PAT Wing Fixed Base Correction Modal Testing Debrief

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Presentation Outline

Note: All results shown here are preliminary

The objective of this presentation is to describe the PAT Wing modal testing conducted and results using Fixed Base Correction (FBC) method.

- FBC Theory – Drive point accelerations as references
- Description of Modal Test Setup
- FBC Signal Processing Techniques
    - FRF calculation
    - Partial FRF matrix inversion technique (SMURF)
- Decisions on where to add shakers (if needed)
- FBC Results

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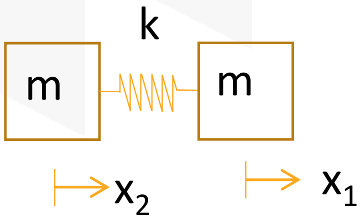
Fixed Base Correction - Theory

- Original fixed base correction theory used constraint shapes as references, but the method is more easily deployed **using drive point accelerations as references**



$$\begin{bmatrix} s^2m+k & -k \\ -k & s^2m+k \end{bmatrix} \begin{Bmatrix} X_1 \\ X_2 \end{Bmatrix} = \begin{Bmatrix} F_1 \\ F_2 \end{Bmatrix}$$

F_1 and F_2 as References: ω^2_n= 0,2k/m

$$X_1 = \frac{s^2m_2+k}{(s^2m+k)(s^2m+k)-k^2}F_1 + \frac{k}{(s^2m+k)(s^2m+k)-k^2}F_2$$

$$X_2 = \frac{k}{(s^2m+k)(s^2m+k)-k^2}F_1 + \frac{s^2m_2+k}{(s^2m+k)(s^2m+k)-k^2}F_2$$

F_1 and X_2 as References: ω^2_n= k/m

$$X_1 = \frac{1}{(s^2m+k)}F_1 + \frac{k}{(s^2m+k)}X_2$$

$$X_2 = \quad 0F_1 \quad + \quad 1X_2$$

- **Using a drive point accelerometer as reference results in system modes with that DOF fixed**

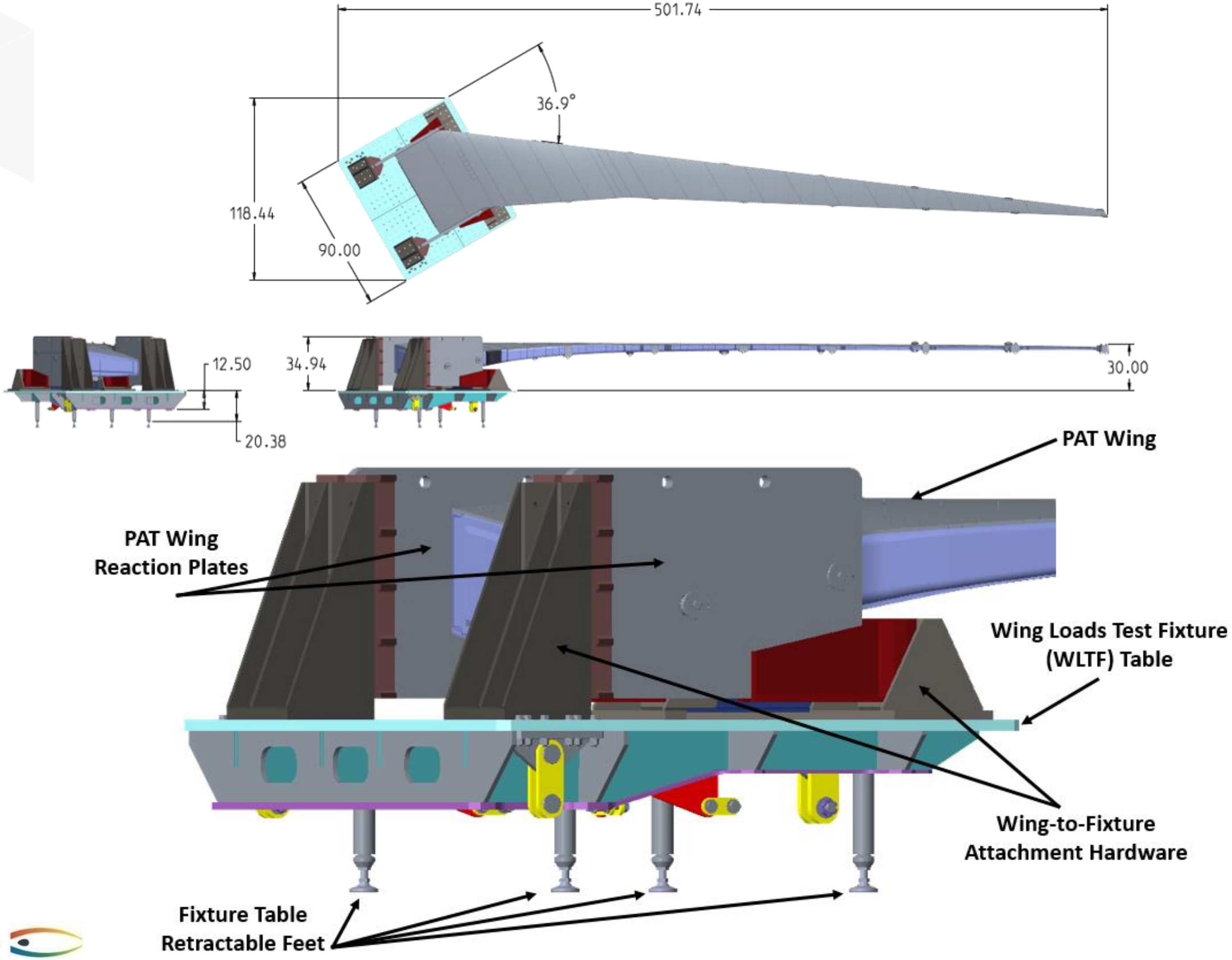
- Make sure drive point FRF are as co-located as practicable
- Make sure drive point FRF are as clean as practicable
    - Use seismic accelerometers as drive points
    - Drive base shakers harder than wingtip shakers

PAT Wing Test Article

- Passive Aeroelastic Tailored (PAT) Wing is a tow-steered graphite epoxy, high aspect ratio, semi-span (≈ 39ft) right wing box
- Designed and built for NASA by Aurora Flight Sciences
- Project funded by NASA ARMD Advanced Air Transport Technology (AATT) Project

PAT Wing Test Setup

Test Goal: Extract all fixed base modes to first torsion mode (near 55 Hz)



Modal Test Physical Boundary Conditions

Using these boundary conditions would lead to a very challenging model updating effort without Fixed Base Correction

- Test physical boundary conditions: White static test fixture on the lab floor with four retractable feet and one location on the fixture that is secured to the lab floor with a strap
  - Dynamically active boundary condition

Static Test Fixture Boundary Condition on Lab Floor

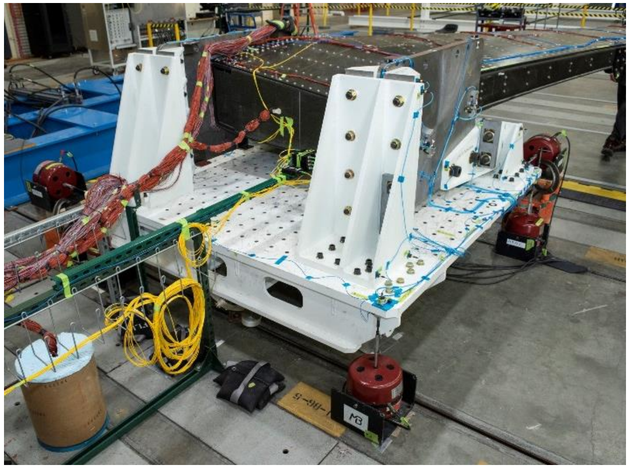
Four Retractable Feet Boundary Condition

