Combined Qualification Vibration Testing and Fixed Base Modal Testing Utilizing a Fixed Based Correction Method

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Author Statement:

- It was the sincere hope that James could be here to share his insights and lessons learned with you. Due to the federal government shutdown, that unfortunately was not possible.

- An important statement that should be made up front is that a lot of the research performed and documented in this paper has not been fully completed, therefore final conclusions have not been made.

Overview

- The vision of this research is to someday be able to recover fixed based modes from vibration tests that are performed on flexible interfaces.

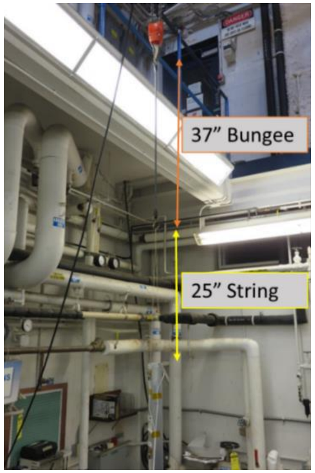
- This presentation documents the very preliminary steps of starting to work towards that vision.

- Major points of discussion focus on basic trade studies performed prior to the testing on the shaker table, the test setup and infrastructure required, and finally describing some of the challenges and lessons learned thus far.

- The methodologies used in this research to remove the base motion were first implemented and proved out by Kevin Napolitano and ATA Engineering. Please look to their documentation for analytical derivations and further case studies.

Simple Beam Pathfinder Setup

- This idea stemmed from work done at ATA previously. It was an attempt to prove out the method before getting to complex.
- The setup of this simple free-free beam test involved a 2” square 6061-T6 aluminum hollow cross-section beam that was 87” long and had a wall thickness of 0.125” thick hung from a string and bungee cord.
- The beam was divided into six equal sections and 7 uniaxial accelerometers were placed along the beam in each of the two lateral beam directions. A single uniaxial accelerometer was placed at the top of the beam.
- A total of 10 impacts were averaged together at each of the 15 accelerometer measurement locations.
- The test was exercised to verify that modal parameters from this free-free modal hammer survey could also yield the accurate results of other restrained boundary conditions:
  - Pinned at one end
  - Pinned at both ends
  - Pinned at the ends as well as in the middle

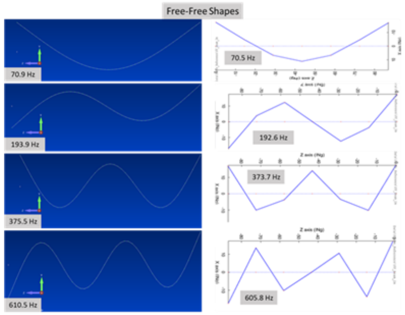


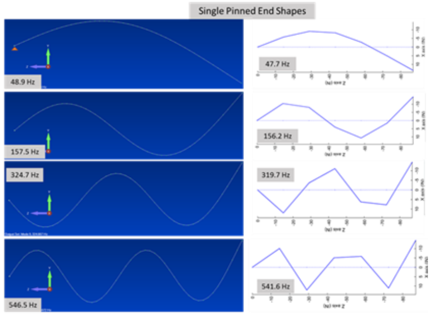
Simple Beam Pathfinder Results

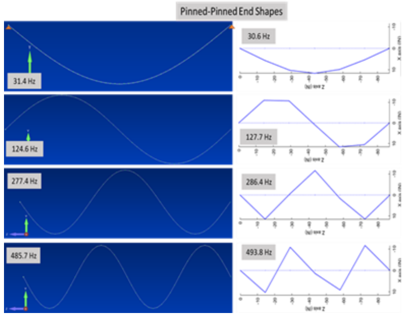
- This study verified that a fixed-base correction technique could be used effectively to extract modal parameters for different boundary conditions from a free-free modal test.

