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Sandia NRT Blade-0 Laboratory Modal Survey

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For: Sandia National Laboratories

By: National Renewable Energy Laboratory

Sara Fairchild

Ryan Beach

Lindsey Proell

Scott Hughes

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Introduction

Modal testing was performed on the Sandia NRT Blade-0 in building A-60 at NREL/NWTC. Modal testing was intended to identify the fundamental frequencies of the blade. The blade was cantilevered to the A-60 test stand. Fundamental frequencies were identified using impact modal testing. Additional tests included free-decay testing to quantify damping at small displacements. Small-displacement modal testing aims to minimize the influence of aerodynamic damping; roaming accelerometer impact testing with the development of a dynamic frame model enabled visualization of mode shapes.

- Performed under Inter Agency Agreement with Sandia National Laboratory
  - Sandia PO 1793182
  - NREL Subtask WUJJ1000
- Achieves modal testing requirements of IEC 61400-23
- Three different test approaches
  - Fixed Accelerometer Impact
    - Minimize mass loading for accurate frequency measurement
    - April 26, 2017
  - Free decay with laser tracker
    - Evaluate damping at small displacements
    - May 12 and 15, 2017
  - Mode Visualization
    - Roam accelerometers along blade span to visually identify mode shapes
    - June 2, 5, and 6, 2017

Slides are titled using the following color code:

General Information

Fixed Accelerometer Impact Information

Free Decay Information

Mode Visualization

Setup

- Blade mounted to test stand in Building A-60
- Test stand tilted forward by 2 degrees
- M20 180mm bolts with 5 washers used to mount blade to adapter plate
  - Not the same fasteners and torque values used for subsequent static and fatigue testing

Reported Values

- Reported values are the best estimate of modal properties from each of three modal experiment types performed.

Mode #	Mode Description	Frequency [Hz]	Frequency Uncertainty [% of Reading]	Frequency Source	Damping [% Critical]	Damping Uncertainty [% of Reading]	Damping Source
1	1st Flat	2.19	0.25	1	0.11	4.8	2
2	1st Edge	4.92	0.25	1	0.20	4.8	2
3	2nd Flat	7.06	0.25	1	0.14	Not reported	1
4	3rd Flat	14.5	0.25	1	0.16	Not reported	1
5	2nd Edge	18.1	0.25	1	0.23	Not reported	1
6	4th Flat / Torsion	24.0	0.25	1	0.20	Not reported	1
7	1st Torsion	26.6	0.25	1	0.19	Not reported	1
8	Flat / Edge / Torsion	35.7	0.25	1	0.24	Not reported	1
9	3rd Edge	42.0	0.25	1	0.40	Not reported	1
10	2nd Torsion	46.2	0.25	1	0.30	Not reported	3

1 – Fixed Accelerometer Impact
2 – Free Decay
3 – Mode Visualization Roaming Accelerometer

Equipment

Impact Test Equipment

- PCB 352M202 accelerometers (4)
  - +- 5g
  - Nominal sensitivity 1000 mV/g
- PCB 086C41 impact hammer
  - Grey tip
  - s/n 28212
- VXI CT100C Chassis
  - s/n 113653
- EX2500A LXI-VXI Interface
  - s/n 122689
- VT1432B Digitizer
  - s/n US45003438
- ME'scope installed on laptop
  - Version5.2.2012.0302

Laser Tracker Equipment for free decay measurement

Item	Serial Number / Software Version	Calibration Date
API Tracker 3	LTS36821208	April 20,2015
Spherically mounted Retroreflector (SMR)	API 11725	n/a
SpatialAnalyzer Software	SA 2015.06.12_6003	n/a

PCB 352M202 Accelerometers for Impact Testing

Serial Number	mV/g @ 10 Hz	Last Calibration Date	Location on Blade	Fixed Impact use
103551	1019.8656	7/20/2016	TE_X	X
103904	987.5186	7/20/2016	TE_Y	X
103535	1010	5/8/2009	LE_Y	
103555	1013.9616	12/2/2014	LE_X	

Fixed Accelerometer Impact

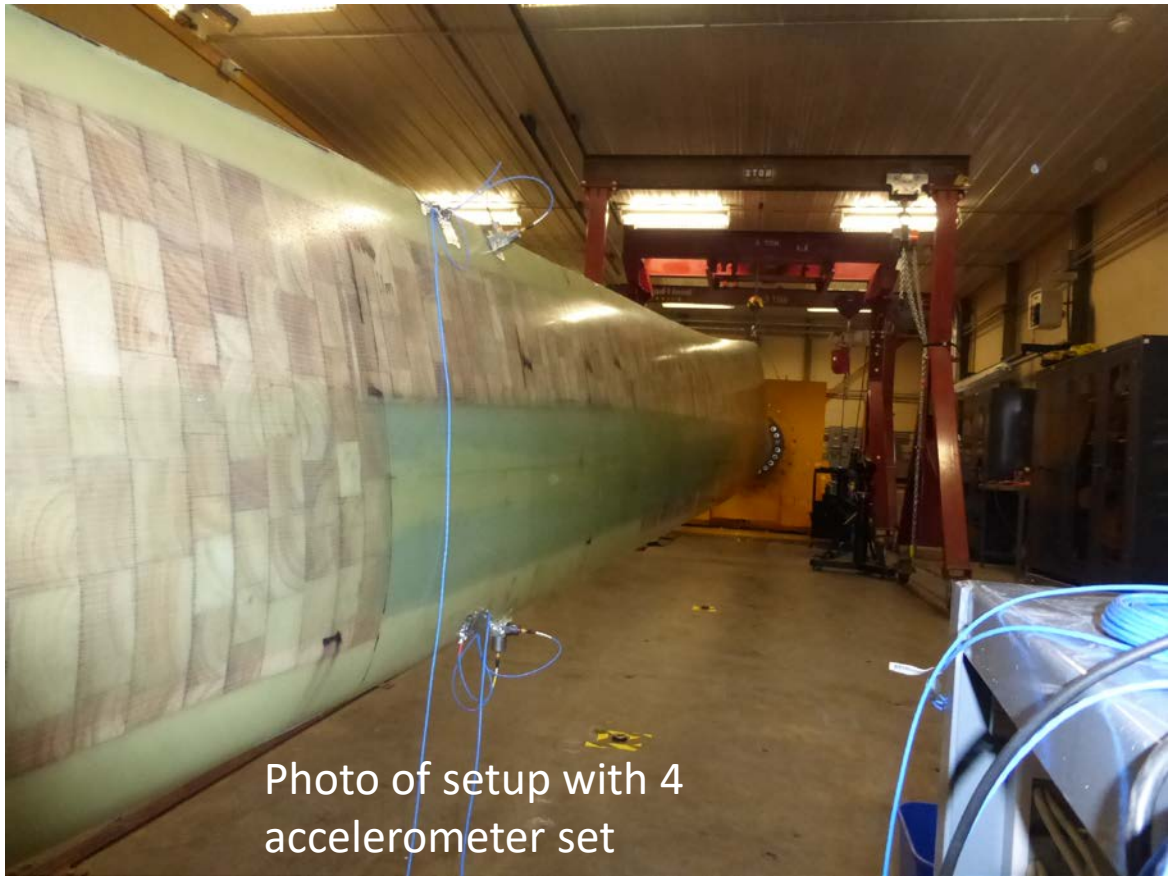
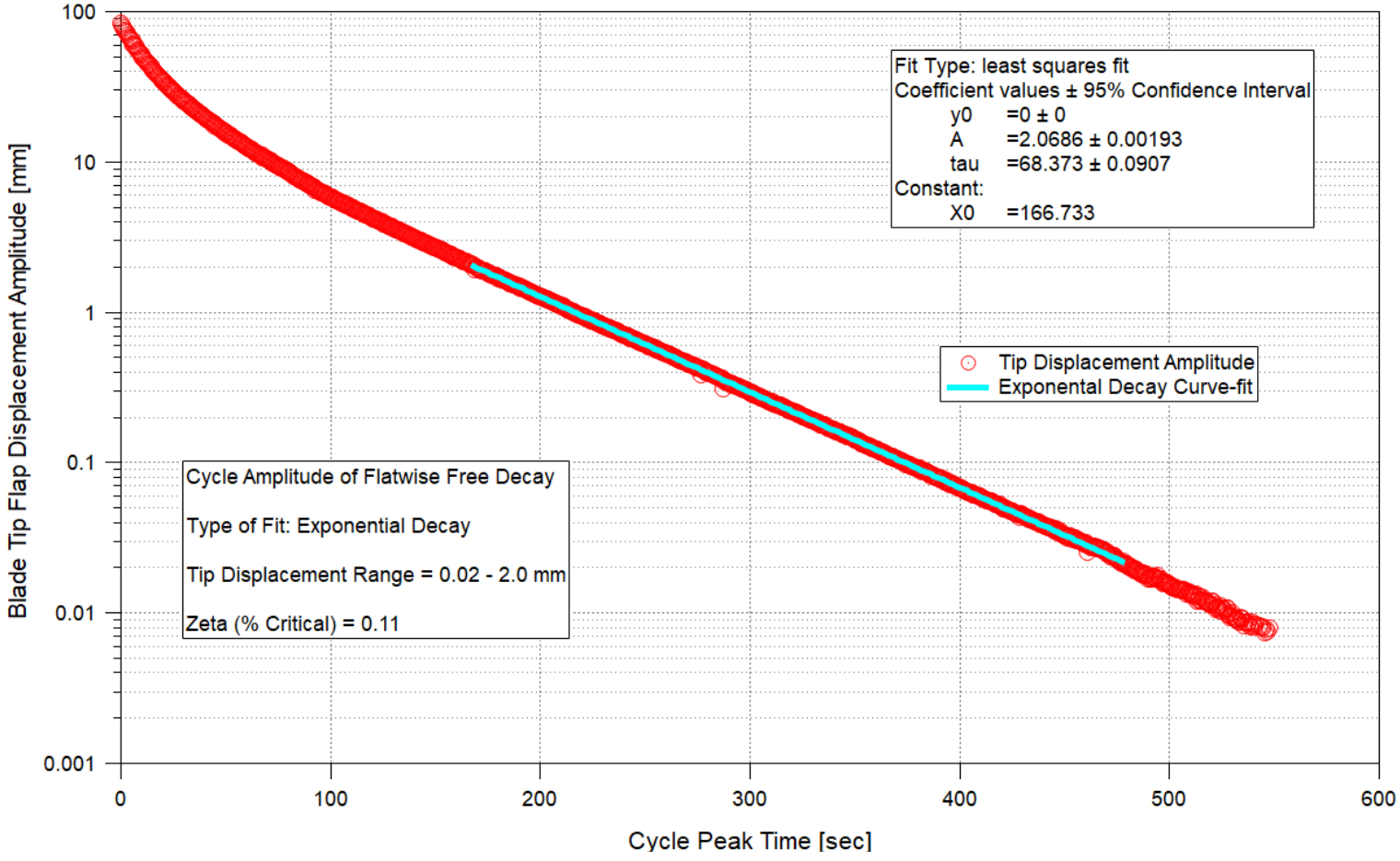