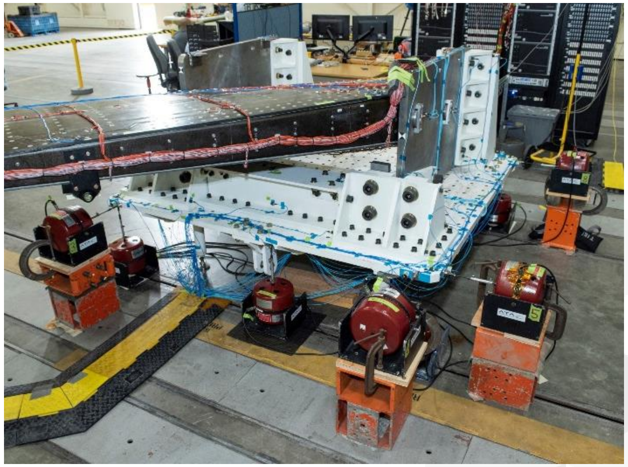
Table Secured with Strap to FLL Floor Boundary Condition

Initial Modal Test Setup

- ≈ 270 Accelerometers
- 10 Shakers/load cells
  - 10 Seismic accels (drive points)
- True Random Input
  - Flexibility in signal processing

Config. 1: 9 Base Shakers



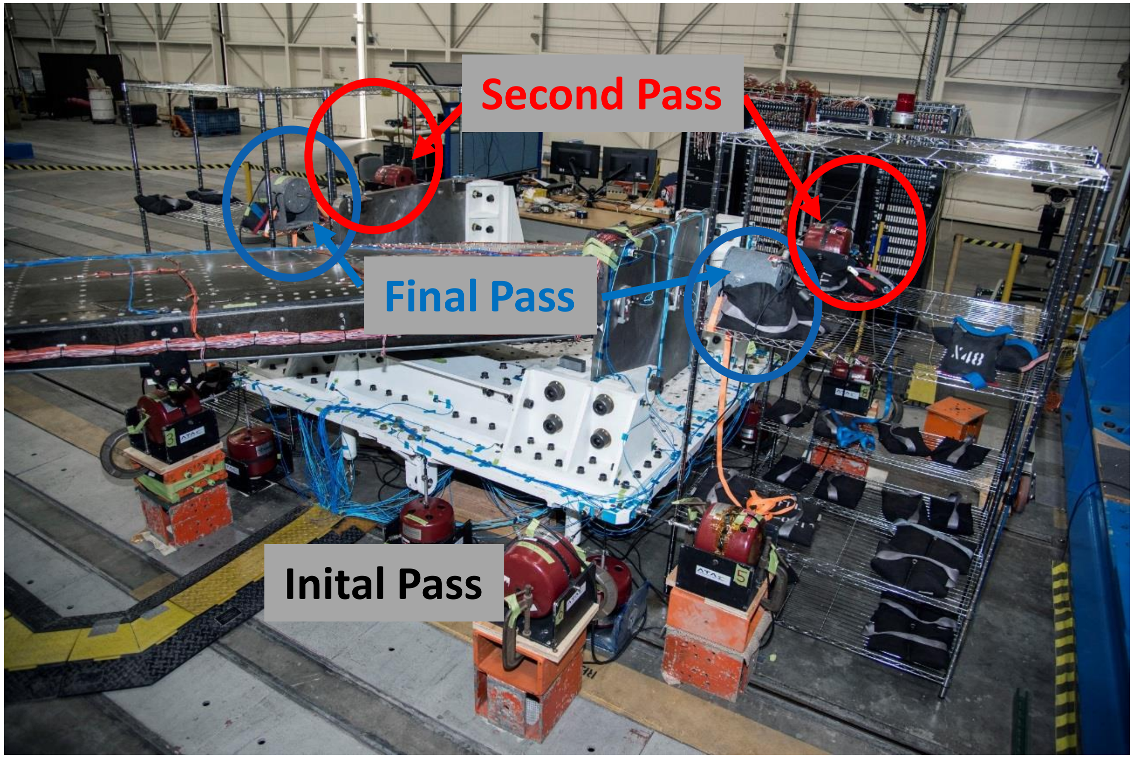


Wingtip Shaker

Three Shaker Configurations

- Config. 1 (Initial Pass): 10 shakers – 9 on white static test fixture, 1 on wingtip
- Config. 2 (Second Pass): 12 shakers – Added 2 to aft white triangular brackets (lateral)
- Config. 3 (Final Pass): 14 shakers – Added 2 more to fwd wing root metallic plates (lateral)

Shaker Layout



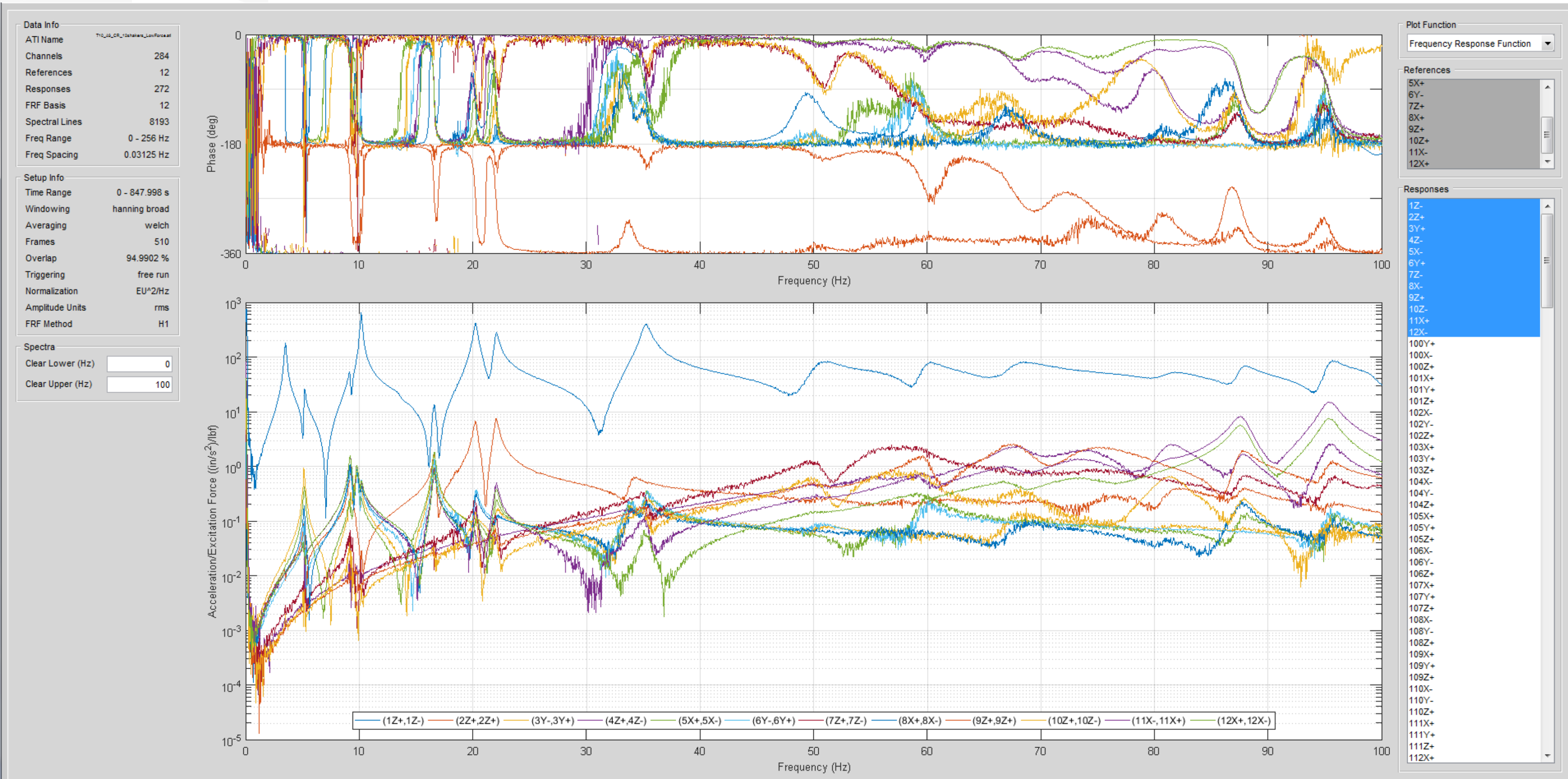
Fixed Base Correction - Signal Processing is Iterative