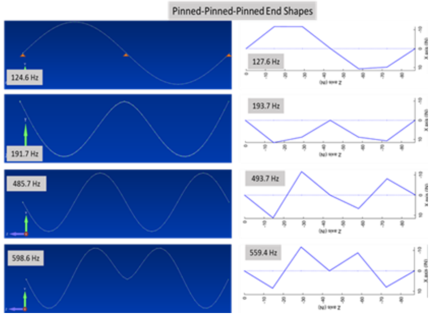
- It was found to be more difficult to extract clean modes shapes when the boundary conditions became more complicated. Thus, when trying to simulate the pinned-pinned-pinned condition, while the deformation shapes and frequencies appeared to be correct, the cross-orthogonality was not nearly as clean.

- Lesson Learned: The symmetric cross section made this simple study more complicated than desired due to it having closely spaced modes pairs at every frequency. It would be better to avoid this in future simple studies.

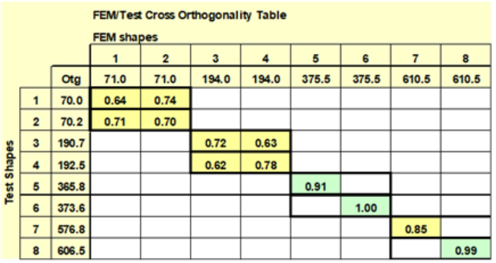








Free-Free

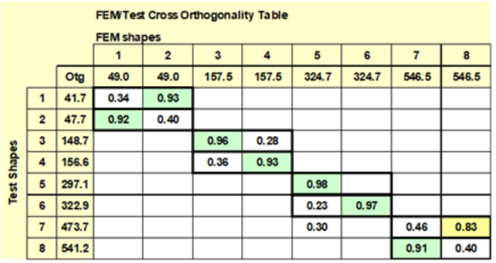


FEM/Test Cross Orthogonality Table

FEM shapes

Test Shapes	Otg	1 71.0	2 71.0	3 194.0	4 194.0	5 375.5	6 375.5	7 610.5	8 610.5
1	70.0	0.64	0.74						
2	70.2	0.71	0.70						
3	190.7			0.72	0.63				
4	192.5			0.62	0.78				
5	365.8					0.91			
6	373.6						1.00		
7	576.8							0.85	
8	606.5								0.99

Single-Pinned

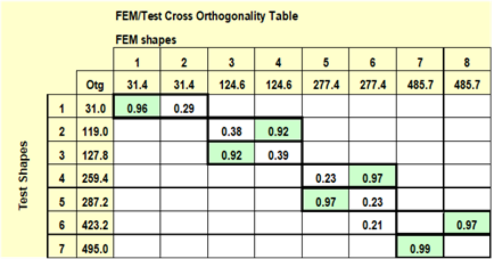


FEM/Test Cross Orthogonality Table

FEM shapes

Test Shapes	Otg	1 49.0	2 49.0	3 157.5	4 157.5	5 324.7	6 324.7	7 546.5	8 546.5
1	41.7	0.34	0.93						
2	47.7	0.92	0.40						
3	148.7			0.96	0.28				
4	156.6			0.36	0.93				
5	297.1					0.98			
6	322.9					0.23	0.97		
7	473.7					0.30		0.46	0.83
8	541.2							0.91	0.40

Pinned-Pinned

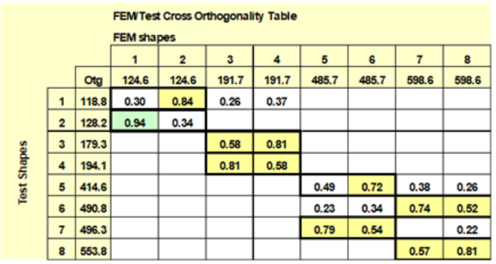


FEM/Test Cross Orthogonality Table

FEM shapes

Test Shapes	Otg	1 31.4	2 31.4	3 124.6	4 124.6	5 277.4	6 277.4	7 485.7	8 485.7
1	31.0	0.96	0.29						
2	119.0			0.38	0.92				
3	127.8			0.92	0.39				
4	259.4					0.23	0.97		
5	287.2					0.97	0.23		
6	423.2						0.21		0.97
7	495.0							0.99	

