National Renewable Energy Laboratory

Blade Modal Survey Test Note:
TX-100-007 Cantilevered Mounted Blade

Test Personnel:

Richard M. Osgood, NREL

G. H. McFarland, MVE

Test Date: 23 -24 June 2005

Cantilever mounting configuration description:

Blade is mounted horizontally on the small blade test stand in Bldg. 251 high-bay (HB). The blade's leading edge is facing down toward the HB floor. The blade root is firmly bolted to the face of the test stand, which is located at the west end of the HB. The blade root attachment approximates a cantilever beam boundary configuration. The blade root bolt orientation is chosen at a station where the observed reference chord is parallel with the HB vertical. The blade's high pressure side faces HB-south <suction side facing HB-north>. Blade stations are assigned with increasing values root to tip <increasing radial stations west to east>.

- See Figure 1: Cantilever blade modal test setup.
- See Figure 2: Modal acceleration response map.

Figure 1: Cantilever blade modal test setup.

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Modal Acceleration Response Map – High Pressure Side View

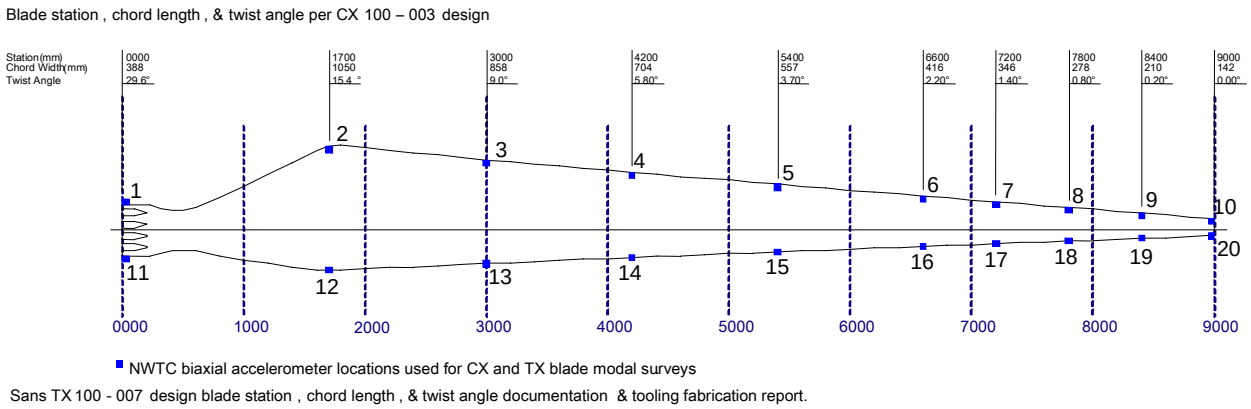


Figure 2: Modal acceleration response map.

Modal survey global coordinate system convention <Lab coordinates>:

- **+X** axis is directed from high pressure to suction side of blade <flap bending dof>
- **+Y** axis is directed from leading- to trailing-edge <lag bending dof>
- **+Z** axis is a radial line from root to tip <& coincidental with the twist line of chords>
- The origin is located at the center of the blade root bolt circle

Table 1 below, lists the coordinates (with respect to the lab reference) that are assigned to the modal map points where acceleration responses in the flap and lag degree of freedoms are measured. The biaxial accelerometers are aligned to measure the flap and lag motion of the blade and their alignment errors with the X & Y Lab coordinates are given in Table 2.

Table 1: Modal map coordinates given for the lab reference frame.

Modal Point #	TE / LE Comp element	Lab Twist Angle (deg)	TE or LE Chord (mm)	X - Lab Coord (mm)	Y- Lab Coord (mm)	Z- Lab Coord (mm)	TE or LE Chord (in)	X - Lab Coord (in)	Y- Lab Coord (in)	Z- Lab Coord (in)
1	TE	17.6	199	60	190	0	7.83	2.37	7.47	0.00
2	TE	3.4	709	42	708	1700	27.91	1.66	27.86	66.93
3	TE	-3.0	584	-31	583	3000	22.99	-1.20	22.96	118.11
4	TE	-6.2	479	-52	476	4200	18.86	-2.04	18.75	165.35
5	TE	-8.3	379	-55	375	5400	14.92	-2.15	14.76	212.60
6	TE	-9.8	283	-48	279	6600	11.14	-1.90	10.98	259.84
7	TE	-10.6	236	-43	232	7200	9.29	-1.71	9.13	283.46
8	TE	-11.2	189	-37	185	7800	7.44	-1.45	7.30	307.09
9	TE	-11.8	143	-29	140	8400	5.63	-1.15	5.51	330.71
10	TE	-12.0	97	-20	95	9000	3.82	-0.79	3.74	354.33
11	LE	17.6	199	-60	-190	0	7.83	-2.37	-7.47	0.00
12	LE	3.4	341	-20	-340	1700	13.43	-0.80	-13.40	66.93
13	LE	-3.0	275	14	-275	3000	10.83	0.57	-10.81	118.11
14	LE	-6.2	226	24	-225	4200	8.90	0.96	-8.85	165.35
15	LE	-8.3	178	26	-176	5400	7.01	1.01	-6.93	212.60
16	LE	-9.8	133	23	-131	6600	5.24	0.89	-5.16	259.84
17	LE	-10.6	111	20	-109	7200	4.37	0.80	-4.30	283.46
18	LE	-11.2	89	17	-87	7800	3.50	0.68	-3.44	307.09
19	LE	-11.8	67	14	-66	8400	2.64	0.54	-2.58	330.71
20	LE	-12.0	46	10	-45	9000	1.81	0.38	-1.77	354.33

Test specimen description:

The TX series blade is an experimental carbon-hybrid 9-meter prototype blade employing a twisted-coupled design concept that is intended to reduce overall weight while maintaining an acceptable operating tip deflection range. The blade is designed for a 100-kW size wind turbine and incorporates both epoxy-glass and carbon fiber structural materials.