- Forces usually have the highest S/N ratio and are therefore usually the best choice as basis vectors
  - Step 1. Calculate A/F FRF
  - Step 2. Use IMAT **`SMURF`** function to perform partial inversion of FRF matrix
    - Example: `g=smurf(f,ref(2:end),ref(2:end))`, where
      - F is the FRFs in all positive DOF (`f=fn2pos(f)`)
        - Not strictly necessary, but easier to manage
      - REF is the reference dof (`[ref,res]=ref_res(f)`)
  - Step 3. Review FRF, and try new signal processing parameters if needed
  - Step 4. Fit modes using FRF associated with wingtip shaker FRF

Config 2: 12 Shakers

Filename: T10_A3_CR_12shakers_LowForce.ati

- ➢ Step 1: Calculate A/F FRF (using ALL shaker load cells)



Data Info

ATI Name	T10_A3_CR_12shakers_LowForce.ati
Channels	284
References	12
Responses	272
FRF Basis	12
Spectral Lines	8193
Freq Range	0 - 256 Hz
Freq Spacing	0.03125 Hz

Setup Info

Time Range	0 - 847.998 s
Windowing	hanning broad
Averaging	welch
Frames	510
Overlap	94.9902 %
Triggering	free run
Normalization	EU^2/Hz
Amplitude Units	rms
FRF Method	H1

Spectra

Clear Lower (Hz)	0
Clear Upper (Hz)	100

Plot Function

Frequency Response Function

References

5X+
6Y-
7Z+
8X+
9Z+
10Z+
11X-
12X+

Responses

1Z-
2Z+
3Y+
4Z-
5X-
6Y+
7Z-
8X-
9Z+
10Z-
11X+
12X-
100Y+
100X-
100Z+
101X+
101Y+
101Z+
102X-
102Y-
102Z+
103X+
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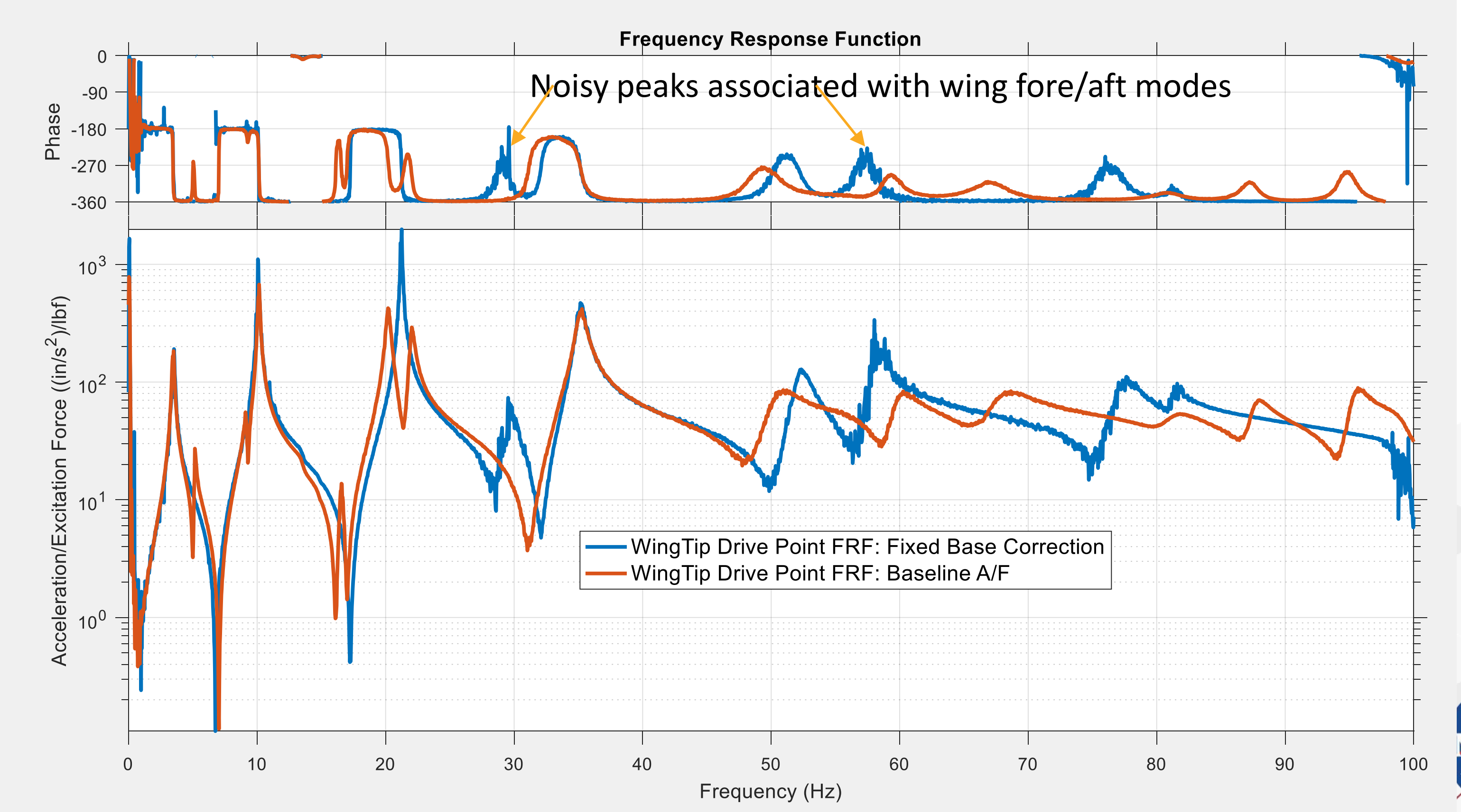
105Z+
106X-
106Y-
106Z+
107X+
107Y+
107Z+
108X-
108Y-
108Z+
109X+
109Y+
109Z+
110X-
110Y-
110Z+
111X+
111Y+
111Z+
112X+