Pinned-Pinned-Pinned



FEM/Test Cross Orthogonality Table

FEM shapes

Test Shapes	Otg	1 124.6	2 124.6	3 191.7	4 191.7	5 485.7	6 485.7	7 598.6	8 598.6
1	118.8	0.30	0.84	0.26	0.37				
2	128.2	0.94	0.34						
3	179.3			0.58	0.81				
4	194.1			0.81	0.58				
5	414.6					0.49	0.72	0.38	0.26
6	490.8					0.23	0.34	0.74	0.52
7	496.3					0.79	0.54		0.22
8	553.8							0.57	0.81

Test Article Selection

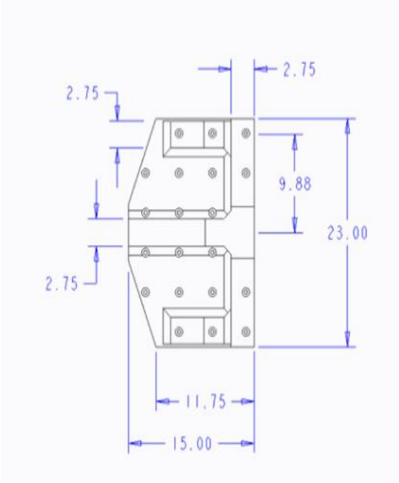
- For the first stage of this research, development of an appropriate test article along with all the infrastructure needed to perform the modal testing on the shaker slip table was the first step.

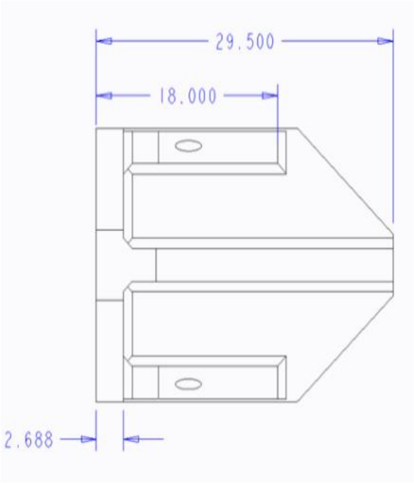
- Initial test article requirements were:
  - Simple design and fabrication
  - Behave linearly
  - Contain sufficient weight to influence the current shaker table dynamics
  - Have its fundamental modes in the same frequency range as most traditional aerospace structures

- Shortly into the process, it became clear that meeting all these requirements would be cost prohibitive and would exceed schedule constraints. As a compromise, an pre-existing magnesium bookend was chosen.

- The design requirement that wasn't able to be met was having its fundamental modes in the range of typical aerospace test articles. At the time, it was felt that this limitation would not be an issue.

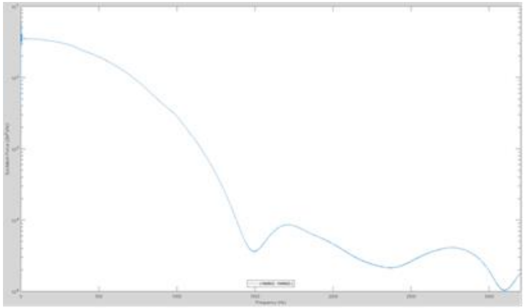
- The magnesium bookend weighed 217 pounds and is a fully welded magnesium structure.