Instrumentation & test equipment:

The modal response of the blade is measured with twenty PCB J356A18 triaxial accelerometers that are attached to the blade at its leading- and trailing-edge at the specified blade stations shown in Figure 2. The X-element of the triaxial accelerometer is orientated with the blade flap bending degree-of-freedom (dof) and the Y-element is aligned with the blade lag bending dof. The Z-element of the triaxial accelerometer <not used> is orientated along the blade's twist axis. Figure 3 shows a triaxial accelerometer that is attached to location #19 on the blade's leading edge. The triaxial accelerometer is attached to a shaped balsa wood block. Hot glue and aluminum tape is used to attach the balsa wood block to the blade. Accelerometer lead wires are also secured to the blade using aluminum tape.

The blade is excited with a PCB 086C02 impact hammer near the blade tip at point #20, see Figure 4. The applied force and collocated acceleration response is measured at the driving point with a Kistler 8638B5 single axis accelerometer. Figure 5 shows the driving point accelerometer orientated with the flap bending modal response for impact excitation applied in the flap direction at point #20.

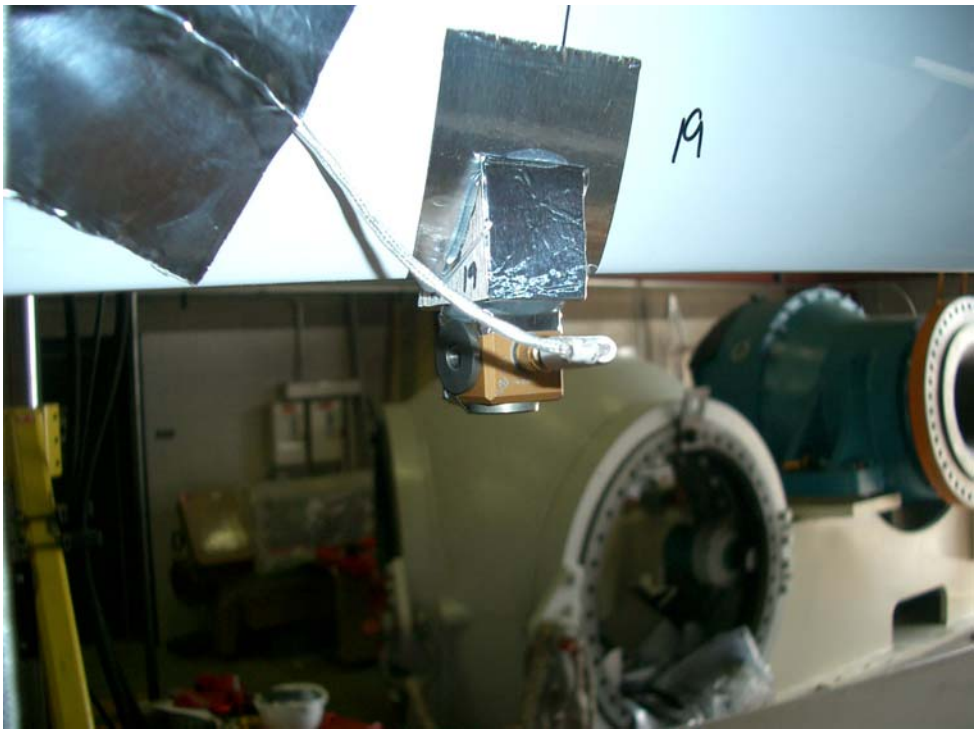


Figure 3: Triaxial accelerometer sensor attached to location #19 on blade leading-edge.

Figure 4: Impact hammer used to excite the flap and lag bending modes of the blade.

Figure 5: Single axis accelerometer orientated for flap response at driving point #21X.

Figure 6 is a schematic showing the layout of the test equipment used in the modal survey. The test equipment consists of three sixteen channel PCB 584A signal conditioners, which low pass filter the accelerometer and impact hammer force signals before conversion to digital format. The force input signal and modal acceleration response signals are captured and digitized by a HP 3566A PC computer controlled multi-channel spectrum analyzer, which signal processes and then stores the reduced modal data for later post processing by commercial experimental modal analysis software.

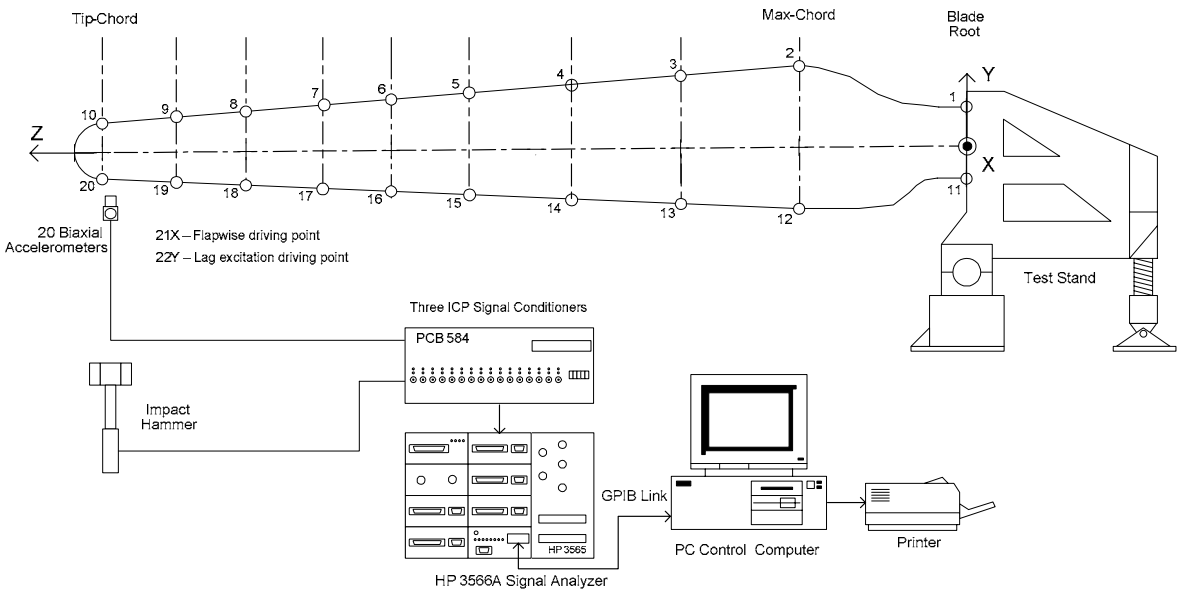
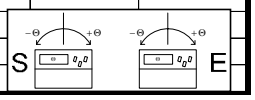


Figure 6: Schematic of test equipment used for modal survey of TX-100 blade.