Photo of setup with 4 accelerometer set

- Minimize mass-loading of instrumentation for accurate frequency measurement
- Blade temperature measured with IR thermometer as 19 C
- 2 Accelerometers installed at 11 m station
  - Accelerometer set mass = 75 g
- Hammer Impact
  - x-direction on spar cap at 9 m station
  - y-direction on trailing edge at 9 m station
- DAQ Setup
  - 60-hz bandwidth
  - 8192 sample acquisition
  - 0.0073 time resolution
  - No windowing
- Average 3 impact hits, FRF peaks for frequency
- Damping reported from ME'scope

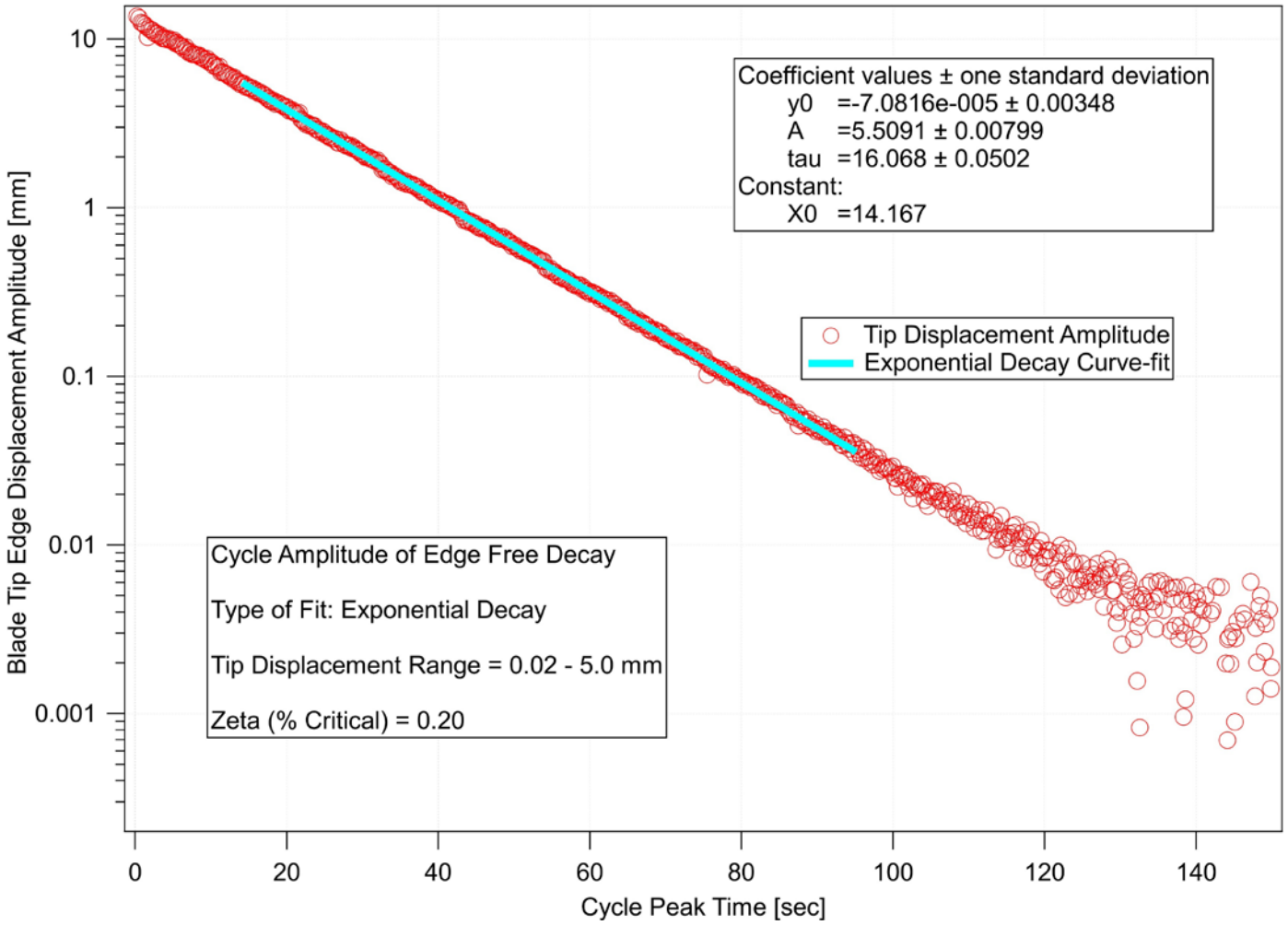
Free Decay Damping – 1st Flat

- API Laser Tracker used to measure tip displacement
- Laser tracker spherically mounted retroreflector (SMR) hot glued to blade tip
- Mass of SMR and nest – 197 g
- Blade manually excited at 1st flat frequency
- Calculate cyclic displacement amplitude
- Curve-fit linear section of log-lin amplitude-time response to report linear viscous damping coefficient
  - Aerodynamic damping minimized at small deflections
- Result – 1st Flat structural damping 0.11 % critical



Free Decay Damping – 1st Edgewise

- API Laser Tracker used to measure tip displacement
- Laser tracker spherically mounted retroreflector (SMR) hot glued to blade tip
- Mass of SMR and nest – 197 g
- Blade manually excited at 1st edge frequency
- Calculate cyclic displacement amplitude
- Curve-fit linear section of log-lin amplitude-time response to report linear viscous damping coefficient
  - Small displacements minimize influence of aerodynamic damping
- Result – 1st edge structural damping 0.20 % critical



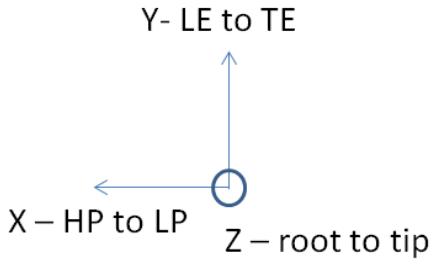
Mode Visualization – Test Procedure

- Shape balsa wood blocks to airfoil at measurement stations
- Apply aluminum tape to blade, hot glue balsa blocks at all stations
- DAQ setup
  - 8192 Samples
  - Time Resolution .007813
  - 64 second acquisition time
  - Force window for hammer
  - No response windowing
- Impact hits at 9 m station
  - FRF averaging for 3 hits
  - ME'scope model and visualization

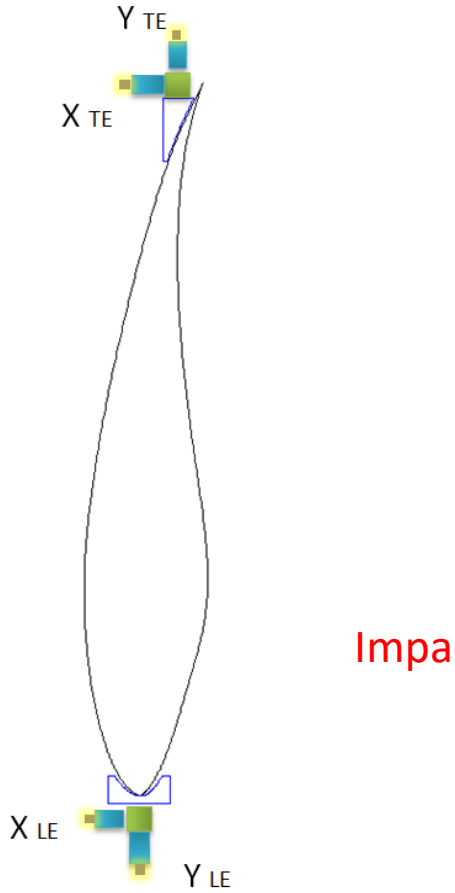
Balsa blocks mounted during mode visualization testing

Mode Visualization – Accelerometers and Impact Hammer

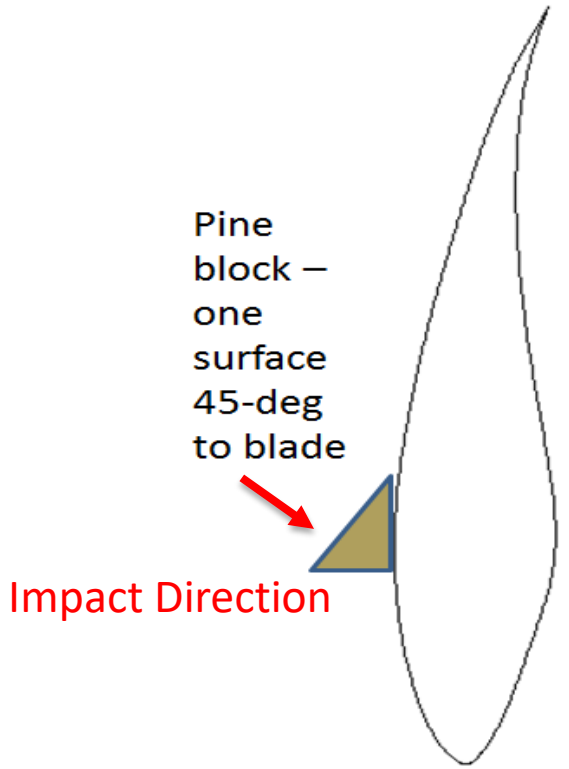
- 4 Accelerometers
  - x, y pair at leading edge
  - x, y pair at trailing edge
  - 4 Accelerometer set roamed between 8 blade stations
- Accelerometer mounting
  - Blade formed balsa blocks hot glued to blade
  - Balsa blocks always on blade, about 60 g at each measurement station
  - Accelerometer set with balsa blocks weighed about 214 g
- Impact Hammer
  - Pine wood block hot glued to blade with 45-deg face
  - Impact driving point at 9 m station on low pressure side
  - Impact on 45-deg face of pine wood block