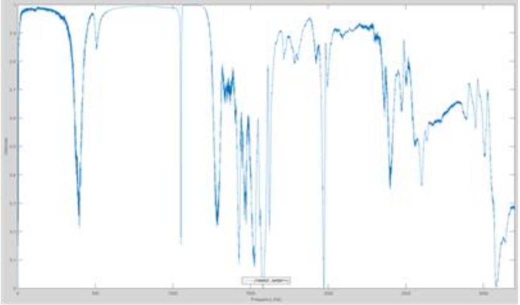


Free-Free Modal Test and Correlation

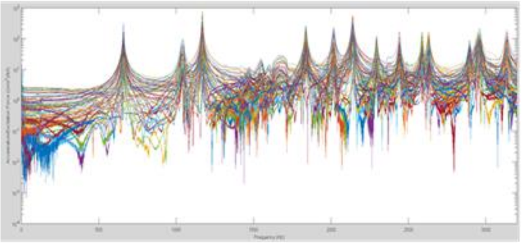
- The test article was suspended from a soft bungee cord displayed in with a bounce mode at ~3Hz and all of the remaining suspension modes (e.g. 1st and 2nd pendulum modes) below 3 Hz.
- An impact mallet with a hard black vinyl tip was utilized to excite the structure. This tip was able to produce high quality excitation with good coherence up to 1400 Hz. However, the FRFs seem to hold their quality of ~2300 Hz.
- To ensure engineers had an accurate FEM of the test article, the free-free test results were used to correlate the FEM. After some iteration and updates, the FEM correlated to the test results very well.



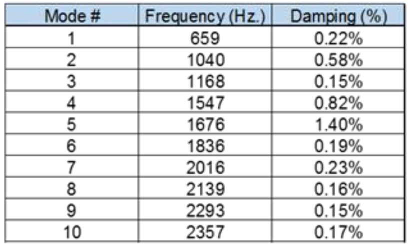
Impact Hammer Autospectra



DOF Coherence

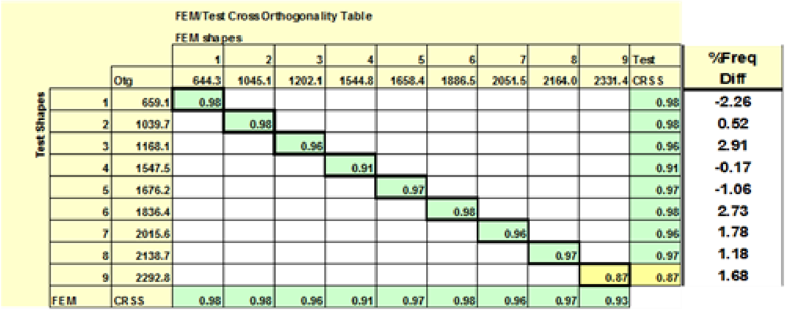


All DOF FRFs



Mode #	Frequency (Hz.)	Damping (%)
1	659	0.22%
2	1040	0.58%
3	1168	0.15%
4	1547	0.82%
5	1676	1.40%
6	1836	0.19%
7	2016	0.23%
8	2139	0.16%
9	2293	0.15%
10	2357	0.17%