Measurement setup, data collection & reduction:

The 48-channel HP 3566A structural spectrum analyzer is programmed to capture 41 channels of acceleration response signals and a single input force signal from the impact hammer. Table 2 is the channel map that assigns flap and lag bending degrees of freedom along the span of the blade to each modal acceleration response location depicted in Figures 2 and 6.

Table 2: Channel map assigning modal degrees of freedom to acceleration measurements.

TX 100 9 meter Blade Modal Survey				SN 007			**Prepared by**: Grant McFarland			
Channel Description per modal acceleration response map.							**Date**: 27 June 05			
DAS	Chnl	Sensor	Serial	Sensitivity	Factory	Sensitivity	Sig.Cond.	Filter	Ref Angle	Ref Angle
Chnl	Descrp	PCB	Number	Factory	Cal	Bench	Rack #	LPF	X-Y	Y-Z
#		Model		Cal	Date	Cal	Chnl#	COF	Deg.	Deg.
				[mV/g]		[mV/g]	Gain =	1.0	Rotation	Rotation
1	Input	086C02	20862	52.8 mV/lb		N/A	5/1			
2	DP	8638B5 *	C121238	1011			5/2			
3	+1X	J356A18	4151	1001	Jul-97		5/3		-1.6	-0.1
4	+1Y	J356A18	4151	972	Jul-97		5/4			
5	+2X	J356A18	4152	988	Jul-97		5/5		-0.7	-1.2
6	+2Y	J356A18	4152	984	Jul-97		5/6			
7	+3X	J356A18	4153	949	Jul-97		5/7		-1.9	0.2
8	+3Y	J356A18	4153	975	Jul-97		5/8			
9	+4X	J356A18	4154	995	Jul-97		5/9		-3.7	-0.3
10	+4Y	J356A18	4154	902	Jul-97		5/10			
11	+5X	J356A18	4155	974	Jul-97		5/11		-2.8	0.1
12	+5Y	J356A18	4155	978	Jul-97		5/12			
13	+6X	J356A18	4156	970	Jul-97		5/13		-0.2	0.3
14	+6Y	J356A18	4156	986	Jul-97		5/14			
15	+7X	J356A18	4157	974	Jul-97		5/15		-0.6	0.3
16	+7Y	J356A18	4157	952	Jul-97		5/16			
17	+8X	J356A18	4158	944	Jul-97		6/1		-2.8	0.2
18	+8Y	J356A18	4158	978	Jul-97		6/2			
19	+9X	J356A18	4169	1007	Jul-97		6/3		-2.3	0.8
20	+9Y	J356A18	4169	962	Jul-97		6/4			
21	+10X	J356A18	4170	924	Jul-97		6/5		-1.3	0.4
22	+10Y	J356A18	4170	1005	Jul-97		6/6			
23	+11X	J356A18	4171	961	Jul-97		6/7		2.8	0.0
24	+11Y	J356A18	4171	978	Jul-97		6/8			
25	+12X	J356A18	4172	1014	Jul-97		6/9		0.8	-1.5
26	+12Y	J356A18	4172	1017	Jul-97		6/10			
27	+13X	J356A18	4173	934	Jul-97		6/11		-1.4	-2.7
28	+13Y	J356A18	4173	1025	Jul-97		6/12			
29	+14X	J356A18	4174	923	Jul-97		6/13		-1.0	-0.9
30	+14Y	J356A18	4174	923	Jul-97		6/14			
31	+15X	J356A18	4175	981	Jul-97		6/15		1.3	-0.4
32	+15Y	J356A18	4175	921	Jul-97		6/16			
33	+16X	J356A18	4176	990	Jul-97		7/1		-0.5	0.5
34	+16Y	J356A18	4176	1055	Jul-97		7/2			
35	+17X	J356A18	4177	997	Jul-97		7/3		-0.8	-1.6
36	+17Y	J356A18	4177	1003	Jul-97		7/4			
37	+-18X	J356A18	4191	916	Jul-97		7/5		-2.1	-1.0
38	+18Y	J356A18	4191	1075	Jul-97		7/6			
39	+19X	J356A18	4192	1072	Jul-97		7/7		0.8	-0.8
40	+19Y	J356A18	4192	1057	Jul-97		7/8			
41	+20X	J356A18	4193	1024	Jul-97		7/9		-3.5	-1.5
42	+20Y	J356A18	4193	1000	Jul-97		7/10			
Comments: ***All sensors manufactured by PCB save driving point Kistler accelerometer.**										
										

The spectrum analyzer is programmed for a base band measurement of 0 to 100-Hz in conjunction with the PCB 584 signal conditioners' low pass analog filters that are upstream of the spectrum analyzer. The PCB 584 analog low pass filter cut-off frequency is set to 100-Hz. The analyzer captures a 32-second time record of each impact excitation and subsequent modal acceleration responses of the blade. The analyzer uses 3200 lines of resolution to compute a

frequency response function from the captured time series of the impact force and acceleration signals. The frequency resolution of the spectrum analyzer's measurement is therefore 31.25-mHz.

To minimize signal processing errors, the spectrum analyzer convolves special time windows with the force and accelerometer time series collected to increase the signal to noise ratio of the measurement and reduce the leakage of spectral energy in the frequency domain of the measurement. A force window of 0.5 seconds is convolved with the impact hammer signal to enhance its signal to noise ratio while the acceleration response signals are convolved with an exponentially decaying time window that has a sufficiently long time constant (128-seconds). The long exponential decay time constant minimizes the amount of artificial damping that is introduced into the estimate of modal damping of each fundamental bending mode that is identified in the measurement bandwidth. To evaluate the quality of the applied impact force, a 50-msec time delay is programmed into the HP 3566A structural analyzer's front-end so that the complete force signal, which is generated by the hammer impact, can be observed.