Accelerometer Naming Convention



Hammer Impact setup



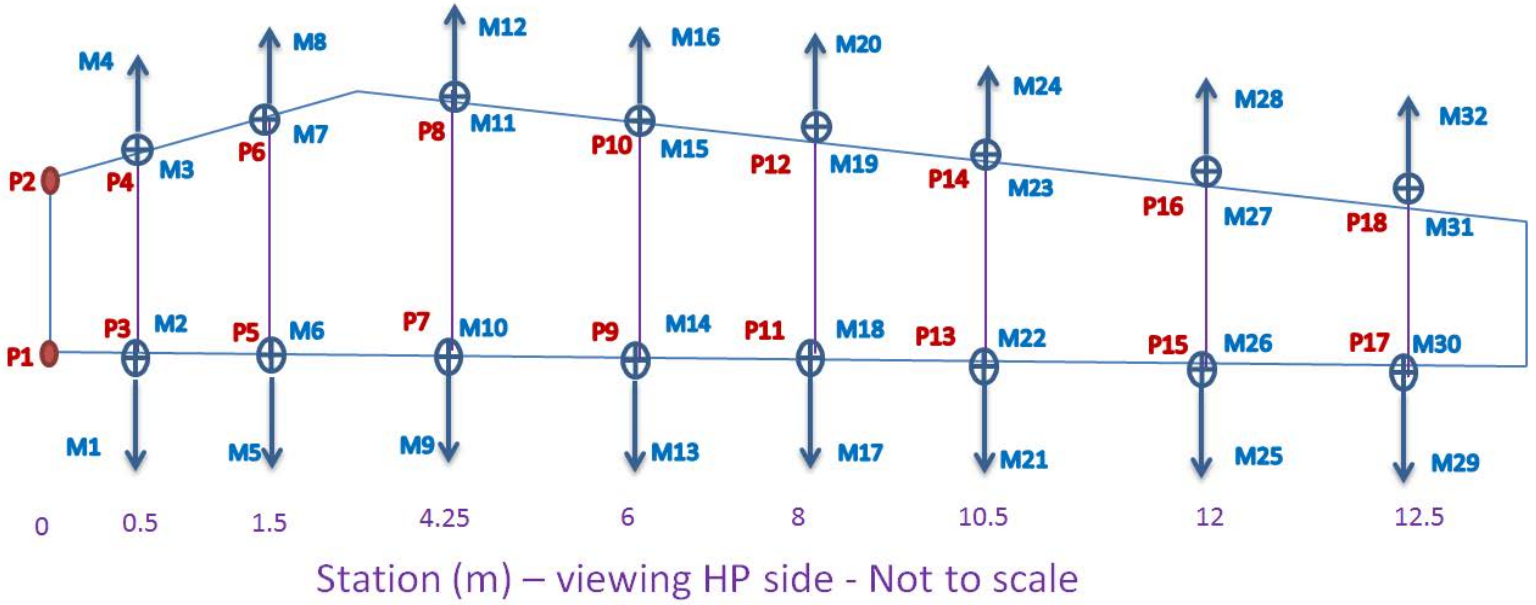
Mode Visualization – Blade Model Accelerometer locations

- X-position assumed zero for model
- Actual Y-position offset by placement of balsa blocks

Measurement Station [m from root]	Chord Length [m]	Blade LE Y-position [m]	Blade TE Y-position [m]
0.5	0.609	-0.305	0.305
1.5	1.116	-0.413	0.703
4.25	1.347	-0.404	0.943
6	1.105	-0.332	0.774
8	0.882	-0.265	0.617
10.5	0.663	-0.199	0.464
12	0.482	-0.145	0.337
12.5	0.365	-0.110	0.256

Mode Visualization – Modal Map

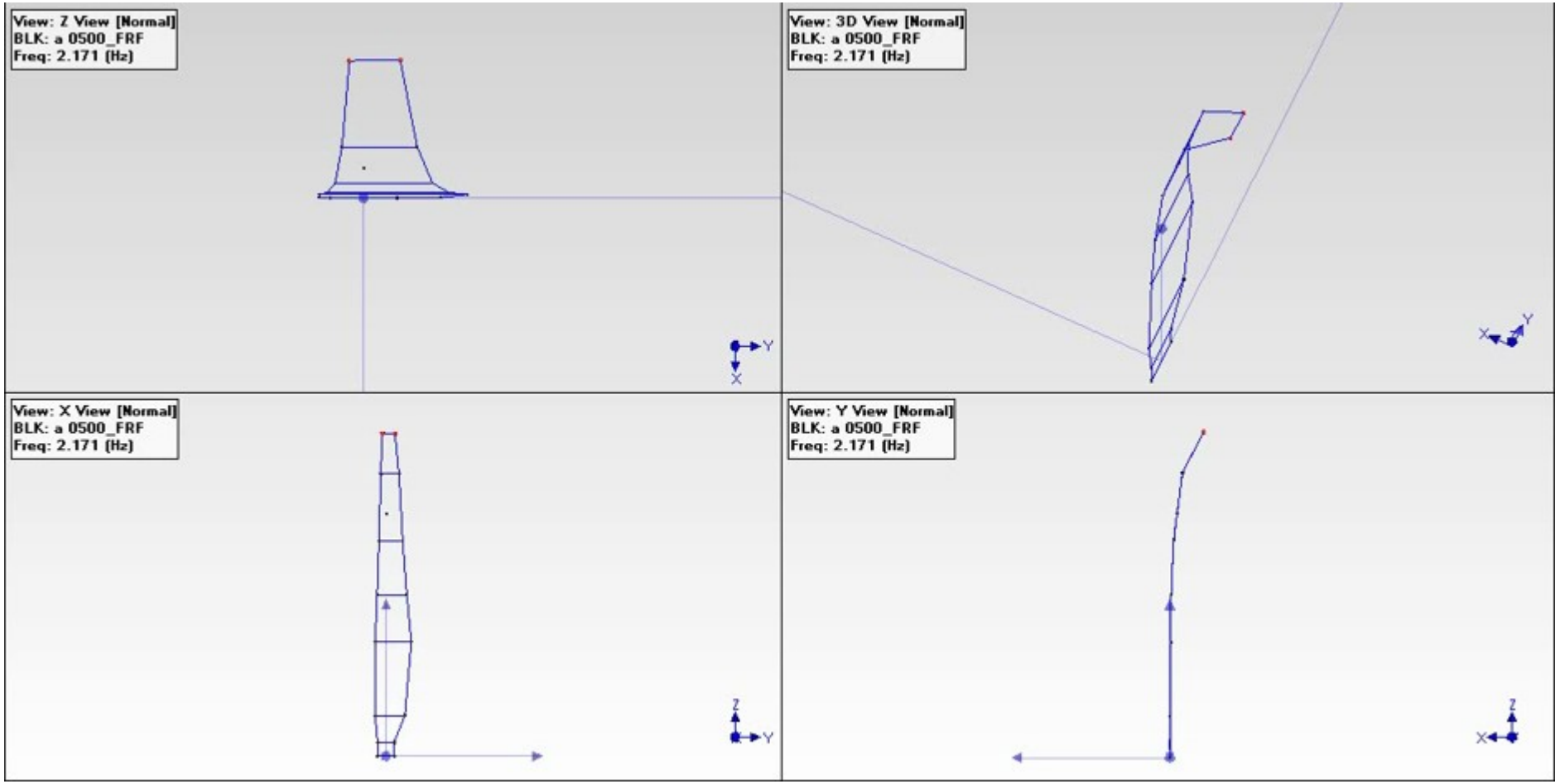
- Hammer impact at 9 m station, LP side
- Accelerometer set roamed at 8 blade stations
- Data from 12.5m accelerometer set not used – scaling and orientation discrepancies
- Modal map used for ME'scope structure



P19 - hammer impact location at the 9 m station (not shown in wire model)

