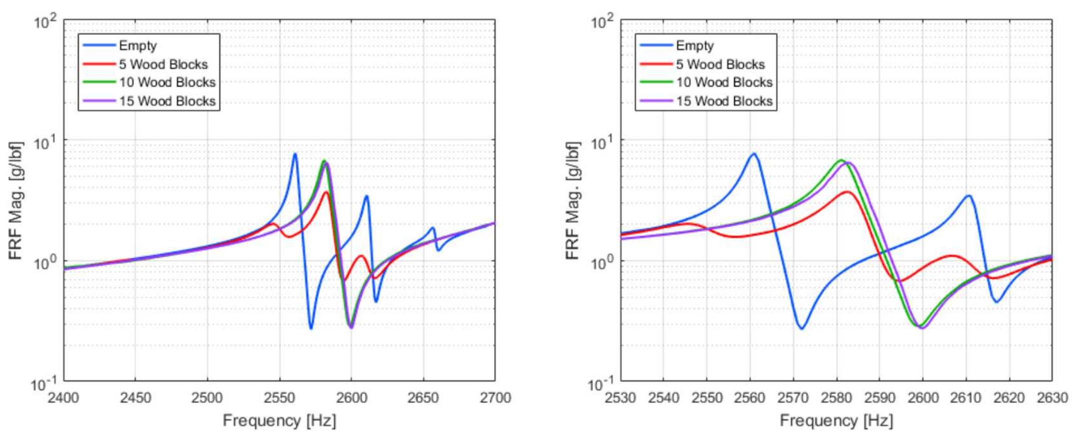

Figure 18: Left: Comparison of different amounts of wooden blocks suspended in the cavity. Right: Zoomed.

4.7. Run-to-Run Variability

With each change to the air cavity, the Z+ end cap had to be removed and replaced. As such, it is important to understand how much change in the FRF is due to the change in the air cavity (i.e. adding more foam, etc.) and how much change is due to the natural variation from run-to-run. Two sets of data were collected to quantify the run-to-run variability. First, three runs were performed back-to-back with no change to the setup between runs. Second, three runs were performed with the Z+ end cap removed and replaced between each run. As expected, there is very good consistency in the FRFs in the first case, demonstrated in Figure 19 and Figure 20. Removing the end cap each time introduces some additional variability, however the change in the FRF amplitude is still within five percent. With these results, the change in FRF amplitude due to changes in the air cavity can more easily be assessed. In general, the change in the FRF amplitude due to changes in the air cavity have been much larger than the run-to-run variability.

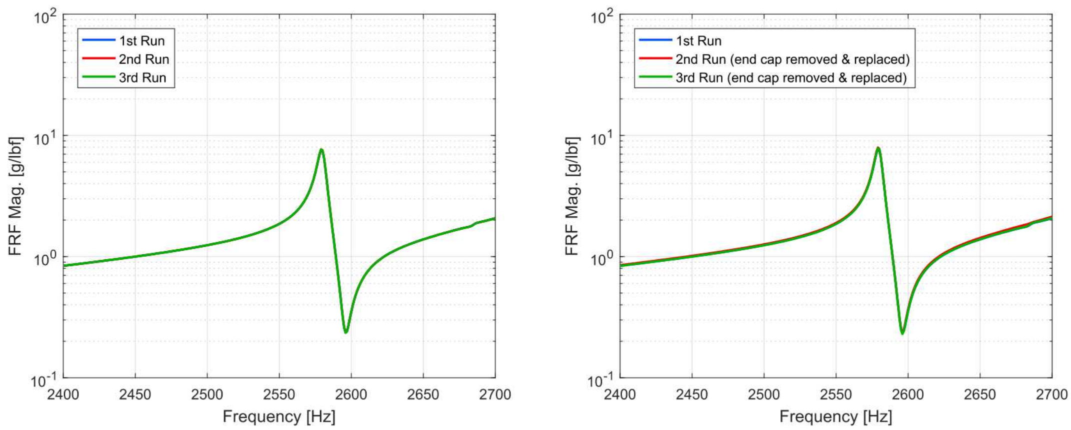

Figure 19: Left: Run-to-run variability without changing the setup between runs. Right: Run-to-run variability when removing the Z+ end cap and reattaching it between each run.