Flapwise excitation of the blade is accomplished by striking the suction side of the blade with the impact hammer near the tip of the blade. Specifically, a blade location on the suction side of the blade is chosen and assigned modal driving point 21X, see Figure 7. This driving point is the mirror image of modal map point 20X on the high pressure side of the blade shown in Figure 5.

Figure 7: Flapwise impact location assigned driving point 21X.

Two flapwise impact data sets (two files per data set) are taken and stored with the following HP 3566A filenames:

- ic_F-TX100-7_a.sta - (analyzer setup filename)
- ic_F-TX100-7_a.dat - (HP Standard Data File (SDF) format)

and,

- ic_F-TX100-7_b.sta
- ic_F-TX100-7_b.dat

Similarly lag excitation of the blade is accomplished by impacting the blade on its leading edge near the blade tip. Driving point 22Y is assigned to this leading edge modal point. This point is also collocated with the modal map point 20Y shown in Figures 2 and 5. One lag excitation data set is collected and stored with the following HP 3566A filenames:

- ic_L-TX100-7_a.sta (analyzer setup filename)
- ic_L-TX100-7_a.dat (HP Standard Data File (SDF) format)

The frequency response functions from five impact tests are averaged together and reduced to an overall structural transfer function (STF), which is stored as a '*.dat' file. The STF contains all the necessary information to experimentally determine the modal properties of the fundamental flap and lag bending modes of the cantilevered blade. In addition, the 100-Hz measurement bandwidth is sufficient to capture the blade's fundamental torsion modes of vibration. The experimental modal properties of the blade include its natural bending and torsion frequencies, their modal damping values and mode shape information. The STF data files are transferred to the PC control computer for subsequent post processing. The post processing of the measured modal data on the PC is performed using standard methods that are available in the modal analysis software, which is licensed to the PC.

Experimental modal analysis:

Industry standard modal analysis software curve fits the frequency response functions (FRFs) to obtain experimental modal parameters, which include natural frequencies, modal damping values, and modes shape functions. First the impact data are partitioned into flap and lag excitation data sets and single input – multiple output curve fitting algorithms are applied to the FRFs to extract the fundamental modal properties of the cantilevered blade. The reduced flap and lag single-input – multiple output data sets are combined to form a multi-reference data base that describes the structural transfer function of the cantilevered blade over the bandwidth of the modal test.

Modal survey test results:

Figure 8 is a spectral plot of the averaged frequency response function that was captured from the flapwise excitation applied to driving point 21X at the blade tip. The peaks in the spectral diagram are evidence of twenty-three natural bending and torsion modes of the blade. Table 3 lists the modal parameters extracted by the modal analysis software, which includes fundamental frequencies, modal damping values, and mode shape description. However, due to the finite number of blade stations where acceleration response data are collected, less than five mode shapes of either flap or lag bending. The number of torsion modes that can be resolved from this data set is limited by the 100-Hz bandwidth of the modal survey.

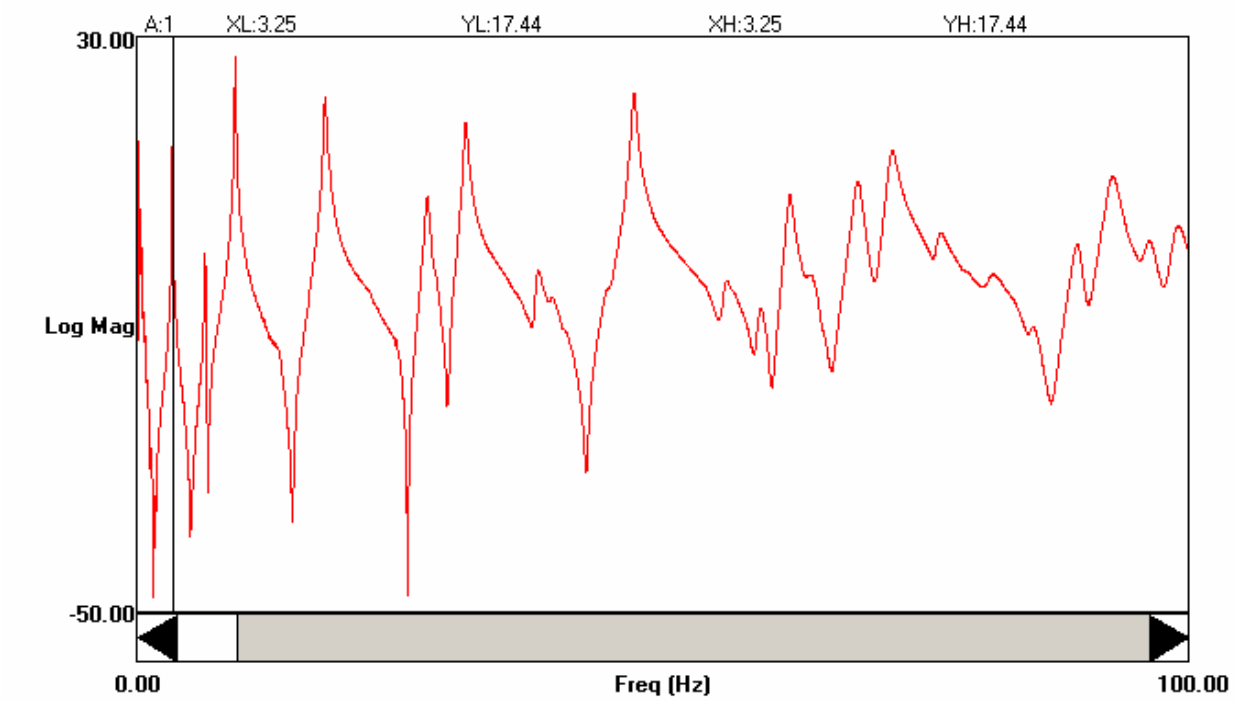


Figure 8: Flapwise driving point 21X ensemble frequency response function plot.

Table 3: Natural frequencies, modal damping values & mode shapes obtained from the flapwise excitation data set.