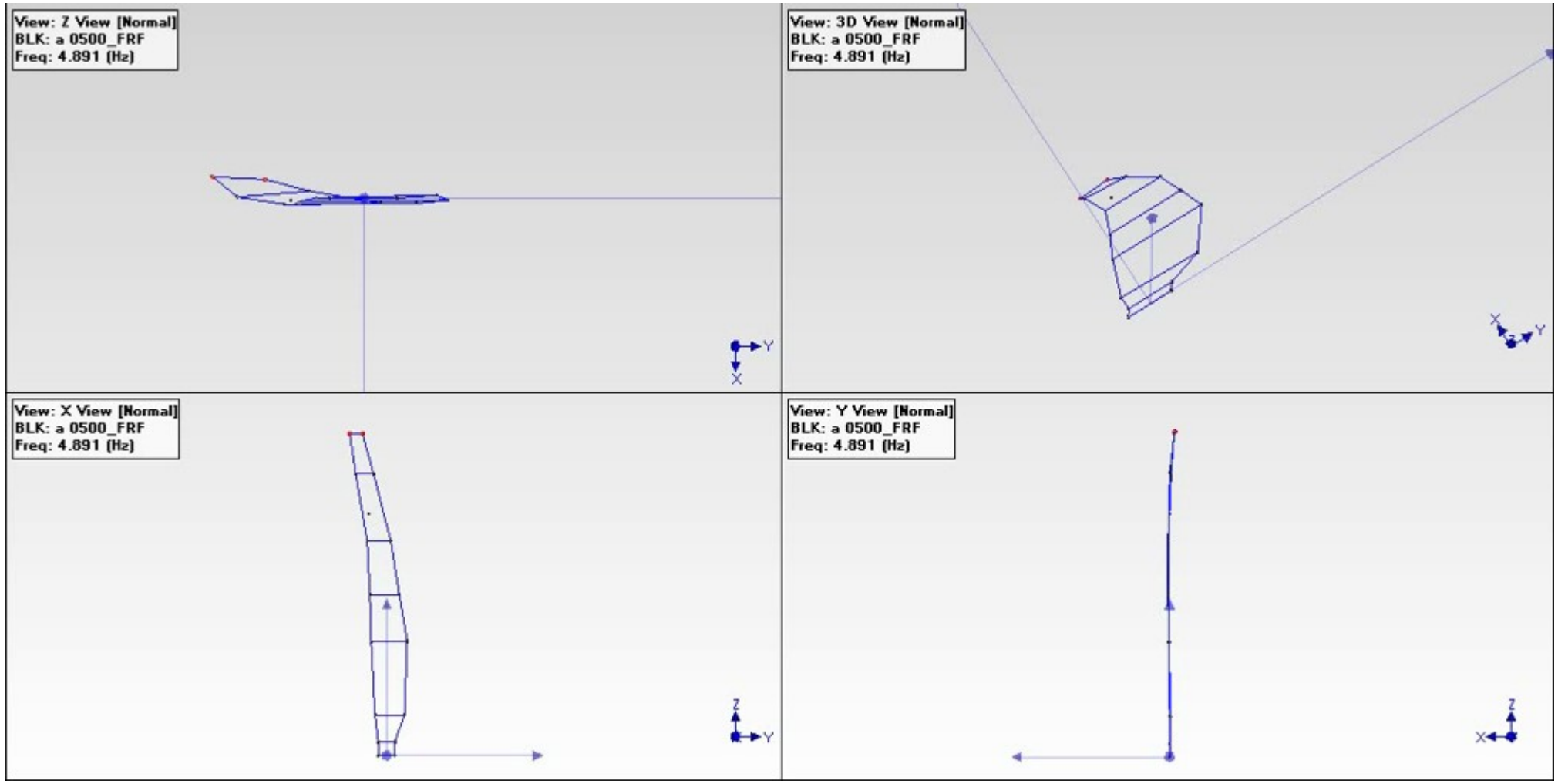
Mode Visualization – Mode 1

- 1st Flat
  - 2.17 Hz



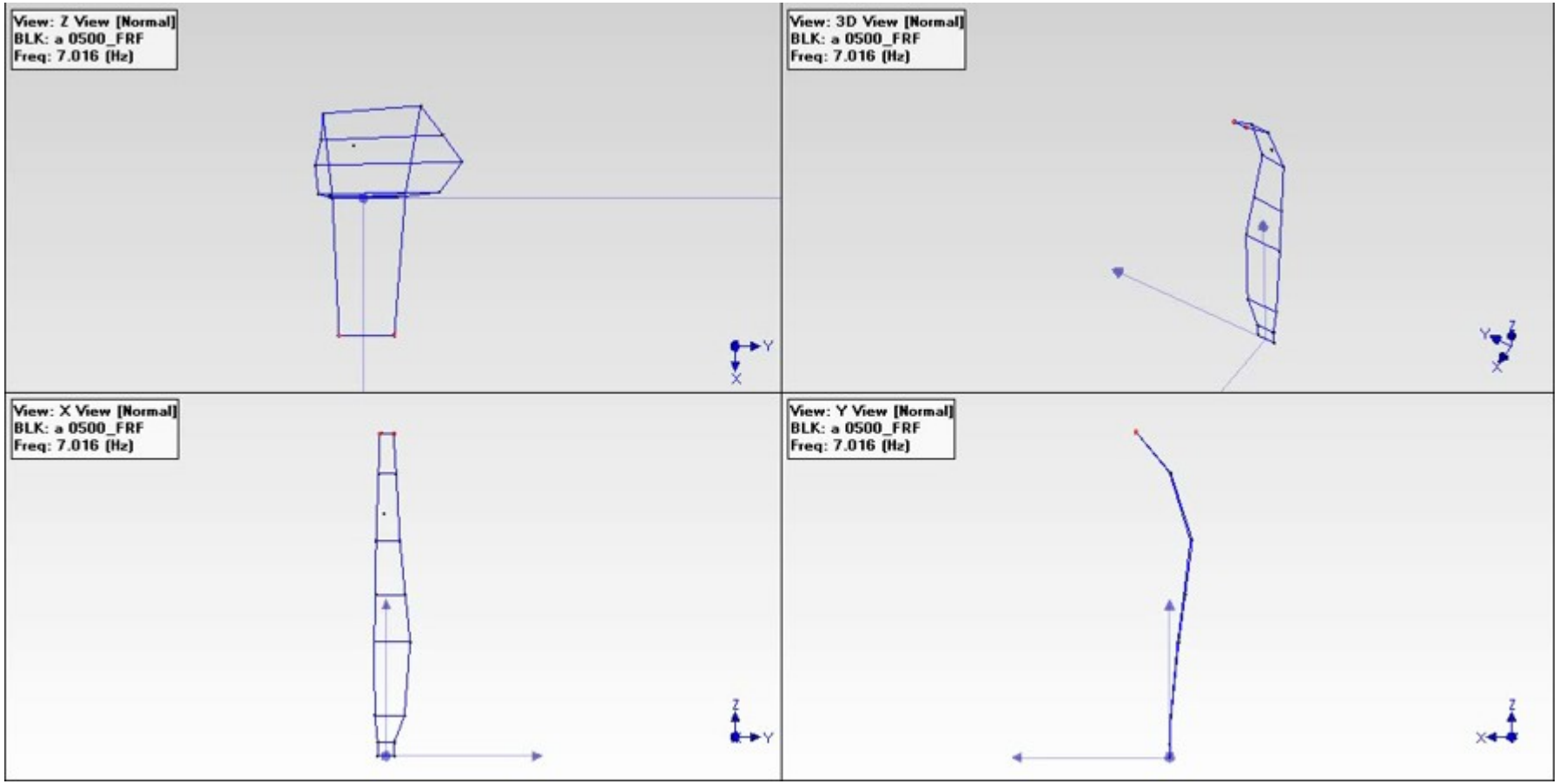
Mode Visualization – Mode 2

- 1st Edge
  - 4.89 Hz



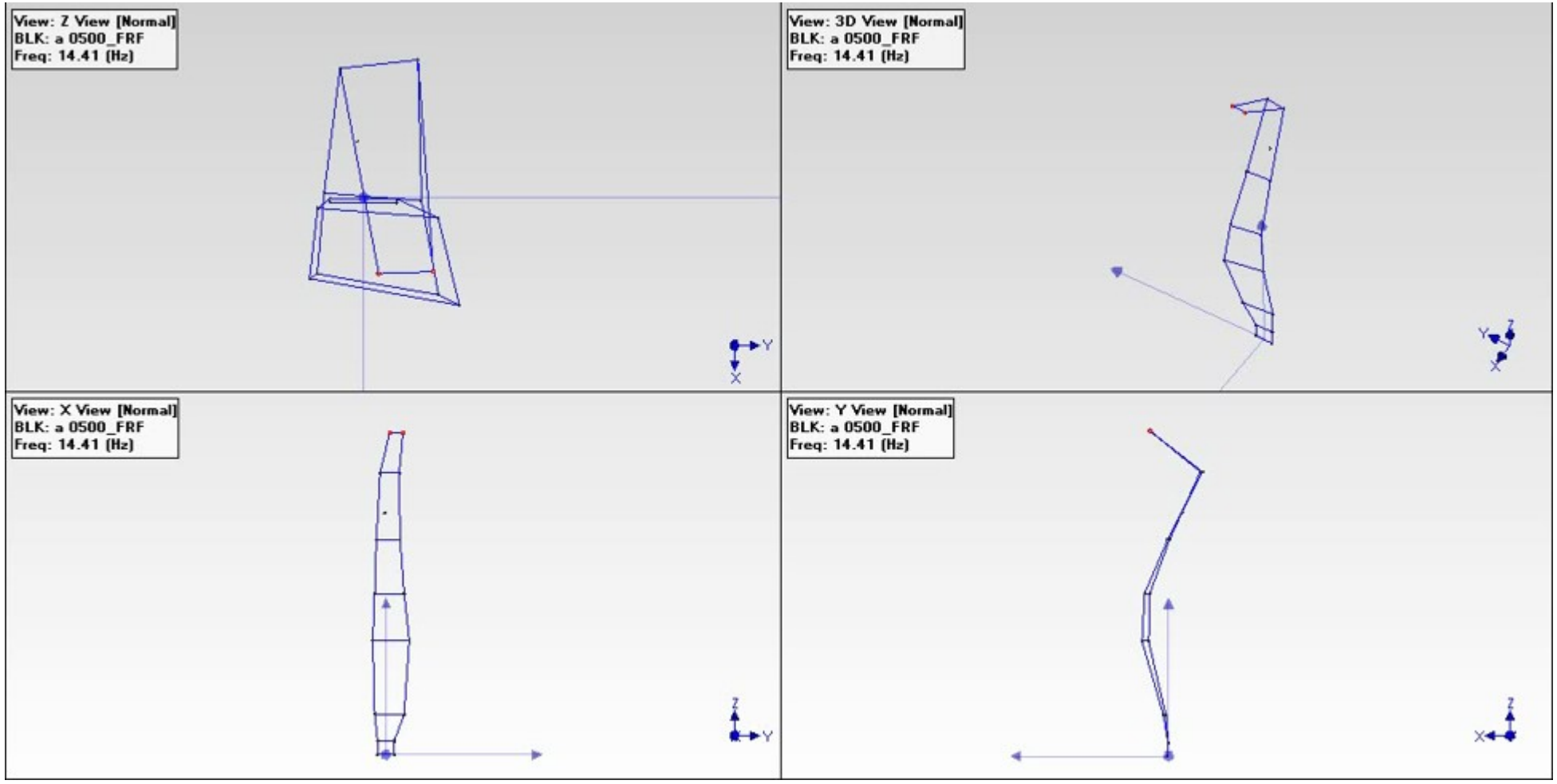
Mode Visualization – Mode 3

- 2nd Flat
  - 7.02 Hz



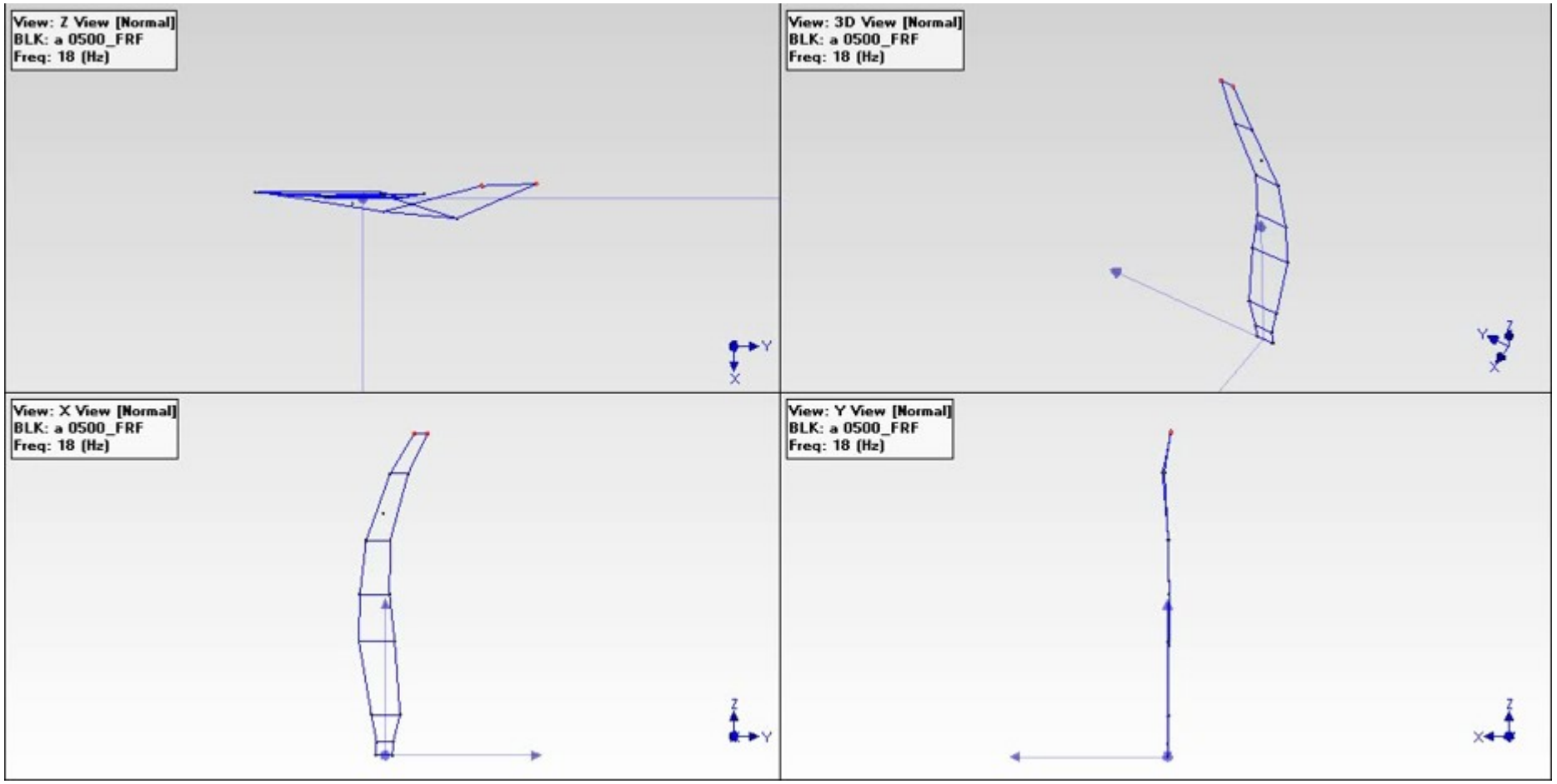
Mode Visualization – Mode 4

- 3rd Flat
  - 14.4 Hz



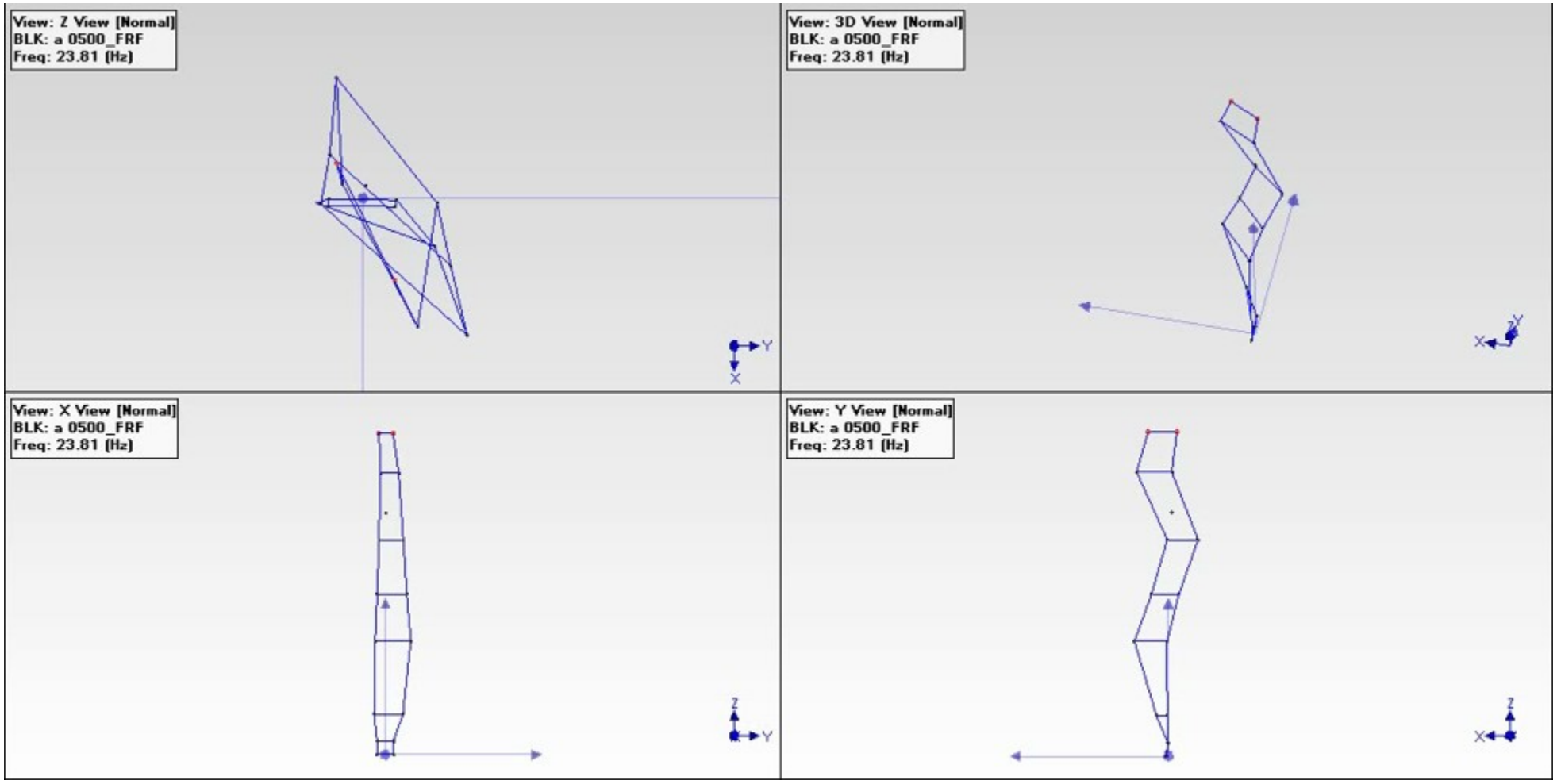
Mode Visualization – Mode 5

- 2nd Edge
  - 18.0 Hz



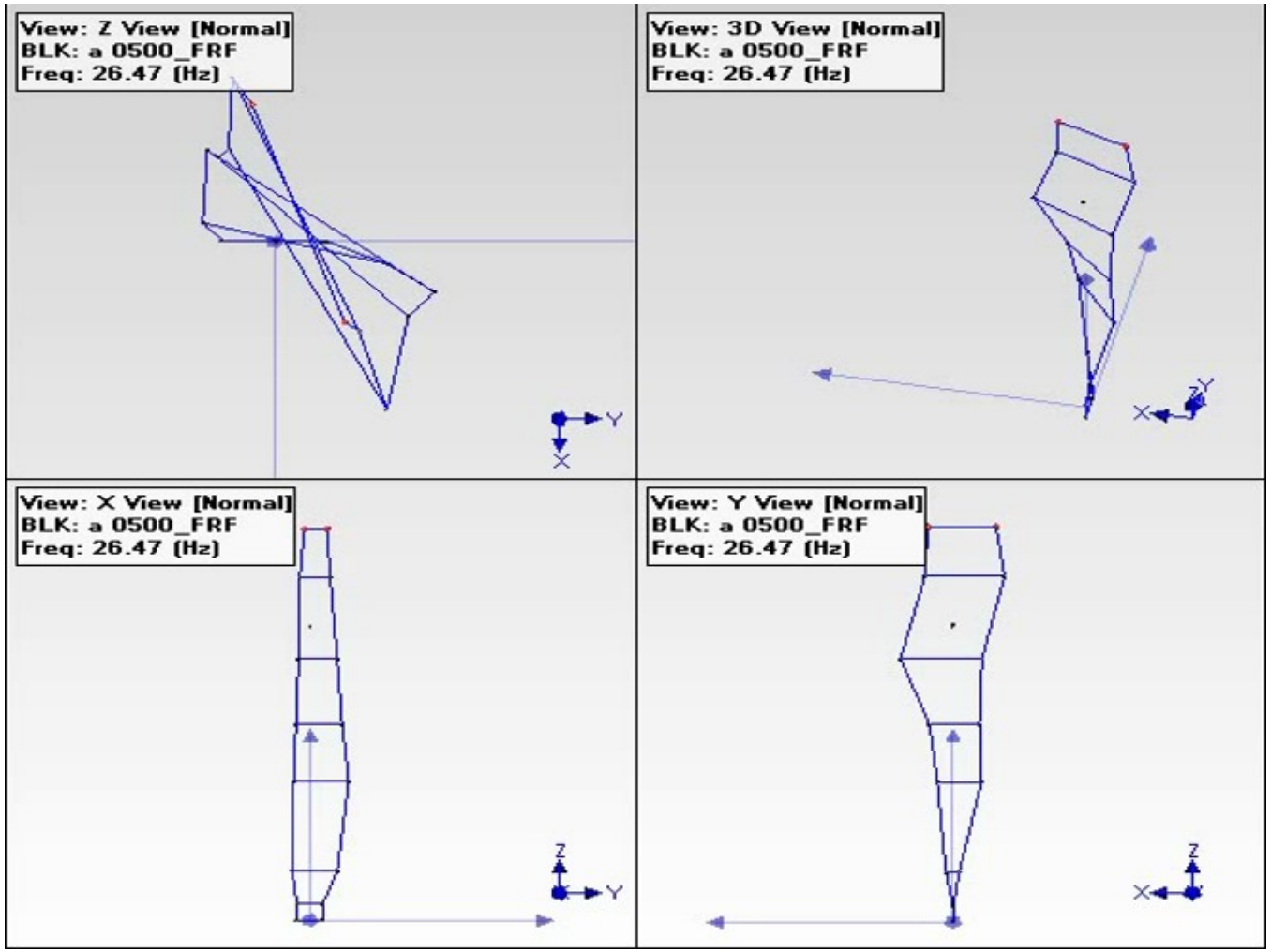
Mode Visualization – Mode 6

- 4th Flat / Torsion
  - 23.8 Hz



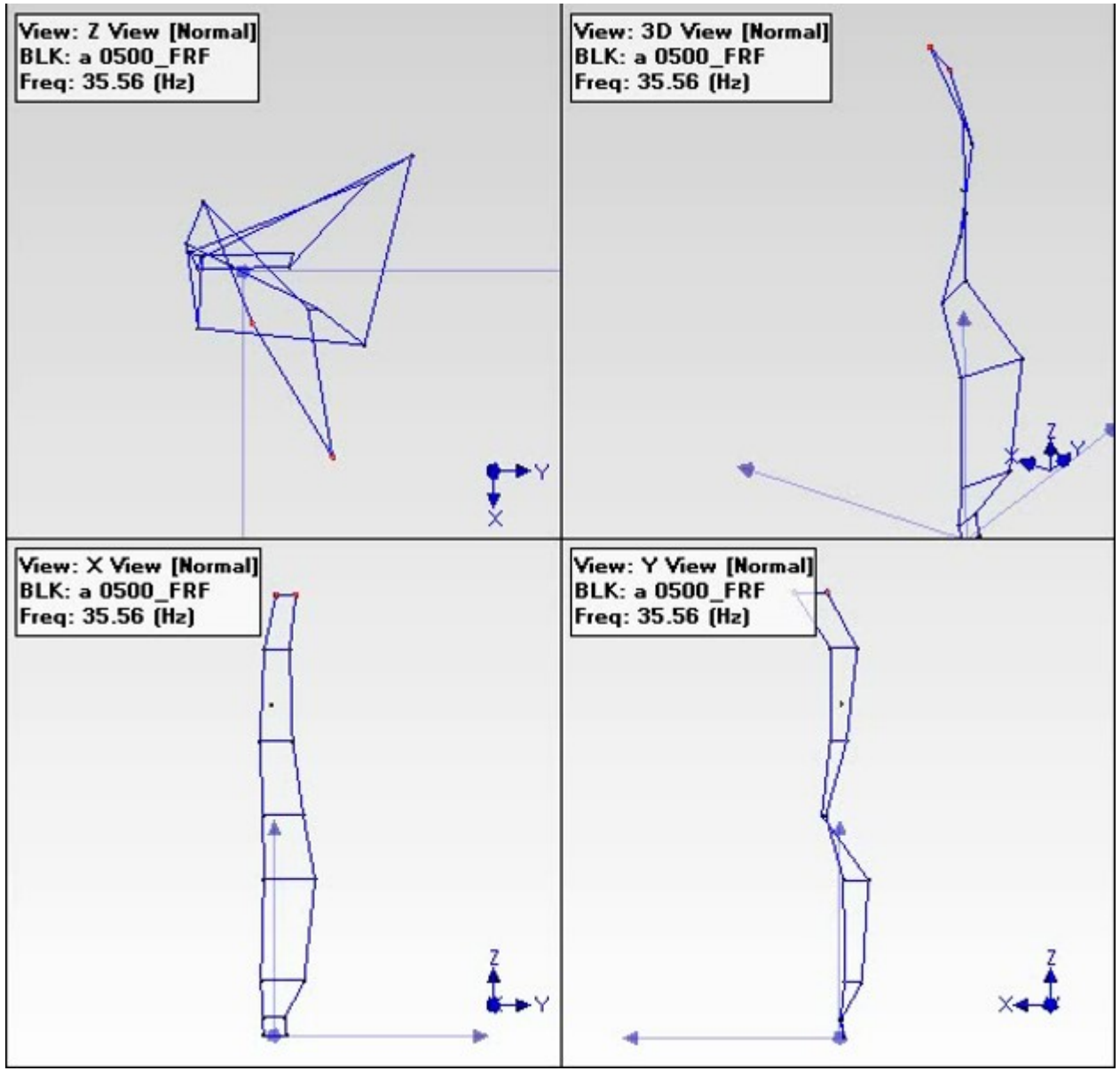
Mode Visualization – Mode 7

- 1st Torsion
  - 26.5 Hz



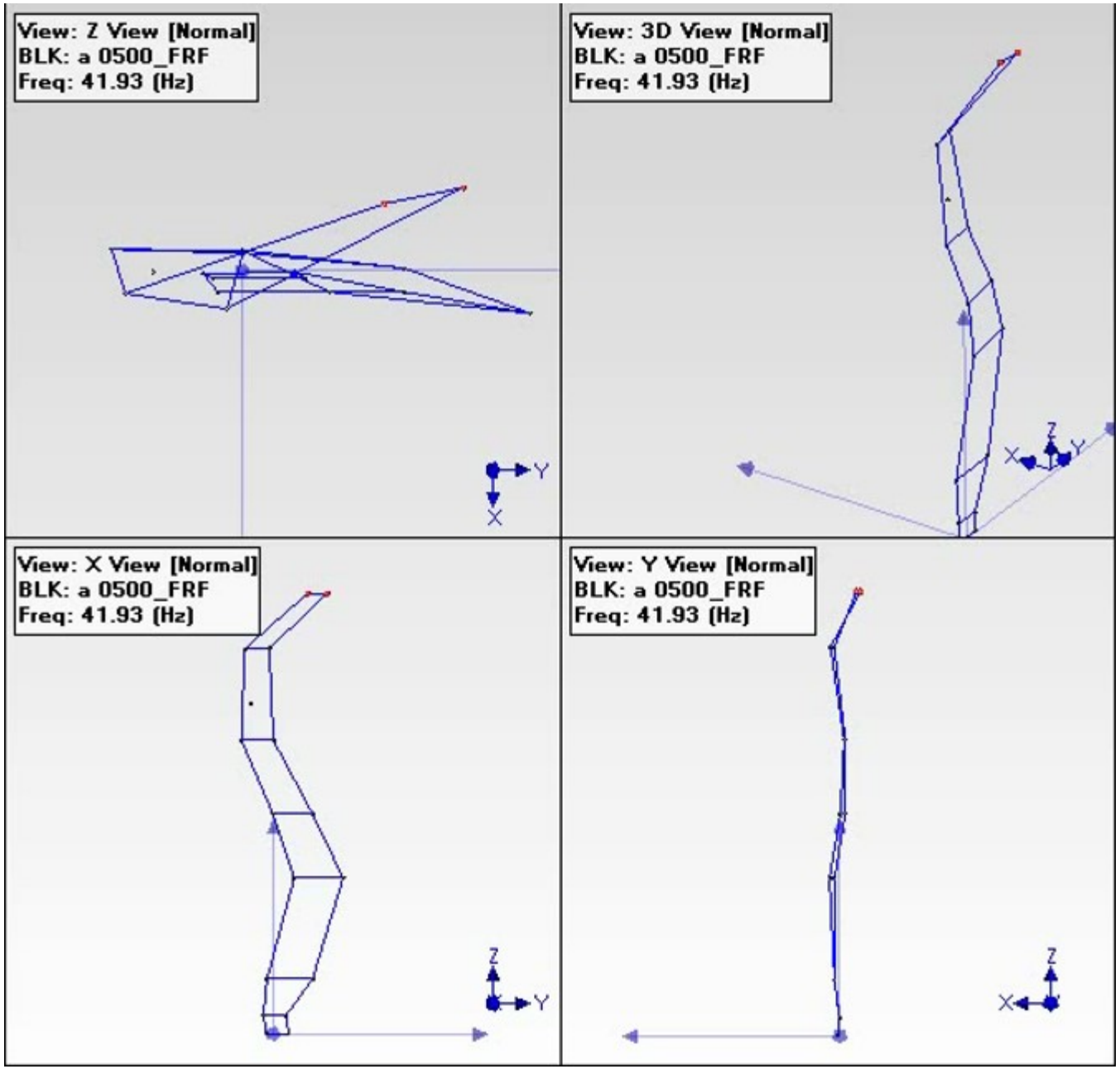
Mode Visualization – Mode 8

- Torsion/Flat/Edge
  - 35.6 Hz



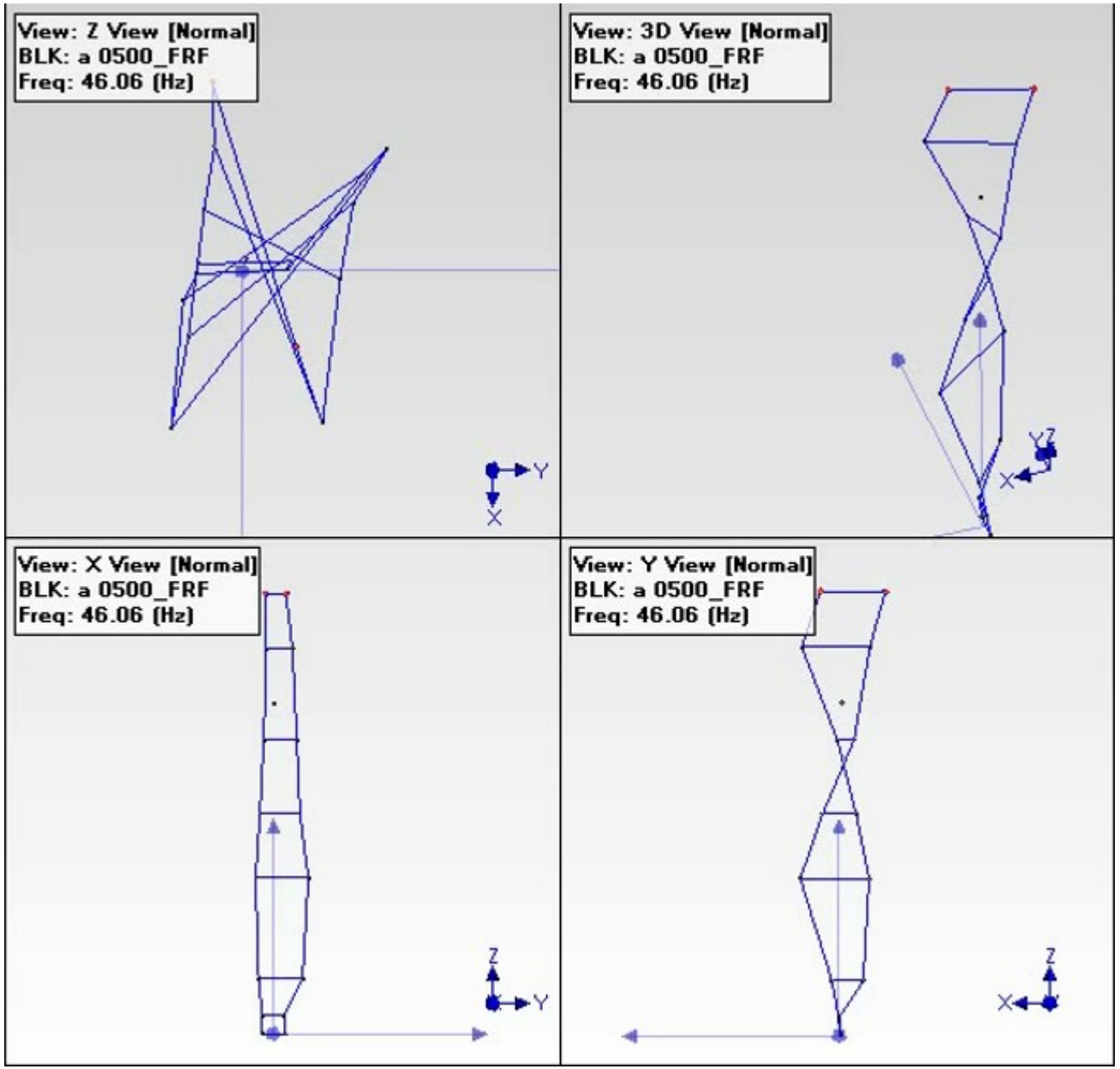