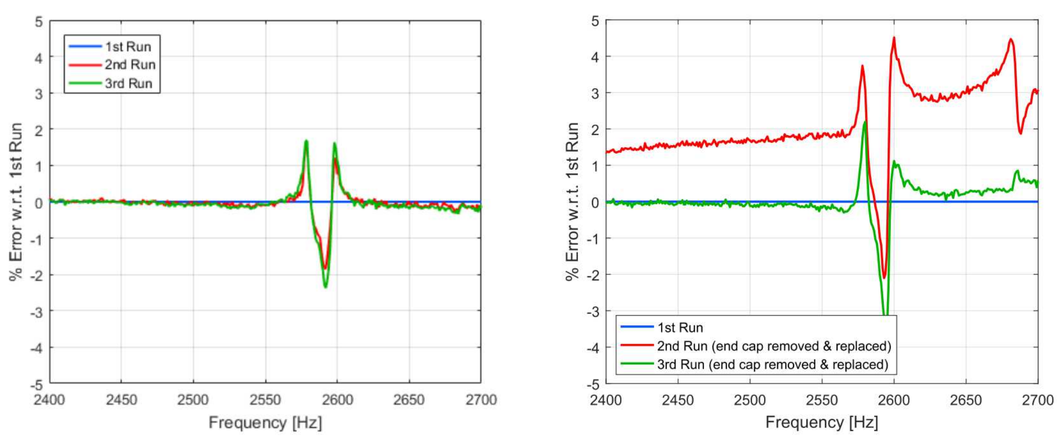

Figure 20: Left: Run-to-run variability represented as a percent error against the first run, with no setup change between runs. Right: End cap removed and reattached between runs.

4.8. Comparison of Methods

A representative run from each type of air cavity change is compared in the plots in Figure 21. This clearly shows that adding absorptive material to add damping to the air component results in a structural response that is quite different from the other responses, namely the damping is higher. Thus, we can say that the response obtained from the structure with high air damping is not the in vacuo structural response. Interestingly, the paper scatterers, rigid foam chunks, wood blocks, and the plastic bag resulted in very similar structural responses. That these resulted in similar responses from very different changes may indicate their common response is the true in vacuo response. The PVC pipe added a large, rigid volume inclusion which resulted in the highest amplitude peak, although there is still evidence of acoustic coupling, albeit at a different frequency. It is unclear how that coupled mode near 2450 Hz affects the structural mode at 2580 Hz.