TX100-007 Blade Cantilever Bending Modes - Flap Excitation, June 23, 2005				
File Name: ic_F-TX100-7_b.dat				
Mode #	**Freq. (Hz)**	**Damp. (Hz)**	**Damp. (%)**	**Mode Shape Description**
1	3.24	15.0E-3	461.7E-3	First flap bending
2	6.34	36.8E-3	579.9E-3	First lag bending + second flap bending
3	9.22	35.5E-3	385.3E-3	Second flap bending
4	17.8	121.5E-3	682.2E-3	Third flap bending
5	27.51	210.6E-3	765.5E-3	Second lag bending + fourth flap bending
6	31.17	174.7E-3	560.5E-3	Fourth flap bending
7	37.94	341.6E-3	900.3E-3	Fourth flap bending + first torsion + lag bending
8	39.43	289.9E-3	735.1E-3	First torsion coupled with lag and flap bending
9	44.79	340.5E-3	760.2E-3	Fifth flap bending + third lag bending & torsion
10	47.21	201.5E-3	426.9E-3	Fifth flap bending + torsion + 3rd lag bending
11	55.88	481.0E-3	860.8E-3	HO flap bending + torsion + lag bending
12	59.14	439.3E-3	742.7E-3	3rd lag bending + ho flap bending+ 2nd torsion
13	62.02	313.9E-3	506.2E-3	2nd torsion + ho flap bending + 4th lag bending
14	64.04	706.6E-3	1.1E+0	4th lag bending + 2nd torsion + ho flap bending
15	68.51	380.6E-3	555.4E-3	2nd torsion + 4th lag bending + ho flap bending
16	71.73	435.5E-3	607.1E-3	HO flap bending + 2nd torsion + 4th lag bending
17	76.12	459.1E-3	603.1E-3	“
18	81.03	745.9E-3	920.4E-3	“

19	85.06	536.8E-3	631.1E-3	“
20	89.43	525.0E-3	587.0E-3	“
21	92.74	591.0E-3	637.2E-3	3rd Torsion + 5th lag bending & ho flap bending
22	96.17	662.8E-3	689.1E-3	5th lag bending + ho flap bending + 3rd torsion
23	98.86	752.6E-3	761.2E-3	Third torsion + 5th lag bending

Figure 9 is the spectral diagram of the ensemble frequency response function that is obtained from lag impact excitation of the blade applied to driving point 22Y located at the leading-edge of the blade tip. In this diagram there are twenty-two significant peaks representing natural flap, lag and torsion modes of vibration for the cantilevered blade. Table 4 catalogs the measured fundamental modal parameters including natural frequencies, modal damping values and mode shape description. As mentioned above, the finite number of spatial response points measured limits the resolution of mode shape information that can be obtained from this data set. The difference between the number of modal peaks found in the two spectral plots for flap and lag excitation of the blade is due to the higher order (HO) 44.79-Hz flap mode, which tends to disappear near the 45-Hz anti-resonance that is depicted in the lag driving point spectral plot of Figure 9.

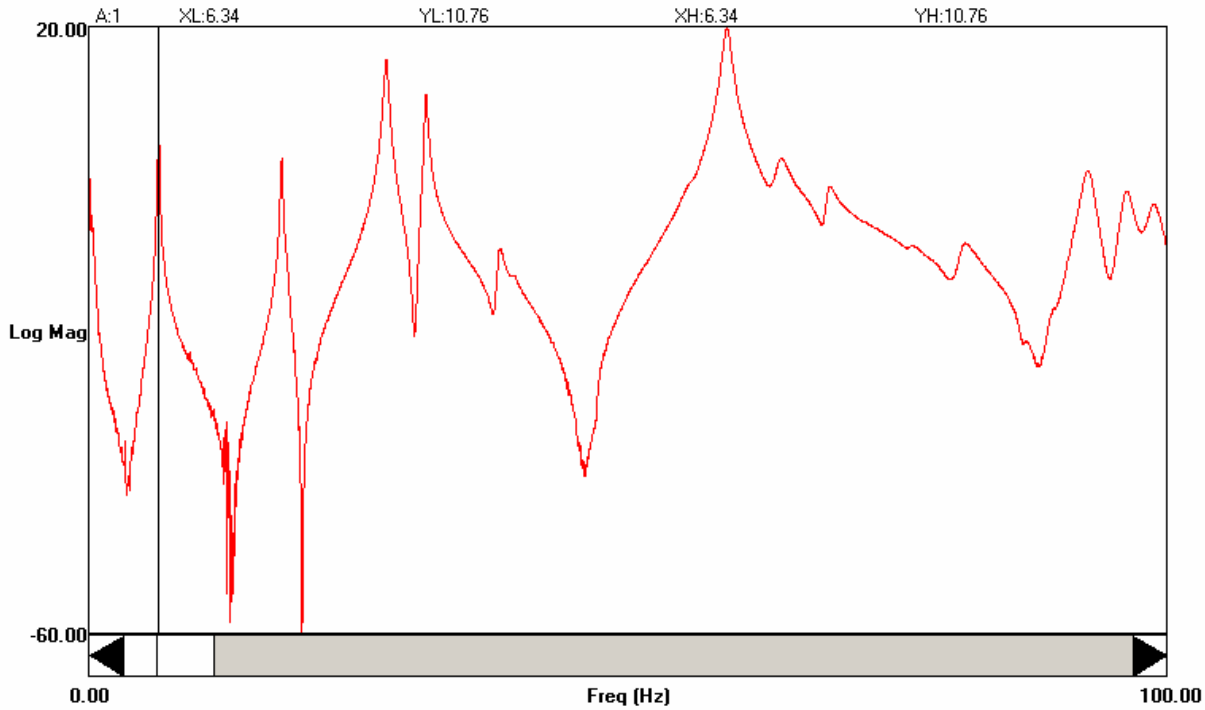


Figure 9: Lag driving point 22Y ensemble frequency response function spectra.

Table 4: Natural frequencies, modal damping values & mode shapes obtained from the lag driving point data set (HO – higher order).