Mode Visualization – Mode 9

- 3rd Edge
  - 41.9 Hz



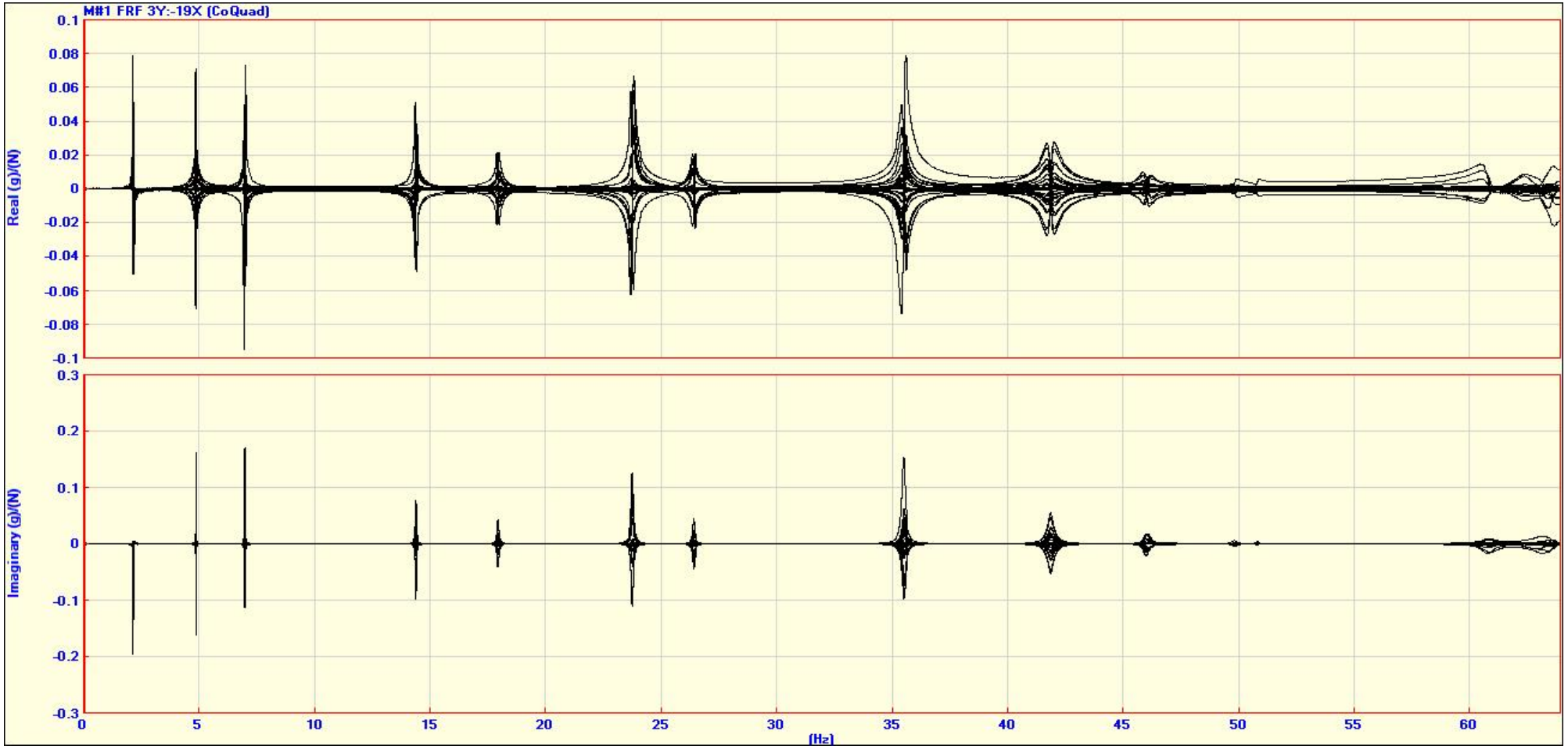
Mode Visualization – Mode 10

- 2nd Torsion
  - 46.1 Hz



Mode Visualization – FRFs

- Co Quad for FRF's used for Mode Visualization from ME'scope



Mode Visualization – Frequency and % Damping

- Frequency and % Damping reported from ME'scope
- Values from FRF data sets for each accelerometer station

	Mode 1		Mode 2		Mode 3		Mode 4		Mode 5		Mode 6		Mode 7		Mode 8		Mode 9	
	2.172		4.894		7.02		14.42		18		23.82		26.5		35.57		42.13	
Accelerometer Station [m]	Hz	% Damp	Hz	% Damp	Hz	% Damp	Hz	% Damp	Hz	% Damp	Hz	% Damp	Hz	% Damp	Hz	% Damp	Hz	% Damp
0.50	2.172		4.894	0.2021	7.021	0.1417	14.41	0.1478	17.9	0.2324	23.82	0.1956			35.57	0.236	41.93	0.3785
1.50	2.172		4.894	0.1954	7.02	0.142	14.42	0.1488	18.01	0.2323	23.82	0.2012	26.5	0.186	35.57	0.2394	42.13	0.3873