Config 2: Use SMURF on Fixture Drive Points

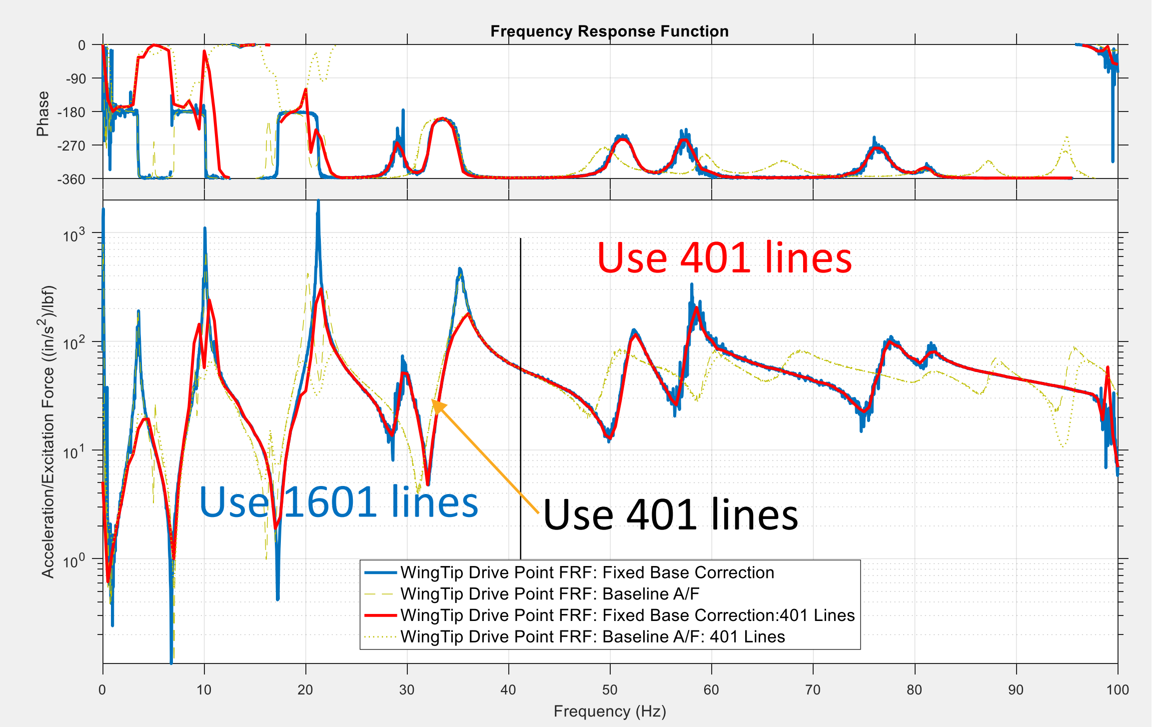
`g=smurf(f,ref(2:end),ref(2:end))`

- Step 2: Partially invert FRF matrix so base drive point accelerometers and wingtip shaker forces are references using SMURF technique. (Use MATLAB IMAT function)



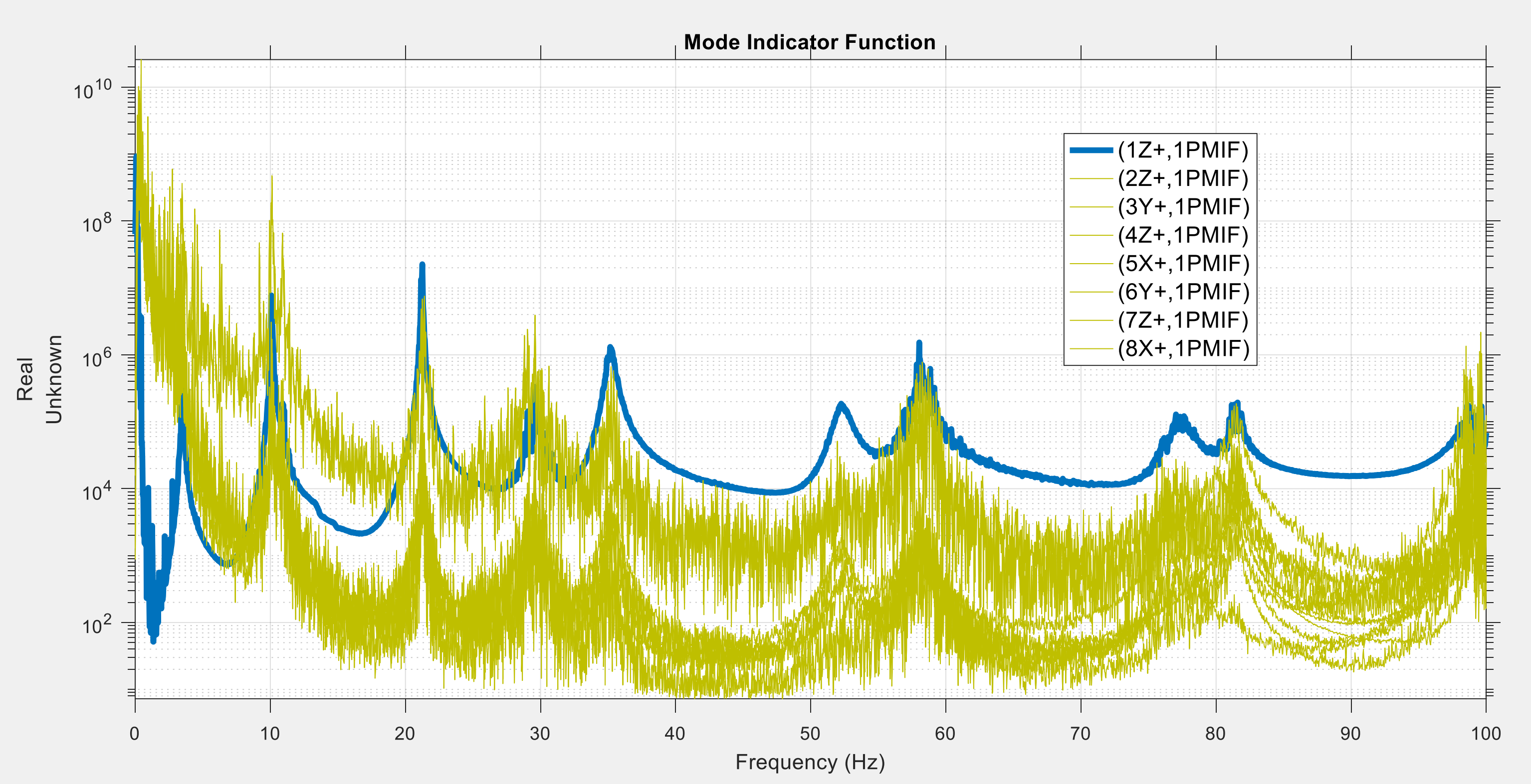
Config 2: Increasing Δf can help clean up FRF

- Step 3: Try different signal processing parameters when needed
- Optimal signal processing parameters may vary with frequency
- Takeaway: Signal processing is iterative



Config 2: A/A FRF are Usually Noisy

Use A/F FRF to fit modes



- Base structure A/A can be cleaned up by using constraint shapes as references, but doing so takes effort and most often the structure A/F FRF are sufficient to extract modes