TX100-007 Blade Cantilever Bending Modes - Lag Excitation, June 23, 2005				
File Name: ic_L-TX100-7_a.dat				
Mode #	Freq. (Hz)	Damp. (Hz)	Damp. (%)	Mode Shape Description
1	3.24	14.2E-3	438.5E-3	First flap bending
2	6.35	35.7E-3	562.3E-3	First lag bending + second flap bending
3	9.22	31.7E-3	344.0E-3	Second flap bending
4	17.8	107.6E-3	604.5E-3	Third flap bending + lag bending
5	27.51	175.0E-3	636.0E-3	Second lag bending+ fourth flap bending
6	31.18	143.0E-3	458.5E-3	Fourth flap bending + lag bending
7	37.93	283.7E-3	747.8E-3	Fourth flap bending + first torsion
8	39.33	187.5E-3	476.7E-3	First torsion + lag and flap bending
9	47.19	210.4E-3	445.8E-3	Fifth flap bending + torsion + third lag bending
10	55.85	428.2E-3	766.7E-3	HO flap bending + lag bending + torsion
11	59.15	368.0E-3	622.2E-3	3rd lag bending + ho flap bending + 2nd torsion
12	62.03	296.3E-3	477.6E-3	2nd torsion + ho flap bending+ 4th lag bending
13	64	634.4E-3	991.2E-3	2nd torsion + 4th lag bending + ho flap bending
14	68.47	404.8E-3	591.2E-3	2nd torsion + 4th lag bending + ho flap bending
15	71.7	470.4E-3	656.1E-3	HO flap bending + 2nd torsion + 4th lag bending
16	76.17	475.5E-3	624.2E-3	HO flap bending+ 2nd torsion + 4th lag bending
17	80.92	746.4E-3	922.4E-3	4th lag bending + ho flap bending+ 2nd torsion
18	84.99	384.2E-3	452.0E-3	“
19	89.42	556.0E-3	621.7E-3	“
20	92.69	613.3E-3	661.6E-3	5th lag bending + ho flap bending + 3rd torsion
21	96.26	628.3E-3	652.8E-3	5th lag bending + 3rd torsion + ho flap bending
22	98.75	756.5E-3	766.1E-3	Third torsion + 5th lag bending

Mode shape plots for the first eight fundamental flap, lag and torsion modes of vibration of the cantilevered blade are listed in Appendix A.

Observations & discussion of test results:

Fifth and high order flap bending modes closely couple with the lag and torsion modes of the blade. This apparent modal coupling complicates the description of higher order mode shapes. In addition, crosstalk between lag and flap bending degrees of freedom is introduced by small systematic misalignment of the biaxial accelerometers that are distributed along the blade. The small amount of crosstalk that is inherent in the frequency response measurements further complicates the delineation of flap, lag and torsion modes of vibration of the blade that are found in the 100-Hz bandwidth of the modal survey. However, the higher order modes may be useful for comparisons with modal predictions from analytical models of the blade. The dynamist may wish to use the extended experimental modal information to observe the effect of truncating higher order modes when matching the lower frequency experimental and analytical fundamental bending modes of the blade. The measured modal damping values found in the flap excitation data are generally higher than the modal damping values observed in the lag excitation data. The difference is attributed to higher unmeasured aerodynamic damping forces found in the flap excitation test than in the applied lag excitation method.

Notes & Exceptions:

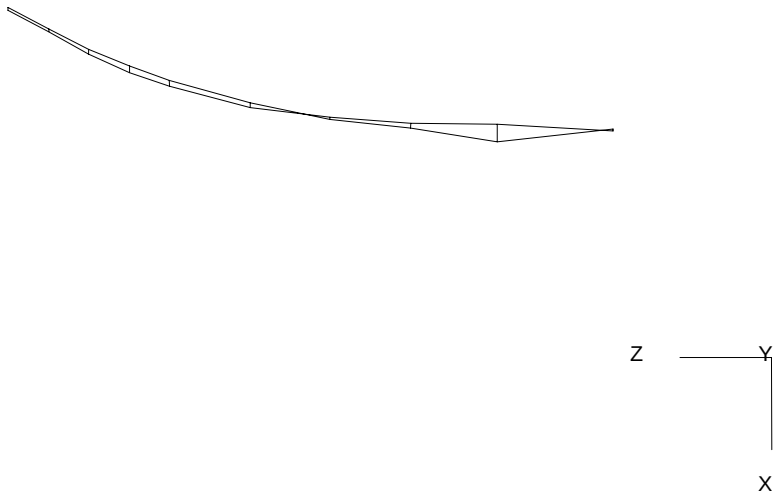
The relationship between the Lab coordinates and the blade geometry is fixed by the mounting orientation of the root plate flange that used to attach the blade to the test stand that is shown in Figure 10. The bolt circle orientation is determined by the single-sling-and-pick method used to support the blade as it is bolted to the test stand. The blade pick method supports the blade and adapter ring at the combined center-of-gravity (C.G.). The C.G. of the blade is marked on the high pressure and suction sides of the blade and is located approximately 2.3 meters from the blade root. The design twist of the blade at the 2.3 meter C.G. station is approximately 12-degrees. The vertical lab reference and chord at the 2.3 meter C.G. station are nearly parallel.

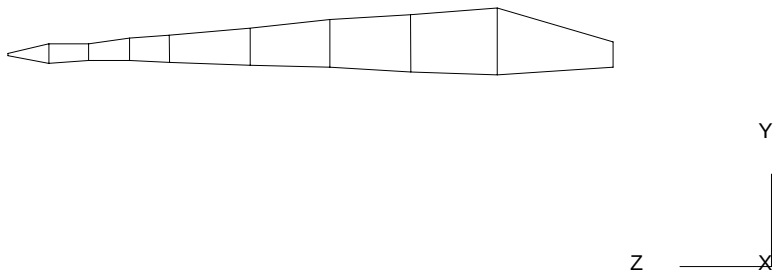
Figure 10: Lab vertical reference alignment with blade adaptor ring bolt circle.