Modal Parameters Extracted



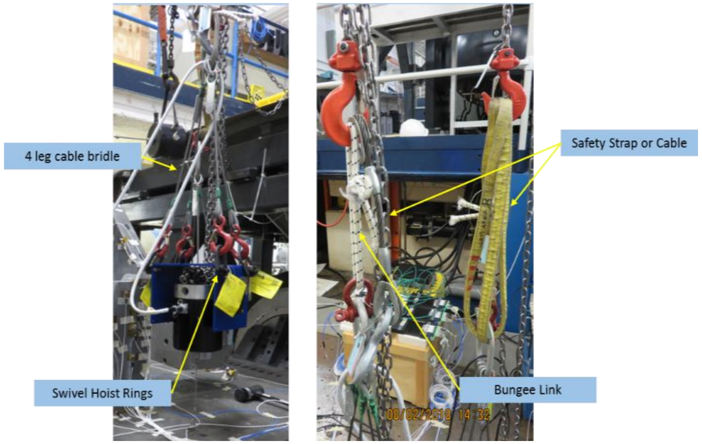
FEM/Test Cross Orthogonality Table

FEM shapes

			1	2	3	4	5	6	7	8	9	Test	%Freq Diff
		Otg	644.3	1045.1	1202.1	1544.8	1658.4	1886.5	2051.5	2164.0	2331.4	CRSS	
Test Shapes	1	659.1	0.98									0.98	-2.26
	2	1039.7		0.98								0.98	0.52
	3	1168.1			0.96							0.96	2.91
	4	1547.5				0.91						0.91	-0.17
	5	1676.2					0.97					0.97	-1.06
	6	1836.4						0.98				0.98	2.73
	7	2015.6							0.96			0.96	1.78
	8	2138.7								0.97		0.97	1.18
	9	2292.8									0.87	0.87	1.68
	FEM	CRSS	0.98	0.98	0.96	0.91	0.97	0.98	0.96	0.97	0.93		

Multi-Shaker Support Setup

- In order to correctly utilize the fixed based correction methods, one basic requirement must always be met. There must be an independent uncorrelated excitation source for every shape that is attempting to be removed.
- The expectation, based on past studies performed by ATA Engineering, was that the removal of the shaker slip table motion would require at least seven external portable shakers.
- The lab has catwalks that run on tracks over its large shakers. It was decided to utilize the same tracks and span S6 x12.5 standard steel I-Beams across. Then manual 1 ton trollies attached to 1 ton hand chain hoists would run along the axis of the I-beams. This would give maximum flexibility in positioning all of the shakers around the slip table.
- The shaker lifting hardware setup contained four major components as shown in the bottom picture to the right.
- The loosely fitted lifting strap was put in place because the bungee cord links were not load tested. Therefore, to ensure safety, the lifting straps would not allow the shakers to fall if the bungees were to break.

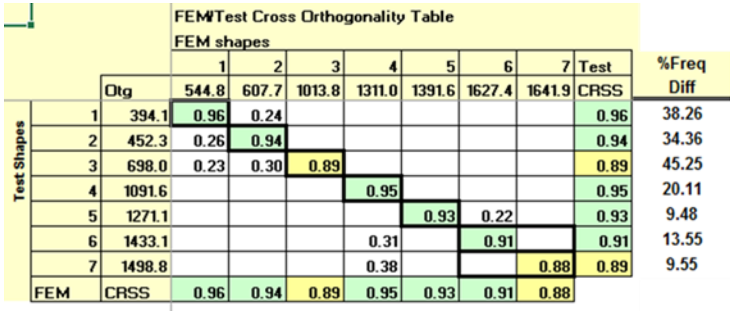


Traditional Fixed Based Modal Test

- It was important to the engineers performing the research to have a good baseline of fixed based modal parameters using the traditionally accepted fixed based approach of testing on a seismic mass modal floor.

- Impact hammer testing using a modal mallet with a black vinyl tip was utilized to excite the test article on the modal floor. All data was processed using the impact hammer measured force as the reference.

- The end result of this testing was that the seven target modes were successfully able to be extracted from the testing and it showed that significant model updating to the boundary conditions should be performed. The RBE2 spider element modeling technique fixing the base of the test article was much too stiff.