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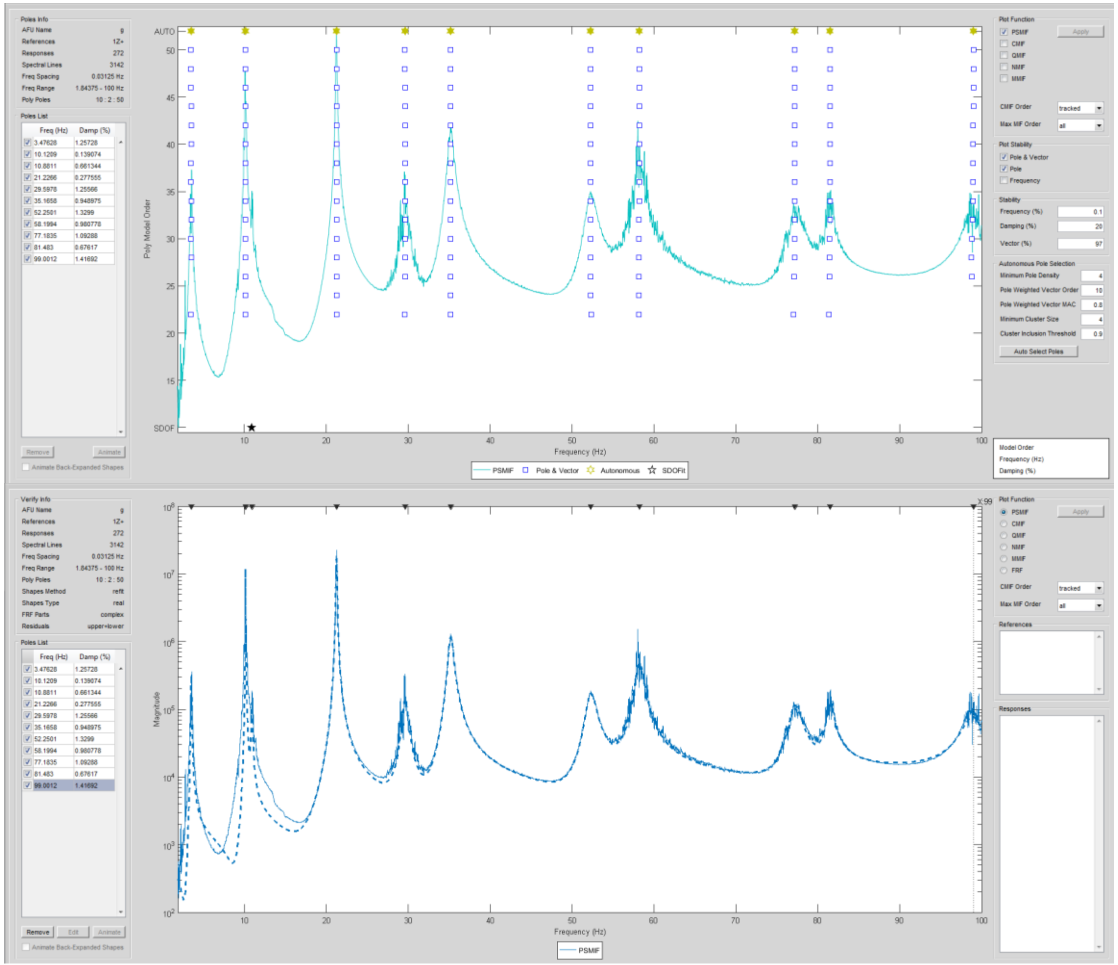
Config 2: Use FRFs associated with Wingtip Shaker Force to Fit Modes

- ➢ Step 4: Fit modes using standard modal analysis software



Poles Info

AFU Name	9
References	1Z+
Responses	272
Spectral Lines	3142
Freq Spacing	0.03125 Hz
Freq Range	1.84375 - 100 Hz
Poly Poles	10 : 2 : 50

Poles List

	Freq (Hz)	Damp (%)
☑	3.47628	1.25728
☑	10.1209	0.139074
☑	10.8811	0.661344
☑	21.2266	0.277555
☑	29.5978	1.25566
☑	35.1658	0.948975
☑	52.2501	1.3299
☑	58.1994	0.980778
☑	77.1835	1.09288
☑	81.483	0.67617
☑	99.0012	1.41692

☐ Animate Back-Expanded Shapes

Plot Function

☑ PSMIF
☐ CMIF
☐ QMIF
☐ NMIF
☐ MMIF

CMIF Order: tracked
Max MIF Order: all

Plot Stability

☑ Pole & Vector
☑ Pole
☐ Frequency

Stability

Frequency (%)	0.1
Damping (%)	20
Vector (%)	97

Autonomous Pole Selection

Minimum Pole Density	4
Pole Weighted Vector Order	10
Pole Weighted Vector MAC	0.8
Minimum Cluster Size	4
Cluster Inclusion Threshold	0.9

Model Order
Frequency (Hz)
Damping (%)

Verify Info

AFU Name	9
References	1Z+
Responses	272
Spectral Lines	3142
Freq Spacing	0.03125 Hz
Freq Range	1.84375 - 100 Hz
Poly Poles	10 : 2 : 50
Shapes Method	refit
Shapes Type	real
FRF Parts	complex
Residuals	upper+lower

Poles List

	Freq (Hz)	Damp (%)
☑	3.47628	1.25728
☑	10.1209	0.139074
☑	10.8811	0.661344
☑	21.2266	0.277555
☑	29.5978	1.25566
☑	35.1658	0.948975
☑	52.2501	1.3299
☑	58.1994	0.980778
☑	77.1835	1.09288
☑	81.483	0.67617
☑	99.0012	1.41692

☐ Animate Back-Expanded Shapes

Plot Function

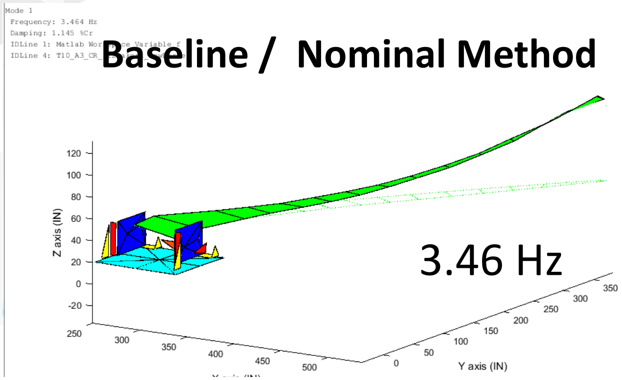
● PSMIF
○ CMIF
○ QMIF
○ NMIF
○ MMIF
○ FRF