References:

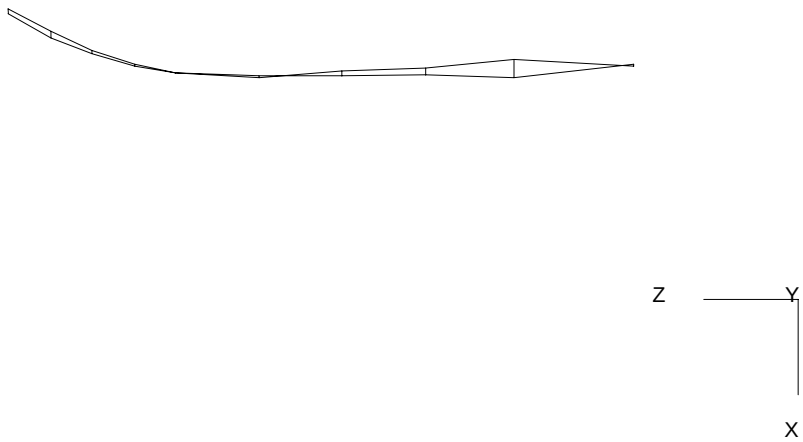
1. Richardson, M.; Kniskern, J., *Identifying modes of Large Structures from Multiple Input and Response Measurements,* SAE Paper Number 760875, 1976, 12 pp.
2. Formenti, D., *Analytical and Experimental Modal Analysis,* University of Cincinnati Modal Testing Workshop white paper, May 23, 1977.
3. Brown, D. et al., *Parameter Estimation Techniques for Modal Analysis,* SAE Paper Number 790221, 1979.
4. Allemang R. J., *Investigation of Some Multiple Input/Output Frequency Response Function Experimental Modal Analysis Techniques,* Ph.D. Dissertation, University of Cincinnati, USA, 1980.

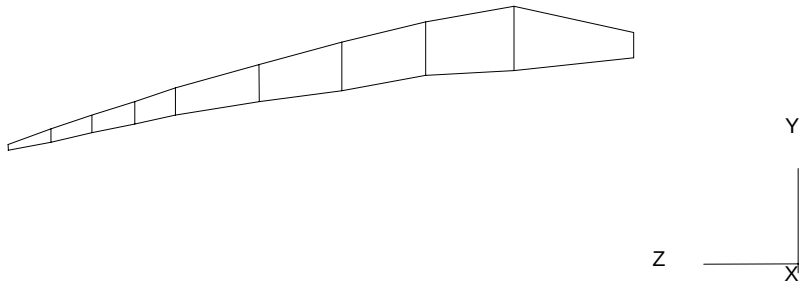
Appendix A



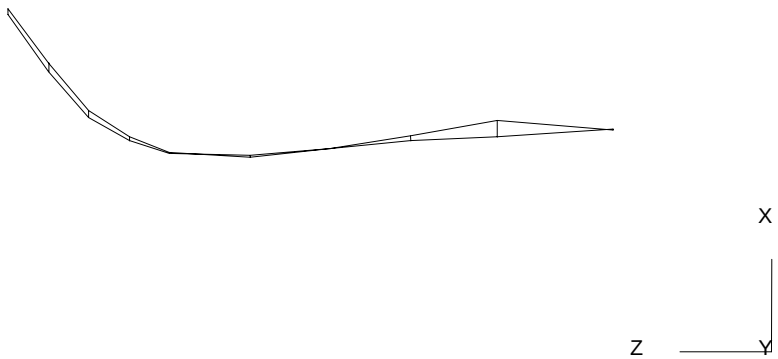


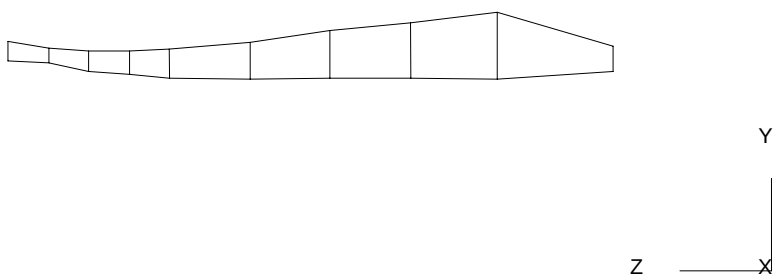
Mode #1: First flap bending; 3.24-Hz & 0.438% damping



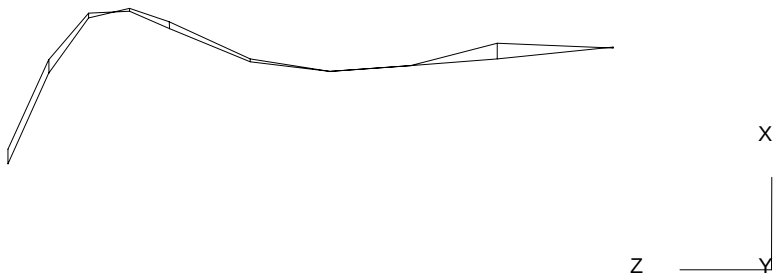


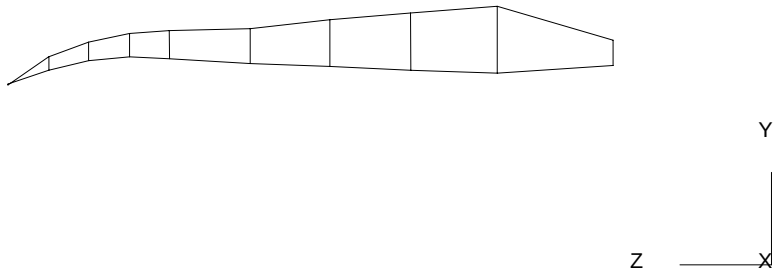
Mode #2: First lag bending + second lag bending; 6.35-Hz & 0.562% damping