FEM/Test Cross Orthogonality Table

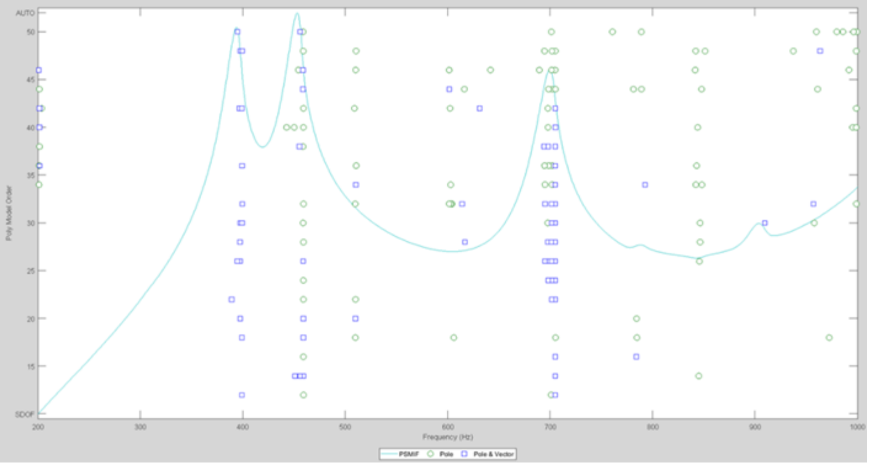
FEM shapes

			1	2	3	4	5	6	7	Test	%Freq Diff
		Otg	544.8	607.7	1013.8	1311.0	1391.6	1627.4	1641.9	CRSS	
Test Shapes	1	394.1	0.96	0.24						0.96	38.26
	2	452.3	0.26	0.94						0.94	34.36
	3	698.0	0.23	0.30	0.89					0.89	45.25
	4	1091.6				0.95				0.95	20.11
	5	1271.1					0.93	0.22		0.93	9.48
	6	1433.1				0.31		0.91		0.91	13.55
	7	1498.8				0.38			0.88	0.89	9.55
	FEM	CRSS	0.96	0.94	0.89	0.95	0.93	0.91	0.88		

Unexpected Challenges

- When looking into the extracted test mode shapes, it was discovered that the modal floor was flexing slightly along with the test article.
  - All testing done in the past on the modal floor had never yielded results where the floor appeared to be excited along with the test article.
  - Most aerospace test articles have fundamental resonances well below 400 Hz. However, the fundamental mode of this test article was ~400 Hz.

- The other thing observed was that the frequency response functions appeared to be “bent” over thus the CMIF was also “bent” over as shown in the figure on the right. The pole estimates were generating several of the same poles just slightly shifted over in frequency.
  - The only explanation of this behavior was that the bookend coming up off the floor. The interface stiffness in the vertical up direction (fasteners only) is much less than in the vertical down direction where the bookend is in contact with the modal floor.

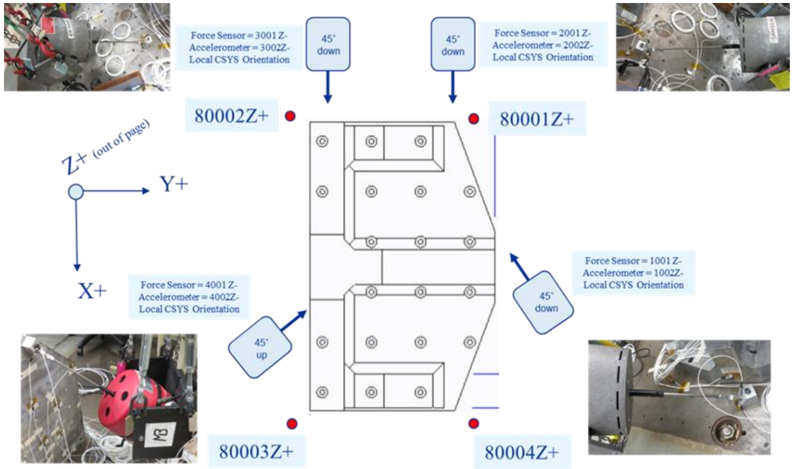


Modal Floor Influence Removal

- Due to the challenges, a change in the test approach was made and a setup to use a fixed based methodology to remove the modal floor base motion was attempted.

- Multi-shaker testing on the modal floor was utilized where four shakers would excite three observed modal floor deformations as well as the test article modes.

- Using two different methodologies to remove the base motion, new modal parameters were extracted from the test data. Results indicated that the effect of the floor compliance (although minimal) was successfully able to be removed using either technique.