CMIF Order: tracked
Max MIF Order: all

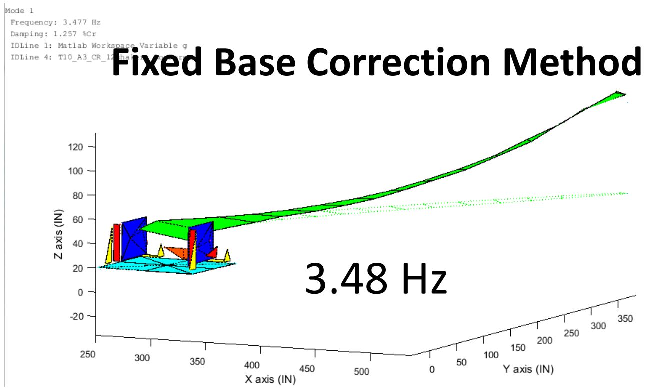
Config 2: 12 Shakers Results

Baseline / Nominal Method

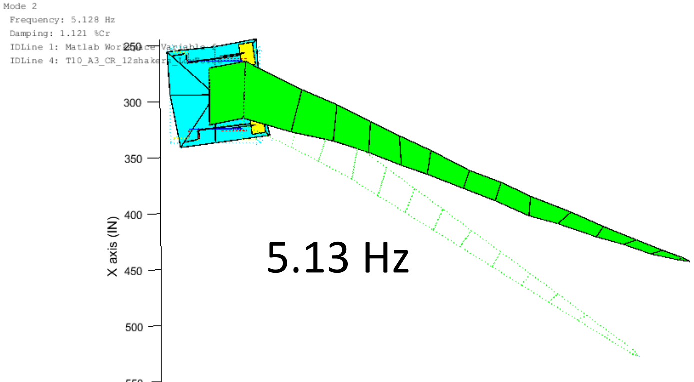
Fixed Base Correction Method



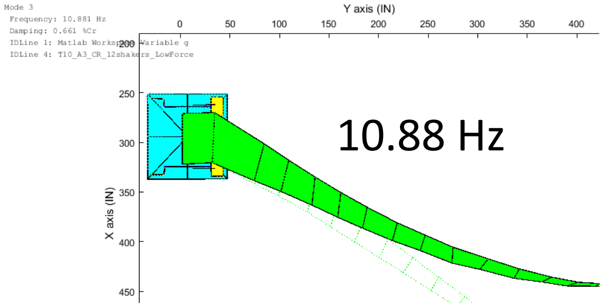
3.46 Hz



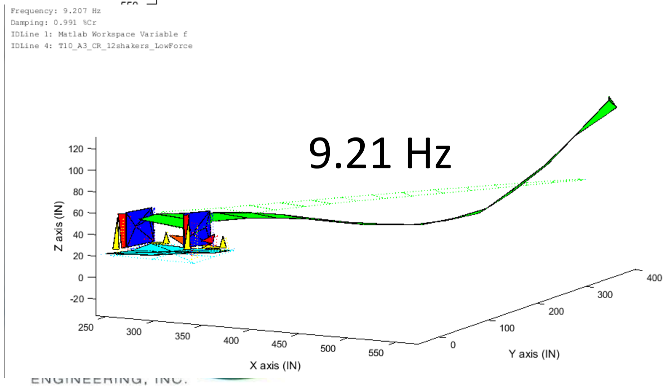
3.48 Hz



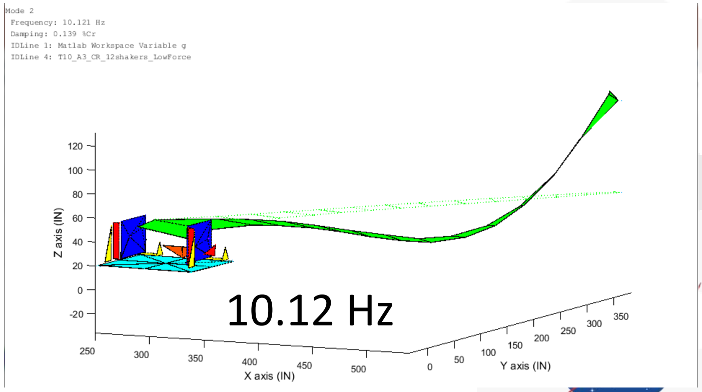
5.13 Hz



10.88 Hz



9.21 Hz

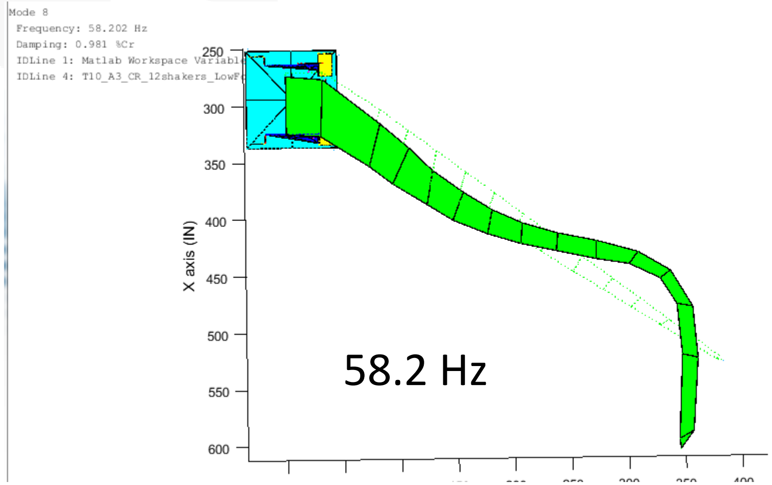


10.12 Hz

Config 3: 14 Shakers Results

Helps remove flexible motion in wing root metallic plates

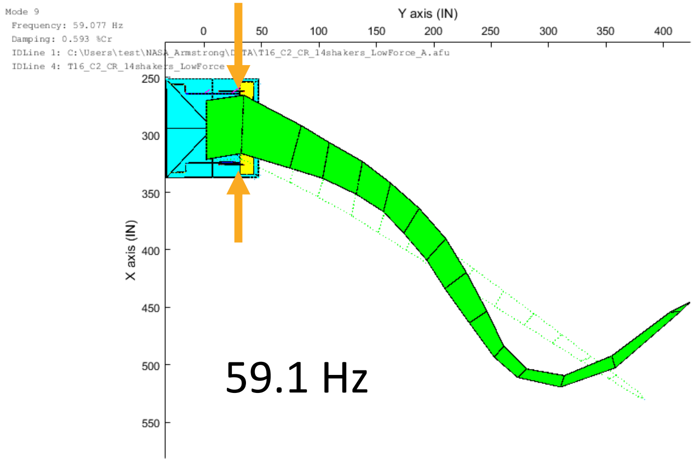
Fixed Base Correction Method
Config 2: 12 Shakers



```
Mode 8
 Frequency: 58.202 Hz
 Damping: 0.981 %Cr
 IDLine 1: Matlab Workspace Variabl
 IDLine 4: T10_A3_CR_12shakers_LowF
```

58.2 Hz

Fixed Base Correction Method
Config 3: 14 Shakers



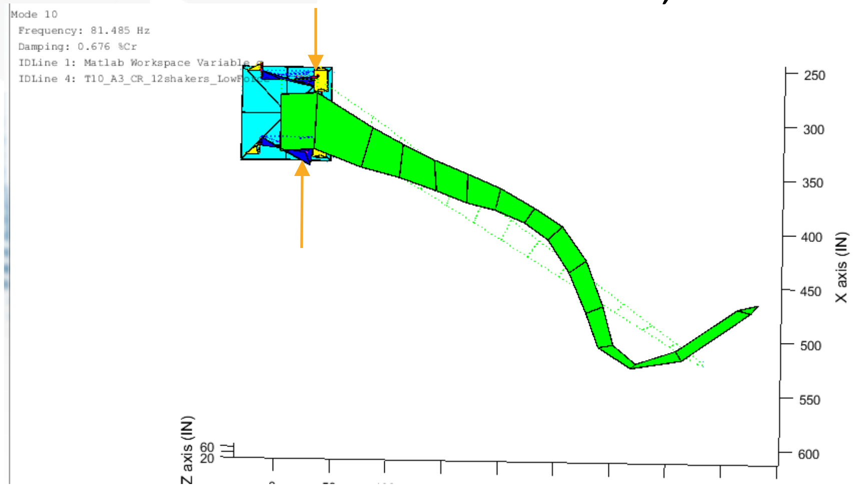
```
Mode 9
 Frequency: 59.077 Hz
 Damping: 0.593 %Cr
 IDLine 1: C:\Users\test\NASA_Armstrong\D TA\T16_C2_CR_14shakers_LowForce_A.afu
 IDLine 4: T16_C2_CR_14shakers_LowForce
```

59.1 Hz

Config 3: 14 Shakers Results

Two additional shakers removes lateral motion, but opens up new concerns

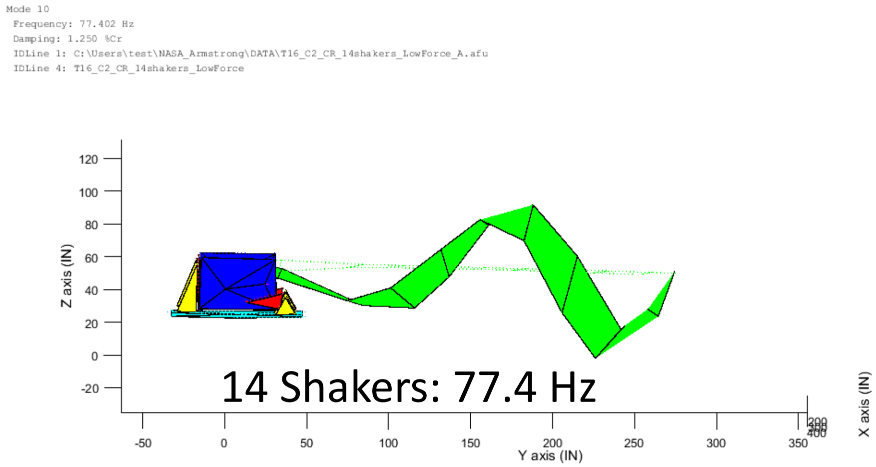
“Infinite Loop” of removing compliance by adding more shakers is limited by time, number of available shakers, or test objective requirements.



```
Mode 10
  Frequency: 81.485 Hz
  Damping: 0.676 %Cr
  IDLine 1: Matlab Workspace Variable
  IDLine 4: T10_A3_CR_12shakers_LowFo
```