4.25	2.179		4.894	0.2	7.02	0.1354	14.41	0.1524	18	0.2405	23.81	0.2021	26.49	0.1943	35.57	0.2404	41.92	0.3887
6.00	2.172	0.1081	4.895	0.1971	7.019	0.1433	14.41	0.151	18	0.2325	23.82	0.2009	26.48	0.1943	35.57	0.2392	41.92	0.3851
8.00	2.177	0.1478	4.892	0.2604	7.018	0.2009	14.42	0.1587	18.01	0.2345	23.81	0.2034	26.45	0.1877	35.58	0.2369	41.93	0.3876
10.50	2.176	0.1411	4.892	0.1867	7.023	0.1346	14.41	0.1499	18.01	0.2328	23.81	0.1994	26.46	0.1938	35.58	0.238	41.95	0.3881
12.00	2.174		4.889	0.2063	7.012	0.1472	14.42	0.1497	17.99	0.2402	23.82	0.2042	26.48	0.1869	35.55	0.2437	41.93	0.3942
12.50	2.169	0.1347	4.885	0.206	6.996	0.1478	14.38	0.1668	17.96	0.2545	23.79	0.2105	26.47	0.1761	35.55	0.2419	41.83	0.3997

Mode Visualization – Modal Assurance Criteria

- MAC values as reported from ME'scope