Uncorrected	SMURF Corrected		DP Accels Corrected	
Freq (Hz)	Freq (Hz)	% Diff	Freq (Hz)	% Diff
394	401	2%	400	1%
452	463	3%	461	2%
698	709	2%	706	1%
1089	1098	1%	1095	1%
1275	1282	1%	1279	0%

Shaker Slip Table Modal Test

- The shaker layout was setup to allow for the removal of the 6 rigid body modes of the slip table from the test article while also exciting the test article modes.

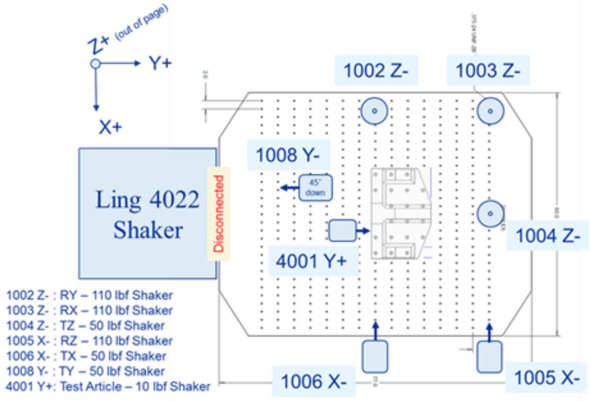
- The large electrodynamic shaker was disconnected from the slip table to start off with. It was intended to utilize the large shaker as one of the independent excitation sources in this first stage of the research, but time did not allow for it.

- Test data was collected with both the slip table oil pumps on and off.

- Very preliminary investigation into the data shows that the final slip table rigid body mode occurs almost 150 Hz below the first test article mode. For every additional mode in the slip table above the last rigid body mode another shaker would need to be added to remove that influence from the test article.
  - The lab didn't own more than seven shakers, thus expansion of the test was not feasible.

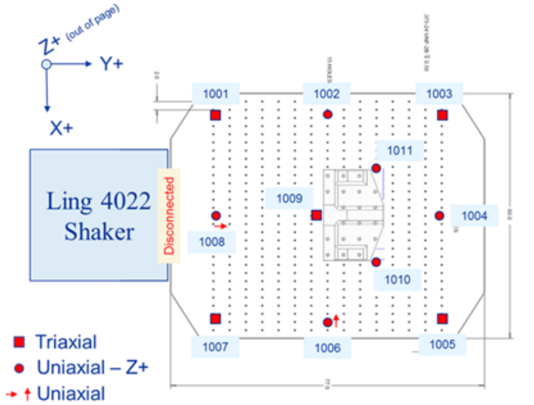
- Impact hammer testing was carried out at each one of the drive point accelerometers to see if that would allow for all the slip table base motion to be removed up to the test article first fundamental mode. That data has not been processed yet to determine its success.

Shaker Layout



1002 Z- : RY – 110 lbf Shaker
1003 Z- : RX – 110 lbf Shaker
1004 Z- : TZ – 50 lbf Shaker
1005 X- : RZ – 110 lbf Shaker
1006 X- : TX – 50 lbf Shaker
1008 Y- : TY – 50 lbf Shaker
4001 Y+: Test Article – 10 lbf Shaker

Drive Point Accelerometer Layout



Summary and Future Work

- In all 85 different tests, shaker and impact hammer, were carried out during this first phase of the research effort. Engineers need time to process and study it to make any real conclusions on the ability to remove base motion.

- There is confidence, built mainly from the preliminary studies, that the fixed based correction options can be successfully employed.

- In regards to the slip table testing, the main lesson learned was that there was simply not enough shakers to remove all the base motion present due to the higher than normal stiffness of the test article.

- There is a concern that the chosen test article is unrealistically too stiff and not really accurately simulating traditional aerospace structures. This concern will most likely drive a test article change to one that is more representative of a realistic aerospace structure.

- If the study of the data taken indicates that the slip table motion is successfully removed with the impact hammer testing, the next step will be to attach the large electrodynamic shaker to the slip table and investigate the ability to run higher level vibe tests and still recover fixed based modes.