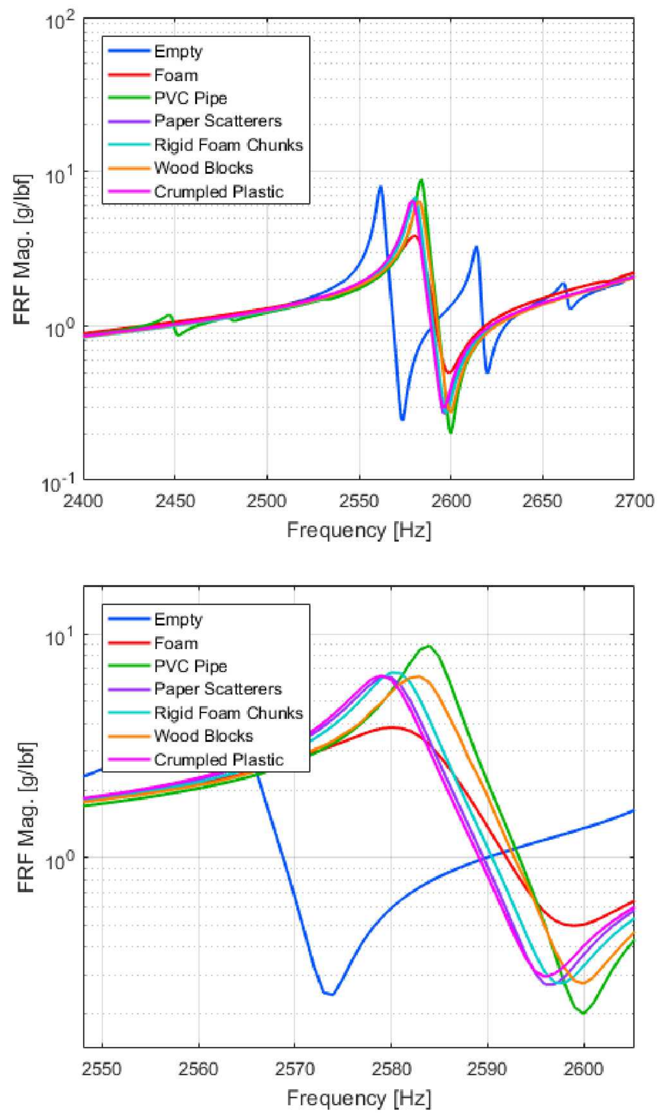

Figure 21: Top: Comparison of the various methods. Bottom: Zoomed.

5. CONCLUSIONS AND FUTURE WORK

5.1. Conclusions

Decoupling of the SAD acoustoelastic system was again attempted, this time using different decoupling methods which focused more on changing the internal boundary conditions rather than changing the air damping. When comparing absorptive foam against the various other methods, it became clear that changing the air damping results in very different structural response. The other methods resulted in similar response overall, with paper and plastic providing nearly identical responses. This may indicate that the decoupling mechanism is the same for both paper and plastic; their acoustic impedance becomes high at high frequency like a mass-law limp, heavy barrier. With high impedance and random orientation, the paper or plastic reflects waves at odd angles which prevents the 3,0 acoustic mode from forming.

Based on these results, the current recommendation to decouple an acoustoelastically-coupled system is to employ some type of boundary condition change to the acoustic cavity. The most convenient method would be to use crumpled (i.e.: randomly-oriented) paper, cardstock, or plastic film dispersed in the cavity. This should be effective for mid to high frequency coupled modes. If the coupling is low frequency, these methods will not work. This testing has indicated that using an acoustically absorptive material, such as open cell foam, can be effective in removing the coupled second peak, but will add artificial damping to the remaining structural peak, which is undesirable.

5.2. Future Work

Though this series of tests has gone further to explore decoupling methods than any previous tests, the question remains: what is the in vacuo structural response? In this report, it is supposed that the uncoupled, structure-only response must be near to the responses presented here, simply because several different methods achieved similar results. The only feasible way to assess the effectiveness of a given method in producing desired response would be to change the amount of scattering material and re-test. If the results with more or less material results in the same response, then 1) that method is effective in decoupling, 2) the response is insensitive to the amount of material, and 3) the converged response is the in vacuo response. However, this is pure conjecture and cannot be verified unless a different test method is employed to reliably achieve the in vacuo structural response. Of course, with the right equipment, time, and resources, a vacuum chamber test could be performed, however this seems an extreme solution to a simple problem.

6. REFERENCES

1. R. B. Davis, "Techniques to assess acoustic-structure interaction in liquid rocket engines (PhD Dissertation)," Duke University, 2008.
2. E. H. Dowell, G. F. Gorman III and D. A. Smith, "Acoustoelasticity: General Theory, Acoustic Natural Modes and Forced Response to Sinusoidal Excitation, Including Comparisons with Experiment," Journal of Sound and Vibration, vol. 52, no. 4, pp. 519-542, 1977.
3. R. Schultz and B. R. Pacini, "Mitigation of Structural-acoustic Mode Coupling in a Modal Test of a Hollow Structure," in *IMAC-XXXV International Modal Analysis Conference*, Garden Grove, CA, 2017.
4. D. Fowler, G. Lopp, D. Bansal, R. Schultz, M. Brake and M. Shepherd, "Experimental Demonstration of a Tunable Acoustoelastic System," in *International Modal Analysis Conference XXXVI*, Orlando, FL, 2018.

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