Shape Frequency [Hz]	2.175	4.891	6.995	14.34	17.98	23.81	26.46	35.56	41.93	46.09
2.175	1.0000	0.0145	0.7843	0.1461	0.0009	0.0101	0.0063	0.0773	0.0133	0.0108
4.891	0.0145	1.0000	0.0092	0.0158	0.1694	0.0001	0.0000	0.0147	0.0368	0.0003
6.995	0.7843	0.0092	1.0000	0.1591	0.0011	0.0004	0.0028	0.0204	0.0053	0.0027
14.34	0.1461	0.0158	0.1591	1.0000	0.0031	0.0179	0.0019	0.0190	0.0013	0.0161
17.98	0.0009	0.1694	0.0011	0.0031	1.0000	0.0011	0.0004	0.0012	0.0591	0.0006
23.81	0.0101	0.0001	0.0004	0.0179	0.0011	1.0000	0.3334	0.0014	0.0047	0.0201
26.46	0.0063	0.0000	0.0028	0.0019	0.0004	0.3334	1.0000	0.0646	0.0009	0.0755
35.56	0.0773	0.0147	0.0204	0.0190	0.0012	0.0014	0.0646	1.0000	0.0011	0.1257
41.93	0.0133	0.0368	0.0053	0.0013	0.0591	0.0047	0.0009	0.0011	1.0000	0.0001
46.09	0.0108	0.0003	0.0027	0.0161	0.0006	0.0201	0.0755	0.1257	0.0001	1.0000