12 Shakers: 81.5 Hz

81 Hz mode with 12 shakers is eliminated with 14 shakers



```
Mode 10
  Frequency: 77.402 Hz
  Damping: 1.250 %Cr
  IDLine 1: C:\Users\test\NASA_Armstrong\DATA\T16_C2_CR_14shakers_LowForce_A.afu
  IDLine 4: T16_C2_CR_14shakers_LowForce
```

14 Shakers: 77.4 Hz

Some vertical pedestal motion at 74 Hz with 14 shakers
Could mount vertical shakers to remove this mode, however:

1. This mode is higher in frequency than last target mode
2. We ran out of source signal generators

Config 1: 10 Shakers

FEM assumes white static test fixture is fixed

Test Self MAC Table

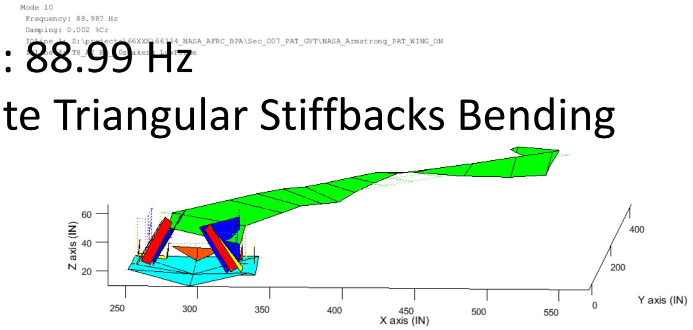
Test Shapes

		1	2	3	4	5	6	7	8	9	10	11
Test Shapes		3.48	10.09	10.77	21.21	29.40	35.14	52.22	57.70	75.66	88.99	98.57
1	3.48	100	32		14		6					
2	10.09	32	100		38		12					
3	10.77			100		29			8		5	6
4	21.21	14	38		100		36	7				
5	29.40			29		100			38	9	10	5
6	35.14	6	12		36		100	24				
7	52.22				7		24	100		6		
8	57.70			8		38			100	27	21	
9	75.66					9		6	27	100	23	
10	88.99			5		10			21	23	100	
11	98.57			6		5						100

FEM/Test Cross MAC Table

FEM Shapes

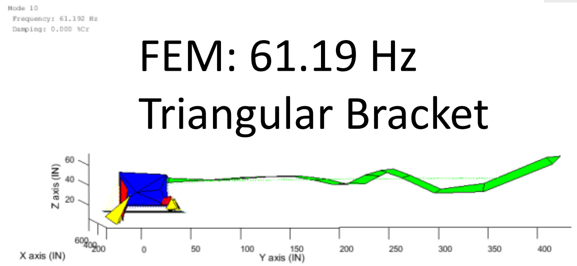
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Test CRSS	Test CRSS
Test Shapes		3.38	10.33	10.95	22.36	29.32	36.61	39.64	51.67	54.89	61.19	62.18	73.43	76.05	92.77	95.87	99.65	104.86	3%	All
1	3.48	98	31																99	99
2	10.09	32	98		41														99	100
3	10.77			92		24													96	97
4	21.21		33		98		44												99	100
5	29.40			39		98		46				29							99	99
6	35.14				31		96			21									98	99
7	52.22						21		65	25				24					81	99
8	57.70					38		65			38	82	20				23		91	99
9	75.66										27	50	65			23	32		80	99
10	88.99											39	27				49		70	95
11	98.57														91				95	99
CRSS	**3%**	99	99	96	99	99	98	81	81	50	61	90	80	49	95	48	70	32		
CRSS	**All**	99	100	97	100	99	99	95	84	64	80	97	83	80	98	69	76	52		



Test: 88.99 Hz

White Triangular Stiffbacks Bending

Test Mode No.	FEM Mode No.	Test Freq (Hz)	FEM Freq (Hz)	Freq Pct Diff	Cross MAC	CRS MAC 3%	CRS MAC All
1	1	3.48	3.38	-2.8	98	99	99
2	2	10.09	10.33	2.3	98	99	100
3	3	10.77	10.95	1.7	92	96	97
4	4	21.21	22.36	5.4	98	99	100
5	5	29.40	29.32	-0.3	98	99	99
6	6	35.14	36.61	4.2	96	98	99
7	8	52.22	51.67	-1.1	65	81	99
8	11	57.70	62.18	7.8	82	91	99
9	12	75.66	73.43	-3.0	65	80	99
10	16	88.99	99.65	12.0	49	70	95
11	14	98.57	92.77	-5.9	91	95	99



FEM: 61.19 Hz

Triangular Bracket

Config 2: 12 Shakers

FEM assumes white static test fixture & four aft triangular stiffbacks are fixed

Test Self MAC Table

Test Shapes

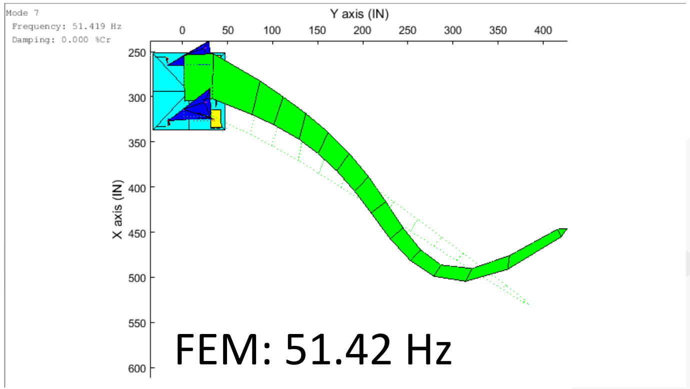
		1	2	3	4	5	6	7	8	9	10	11
Test Shapes		3.48	10.12	10.90	21.23	29.59	35.17	52.25	58.20	77.22	81.50	99.42
1	3.48	100	32		14		6					
2	10.12	32	100		38		12					
3	10.90			100		34			10		5	9
4	21.23	14	38		100		36	7				
5	29.59			34		100			38		16	9
6	35.17	6	12		36		100	24				
7	52.25				7		24	100		20	5	
8	58.20			10		38			100		36	
9	77.22							20		100		
10	81.50			5		16		5	36		100	
11	99.42			9		9						100

Test Mode No.	FEM Mode No.	Test Freq (Hz)	FEM Freq (Hz)	Freq Pct Diff	Cross MAC	CRS XMAC 3%	CRS XMAC All
1	1	3.48	3.38	-2.9	99	99	100
2	2	10.12	10.36	2.4	99	99	100
3	3	10.90	11.16	2.4	97	99	100
4	4	21.23	22.40	5.5	98	99	100
5	5	29.59	30.83	4.2	97	98	99
6	6	35.17	36.90	4.9	96	98	99
7	8	52.25	51.78	-0.9	54	80	99
8	10	58.20	67.82	16.5	73	85	99
9	11	77.22	76.23	-1.3	63	79	98
10	10	81.50	67.82	-16.8	64	80	99
11	12	99.42	93.15	-6.3	95	97	99