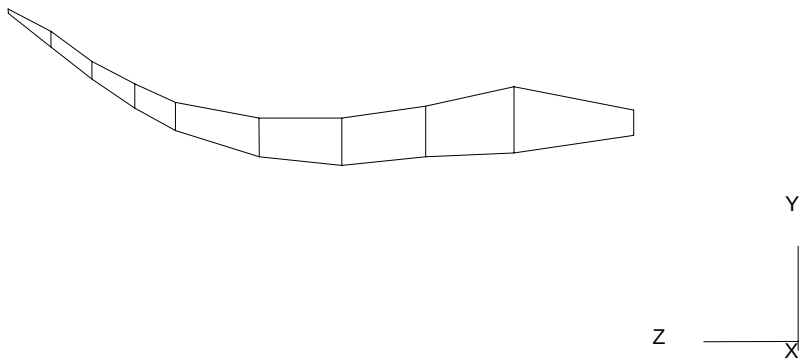


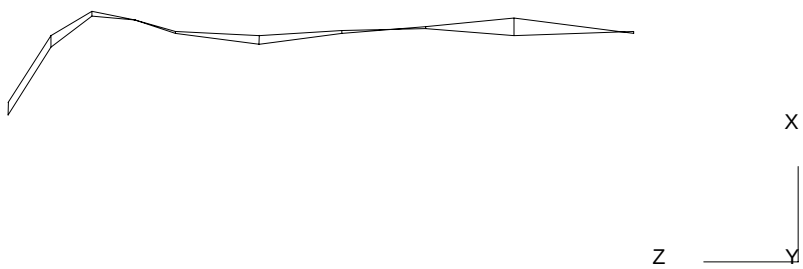
Mode #3: Second flap bending; 9.22-Hz & 0.344% damping



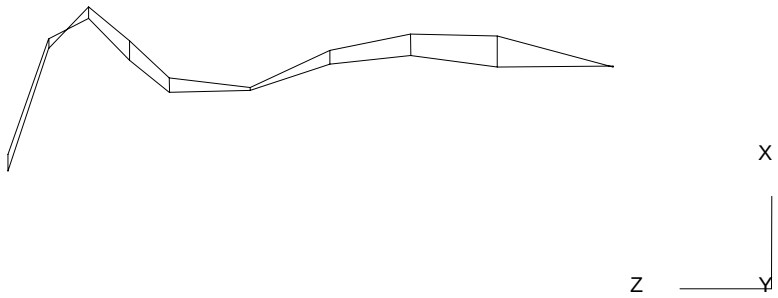


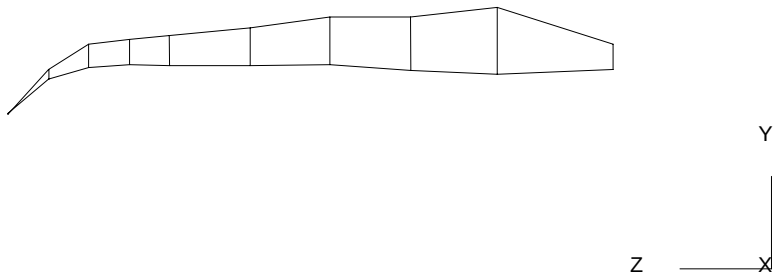
Mode #4: Third flap bending + lag bending; 17.8-Hz & 0.604% damping



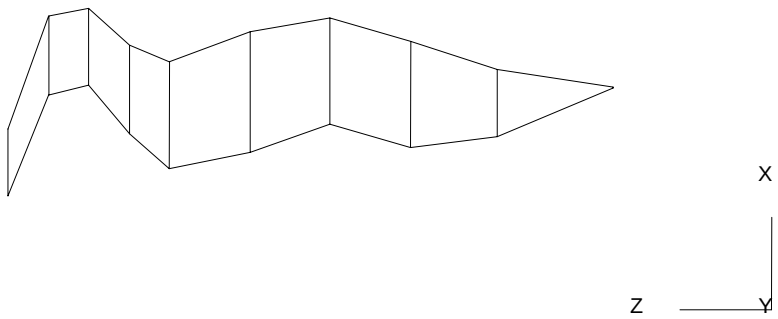


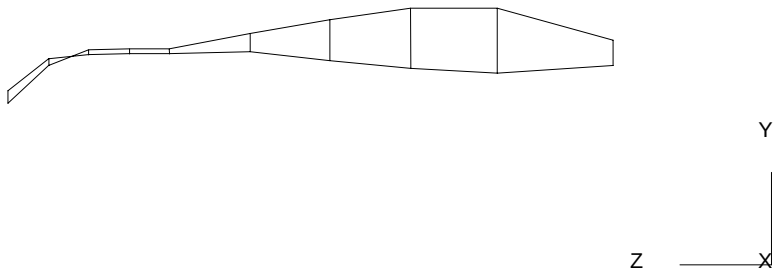
Mode #5: Second lag bending + fourth flap bending; 27.51-Hz, & 0.636%



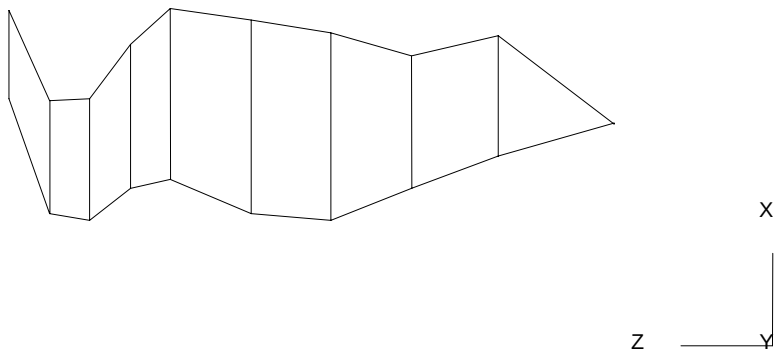


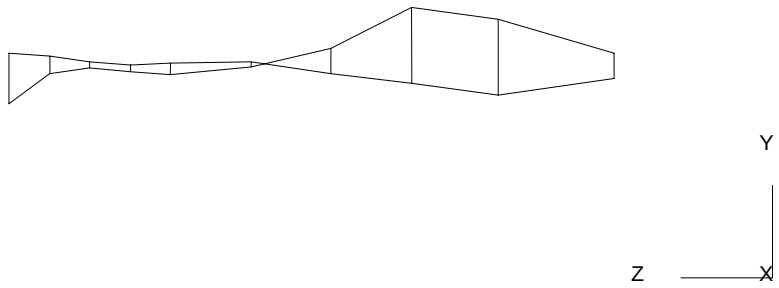
Mode #6: Fourth flap bending + lag bending; 31.17-Hz & 0.458% damping





Mode #7: Fourth flap bending + first torsion; 37.94-Hz & 0.748% damping





Mode #8: First torsion + flap and lag bending; 39.43-Hz & 0.476% damping