Mode Visualization – Mode Shapes

- Unscaled mode shapes from ME'scope

DOFs	Response Direction	Y location	Z location	2.175 (Hz)	4.891 (Hz)	6.995 (Hz)	14.344 (Hz)	17.985 (Hz)	23.809 (Hz)	26.464 (Hz)	35.559 (Hz)	41.928 (Hz)	46.095 (Hz)
3Y:-19X	Y	-0.305	0	3.262E-07	2.465E-05	6.062E-06	3.064E-06	2.393E-04	1.213E-04	8.748E-05	1.038E-03	4.587E-03	2.347E-04
3X:-19X	X	-0.305	0	2.756E-06	1.009E-07	1.383E-05	2.880E-05	2.932E-05	3.998E-04	2.597E-04	2.243E-03	2.017E-03	5.230E-04
4X:-19X	X	0.305	0	2.439E-06	2.686E-06	1.662E-05	3.727E-05	1.815E-05	1.166E-03	6.090E-05	4.265E-03	7.117E-04	2.357E-04
4Y:-19X	Y	0.305	0	1.285E-07	1.647E-05	4.494E-06	2.485E-07	1.904E-04	2.156E-04	1.428E-05	2.017E-04	4.479E-03	1.055E-04
5Y:-19X	Y	-0.305	0.5	3.456E-06	1.923E-04	3.388E-05	4.569E-05	1.616E-03	1.033E-03	4.128E-04	7.005E-03	2.418E-02	6.351E-04
5X:-19X	X	-0.305	0.5	2.923E-05	1.719E-05	1.409E-04	2.581E-04	4.332E-04	2.701E-03	3.019E-03	1.738E-02	1.394E-02	5.196E-03
6X:-19X	X	0.305	0.5	1.951E-05	1.524E-04	1.983E-04	4.930E-04	5.801E-04	2.641E-02	3.468E-03	8.096E-02	1.361E-02	1.831E-02
6Y:-19X	Y	0.305	0.5	2.077E-06	2.470E-04	4.982E-05	6.697E-05	2.216E-03	2.888E-03	9.215E-04	1.672E-02	3.794E-02	2.792E-03
7Y:-19X	Y	0.703	1.5	2.113E-05	1.041E-03	1.799E-04	2.887E-04	9.256E-03	1.462E-03	3.533E-04	1.860E-02	1.008E-01	2.208E-03
7X:-19X	X	0.703	1.5	2.195E-04	1.586E-04	1.537E-03	2.396E-03	1.056E-03	3.287E-03	1.642E-02	1.366E-02	1.419E-02	2.942E-02
8X:-19X	X	-0.404	1.5	2.149E-04	9.954E-05	1.690E-03	3.193E-03	5.286E-04	8.065E-02	8.733E-03	1.083E-01	2.896E-02	2.231E-02
8Y:-19X	Y	-0.404	1.5	1.715E-05	1.072E-03	2.348E-04	2.317E-04	9.456E-03	4.672E-04	2.185E-04	2.463E-02	9.900E-02	3.716E-04
9Y:-19X	Y	0.943	4.25	4.942E-05	1.760E-03	2.069E-04	2.395E-04	9.156E-03	1.890E-03	1.315E-04	4.794E-03	3.332E-02	8.591E-04
9X:-19X	X	0.943	4.25	7.217E-04	3.264E-04	2.046E-03	1.847E-03	1.043E-03	2.399E-02	1.443E-02	5.084E-02	1.413E-02	1.204E-02
10X:-19X	X	-0.332	4.25	7.228E-04	2.785E-04	2.222E-03	2.369E-03	9.968E-04	3.716E-02	1.257E-02	6.585E-02	2.109E-03	1.188E-02
10Y:-19X	Y	-0.332	4.25	5.269E-05	1.792E-03	2.046E-04	2.493E-04	9.116E-03	1.668E-03	1.551E-04	4.013E-03	2.989E-02	1.191E-03
11Y:-19X	Y	-0.774	6	6.282E-05	2.582E-03	4.556E-04	2.279E-04	6.783E-03	1.554E-03	3.588E-05	1.499E-02	6.064E-02	4.284E-04
11X:-19X	X	-0.774	6	1.240E-03	3.106E-04	3.394E-03	8.259E-05	2.014E-04	6.748E-02	1.507E-02	2.462E-02	1.463E-02	1.085E-02
12X:-19X	X	-0.265	6	1.265E-03	2.593E-04	3.704E-03	8.324E-05	3.420E-04	2.585E-03	2.759E-02	3.437E-02	1.234E-02	1.011E-03
12Y:-19X	Y	-0.265	6	7.580E-05	2.610E-03	4.357E-04	2.166E-04	6.599E-03	3.573E-03	8.745E-04	1.401E-02	6.180E-02	8.554E-04
13Y:-19X	Y	0.617	8	2.946E-05	5.249E-03	3.606E-04	2.432E-05	5.517E-03	8.929E-04	1.097E-03	8.444E-03	5.765E-02	9.020E-04
13X:-19X	X	0.617	8	3.410E-03	6.224E-05	1.217E-05	3.076E-03	2.084E-03	7.281E-03	2.780E-02	6.214E-02	1.604E-02	2.296E-02
14X:-19X	X	-0.199	8	3.417E-03	3.487E-04	1.649E-04	3.281E-03	2.952E-03	7.108E-02	1.537E-02	3.390E-02	2.480E-02	2.799E-02
14Y:-19X	Y	-0.199	8	1.725E-04	5.249E-03	3.577E-04	9.757E-05	5.599E-03	1.994E-03	5.809E-04	4.564E-03	5.704E-02	2.251E-03
15Y:-19X	Y	0.464	10.5	1.088E-04	6.781E-03	3.576E-04	6.774E-04	1.935E-02	5.751E-03	2.660E-04	2.766E-02	1.106E-01	1.706E-03
15X:-19X	X	0.464	10.5	7.730E-03	1.077E-03	6.120E-03	1.586E-03	2.004E-03	1.960E-02	2.319E-02	4.592E-02	4.485E-02	3.438E-02
16X:-19X	X	-0.145	10.5	7.782E-03	9.436E-04	6.103E-03	1.554E-03	2.167E-03	4.574E-02	1.310E-02	1.653E-01	5.663E-02	1.346E-02
16Y:-19X	Y	-0.145	10.5	3.118E-05	6.821E-03	2.553E-04	7.141E-04	1.961E-02	3.280E-03	1.485E-03	3.429E-02	1.145E-01	5.128E-04
17Y:-19X	Y	0.337	12	2.062E-03	7.280E-03	3.639E-03	1.191E-04	1.434E-03	2.187E-04	2.443E-05	8.762E-04	8.716E-04	1.306E-04
17X:-19X	X	0.337	12	1.276E-02	2.483E-03	2.019E-02	2.336E-03	2.039E-04	4.571E-03	1.756E-04	2.259E-03	2.751E-04	2.531E-04
18X:-19X	X	-0.11	12	1.304E-02	9.981E-04	2.077E-02	2.363E-03	5.328E-04	1.665E-03	5.292E-04	5.830E-04	4.246E-05	1.279E-04
18Y:-19X	Y	-0.11	12	3.817E-04	7.436E-03	2.359E-04	5.276E-04	1.342E-03	6.758E-04	6.710E-05	6.803E-04	8.317E-04	1.048E-04

Uncertainty Estimation

- Frequency
  - Model stand as rotational spring
  - Stand and adapter compliance ~2.3e9 [Nm / radian]
  - Total Standard Uncertainty = 0.12 % of reading
  - 95% Expanded Uncertainty = 0.25 % of reading

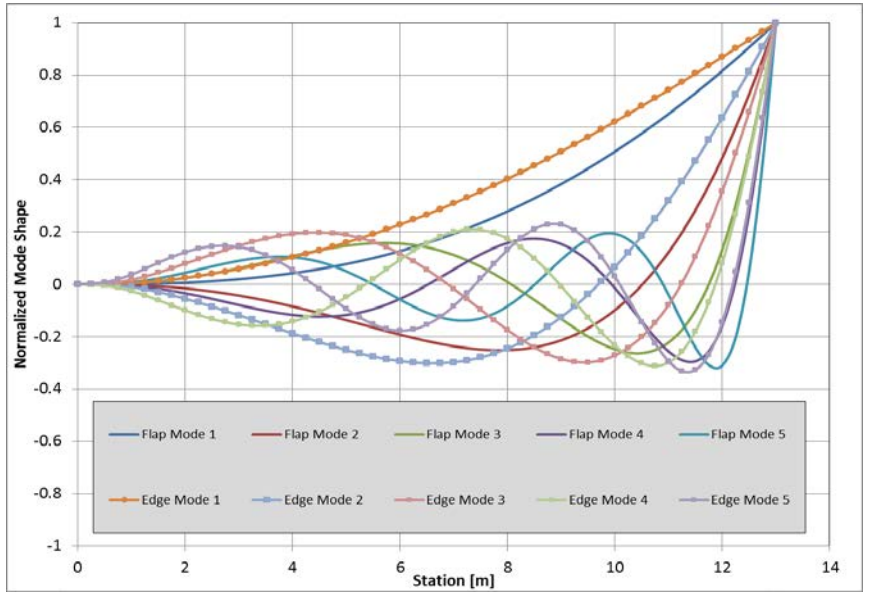
Frequency Error Source	Description & reference	Typical Level (% of reading)	Divisor	Systematic Standard Uncertainty (% of reading)
DAQ Timebase	Equipment Manufacturer	0.00001	2	0.000005
Spectral Bandwidth	Calculation	0.002	2	0.001
Stand Boundary Compliance	Calculation	0.2	1.73	0.12
Repeatability	Measurement	0.05	2	0.005
Mass Loading	Calculation	.08	1.73	.05

- Structural Damping
  - Damping Uncertainty reported for free decay experiments only
  - Evaluated at tip displacement amplitudes less than 5 mm
  - Stand structural damping not considered
  - Total Standard Uncertainty = 2.4 % of reading
  - 95% Expanded Uncertainty = 4.8 % of reading

Damping Error Source	Description & reference	Typical Level (% of reading)	Divisor	Systematic Standard Uncertainty (% of reading)
Aerodynamic Damping	Calculation	2.3	1	2.3
Log Dec Curve Fit	Calculation	0.1	1.73	0.06
Displacement Amplitude	Equipment Manufacturer	1.5	2	0.75
Resampling	Calculation	0.08	1.73	0.05
Instrumentation Cables	Estimate	.05	1.73	0.03

Reference Information

- Frequency values from Wetzel Design Report
- Estimated values from 1-D beam FEA



Bending Mode Shapes from pre-test 1-D Beam FEA

Values from Wetzel Design Report

Mode Shape	Frequency [Hz]
1st Flat	2.2
1st Edge	4.58
2nd Flat	6.85
2nd Edge	13.44

1-D Beam Model Estimates (pure flat, pure lead-lag properties taken from design report spreadsheet)

Mode Shape	Frequency [Hz]
1st Flat	2.19
1st Edge	4.47
2nd Flat	6.87
3rd Flat	14.3
2nd Edge	16.6
4th Flat	24.7
5th Flat	38.2
3rd Edge	39.2