FEM/Test Cross MAC Table

FEM Shapes

		1	2	3	4	5	6	7	8	9	10	11	12	13	Test CRSS	Test CRSS
Test Shapes		3.38	10.36	11.16	22.40	30.83	36.90	51.42	51.78	55.10	67.82	76.23	93.15	100.98	**3%**	**All**
1	3.48	99	31												99	100
2	10.12	32	99		41										99	100
3	10.90			97		27									99	100
4	21.23		34		98		43								99	100
5	29.59			41		97		31			25				98	99
6	35.17				31		96			23					98	99
7	52.25							26	54	28		26			80	99
8	58.20					43		62			73				85	99
9	77.22											63		31	79	98
10	81.50										64	32			80	99
11	99.42												95		97	99
CRSS	**3%**	99	99	99	99	98	98	78	74	53	85	79	97	55		
CRSS	**All**	100	100	100	100	99	99	95	82	65	99	99	99	64		



FEM: 51.42 Hz
Lateral wing root metallic plate mode

Config 3: 14 Shakers

FEM assumes everything but wing is fixed

Test Self MAC Table

Test Shapes

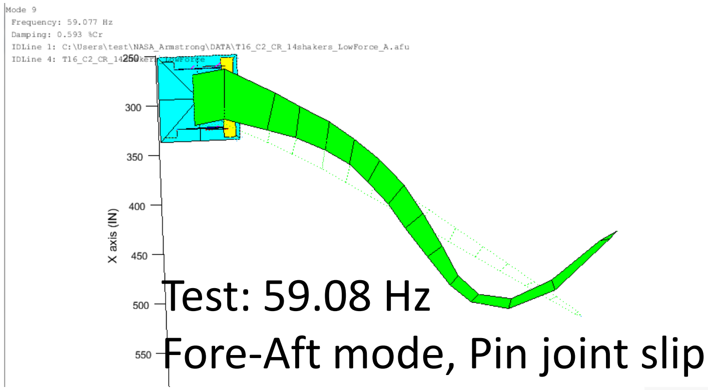
		1	2	3	4	5	6	7	8	9	10	11	12
Test Shapes		3.48	10.05	11.02	21.22	30.15	35.23	52.20	56.67	59.08	77.40	98.45	#####
1	3.48	100	30		13		6						
2	10.05	30	100		37		12						
3	11.02			100		33				8		8	
4	21.22	13	37		100		35	9					
5	30.15			33		100				37		8	
6	35.23	6	12		35		100	25			5		
7	52.20				9		25	100			22		8
8	56.67								100			8	
9	59.08			8		37				100			
10	77.40						5	22			100		21
11	98.45			8		8			8			100	
12	106.17							8			21		100

FEM/Test Cross MAC Table

FEM Shapes

		1	2	3	4	5	6	7	8	9	10	11	12	Test CRSS	Test CRSS
Test Shapes		3.39	10.45	11.35	22.64	31.98	37.46	51.94	55.54	65.92	77.43	93.69	102.17	3%	All
1	3.48	99	29											99	100
2	10.05	31	98		40									99	100
3	11.02			97		26								98	100
4	21.22		35		99		41							99	100
5	30.15			41		96				25				98	100
6	35.23				31		96		20					98	100
7	52.20						20	62	29		22			79	100
8	56.67							42	57					75	100
9	59.08					46				79				89	99
10	77.40										83		22	91	99
11	98.45											95		97	100
12	106.17												74	86	99
CRSS	3%	99	99	98	99	98	98	79	75	89	91	97	86		
CRSS	All	100	100	100	100	99	99	100	99	96	96	99	92		

Test Mode No.	FEM Mode No.	Test Freq (Hz)	FEM Freq (Hz)	Freq Pct Diff	Cross Ortho	CRS XOrtho 3%	CRS XOrtho All
1	1	3.48	3.39	-2.4	99	99	100
2	2	10.05	10.45	4.0	98	99	100
3	3	11.02	11.35	3.0	97	98	100
4	4	21.22	22.64	6.7	99	99	100
5	5	30.15	31.98	6.1	96	98	100
6	6	35.23	37.46	6.3	96	98	100
7	7	52.20	51.94	-0.5	62	79	100
8	8	56.67	55.54	-2.0	57	75	100
9	9	59.08	65.92	11.6	79	89	99
10	10	77.40	77.43	0.0	83	91	99
11	11	98.45	93.69	-4.8	95	97	100
12	12	106.17	102.17	-3.8	74	86	99



Test: 59.08 Hz

Fore-Aft mode, Pin joint slip

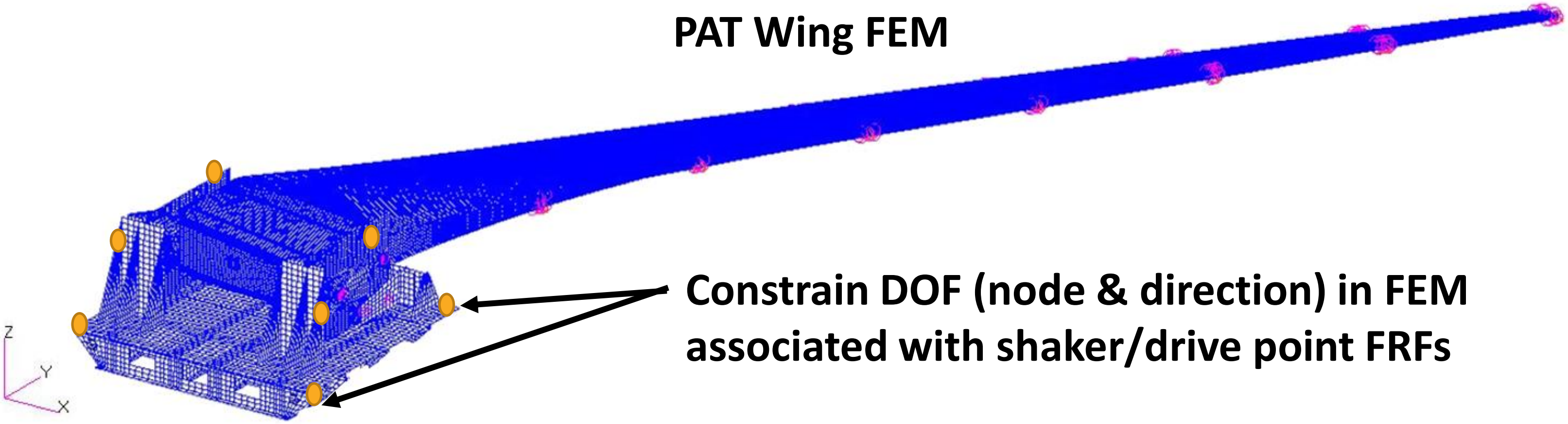
Examples of Mode Shapes

- View Animations of Fixed Base Modes
- Baseline A/F FRF had significant base motion
- Initial shaker set resulted in bending mode of base at 80+ Hz
- Second shaker set removed base bending motion
- Sliding motion of wing root pinned connection amplified when 14 shaker set used

Model Updating Strategy

- Use full finite element model (FEM), but constrain DOF associated with shaker/drive point accelerometers to best match the testing results
  - May have to spread load to avoid stress concentrations & local deformation of “point load” due to single DOF constraint

PAT Wing FEM



Constrain DOF (node & direction) in FEM associated with shaker/drive point FRFs

Test Summary

- Fixed Base Correction method was successfully used to extract fixed base modal results for the PAT wing that was mounted to a dynamically active static test fixture resting unsecured on a test facility floor.
- There are many potential scenarios where this FBC method can be used on future tests of structures mounted on other dynamically active static test fixtures.