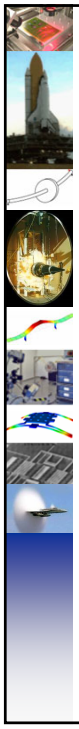
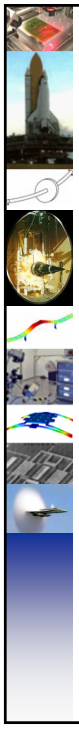


ME/EMA 540

Experimental Vibrations & Dynamic System Analysis

Module #6: Operational Modal Analysis (OMA) / Natural Excitation Technique (NExT)

1



Review of EMA with Frequency Response Functions (FRFs)

- Recall that the basis of EMA is to extract modal parameters from FRFs
  - $\{X\} = [H]\{F\}$ or $\{X\} = \{H_p\}F_p$

$$\{H_p(\omega)\} = \sum_{r=1}^{N} \frac{\{\phi_r\}\phi_{pr}}{\omega_r^2 - \omega^2 + 2i\omega\zeta_r\omega_r}$$

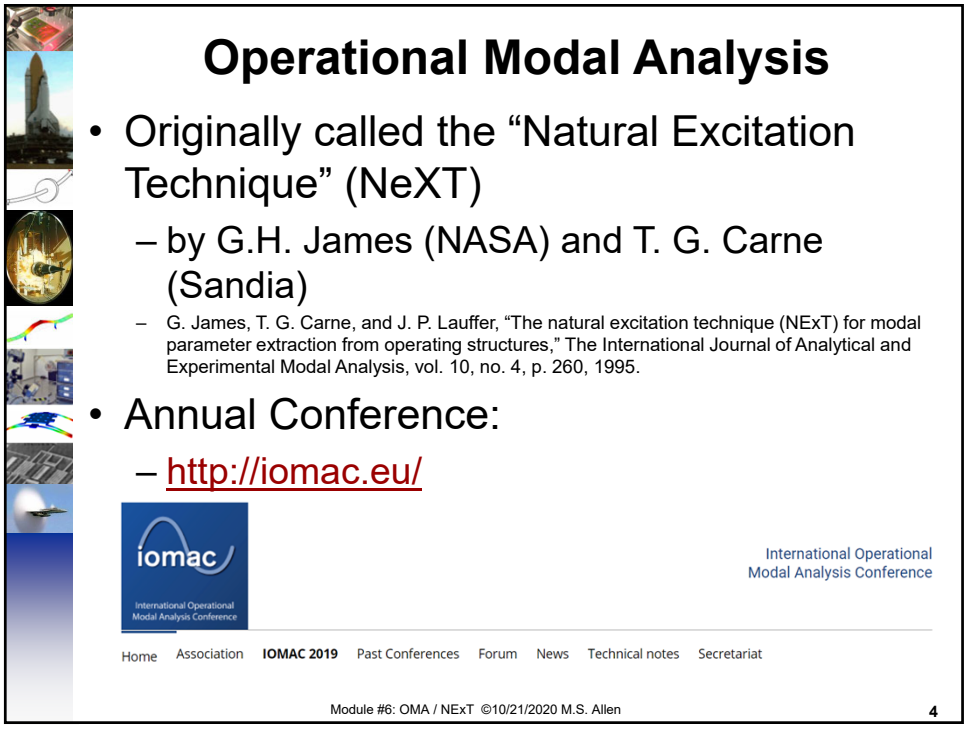
- And FRFs are estimated from the auto and cross spectra:
  - $H_1(\omega) = S_{XF}(\omega)S_{FF}(\omega)^{-1}$

$$S_{XF}(\omega) = \frac{1}{N_{avg}} \sum_{j=1}^{N_{avg}} X_j(\omega)F_j(\omega)^* = E\left(X_j F_j^*\right)$$

2


But what if we can't measure the forces?
3

3


Operational Modal Analysis
• Originally called the "Natural Excitation Technique" (NeXT)
– by G.H. James (NASA) and T. G. Carne (Sandia)
– G. James, T. G. Carne, and J. P. Lauffer, "The natural excitation technique (NExT) for modal parameter extraction from operating structures," The International Journal of Analytical and Experimental Modal Analysis, vol. 10, no. 4, p. 260, 1995.
• Annual Conference:
– http://iomac.eu/
iomac
International Operational Modal Analysis Conference
International Operational Modal Analysis Conference
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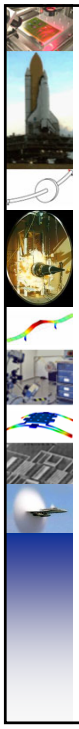
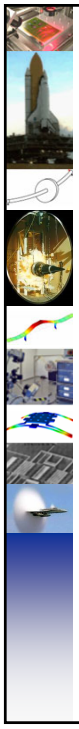
4

4



Derivation of OMA



Operational Modal Analysis

- Summary of Derivations
  - The modes of a structure are readily apparent in the power spectrum of its response to a broadband, white, random input.
  - Peaks -> Natural frequency and damping
  - Mode shapes:

$$S_{x_j x_n}(\omega) = E\left(X_j X_n^*\right)$$

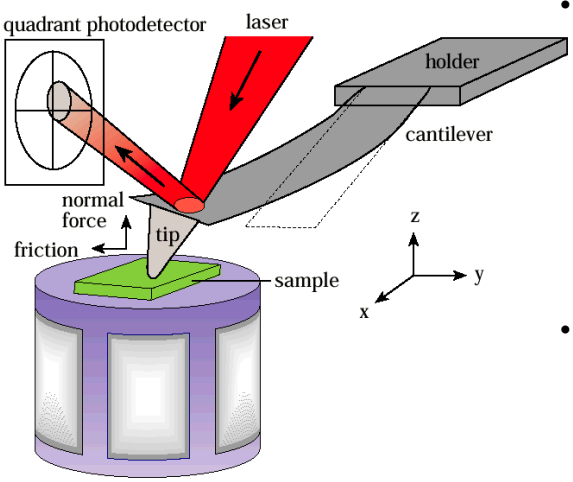
$$S_{x_j x_n}(\omega) = \sum_{r=1}^{N} \frac{\phi_{jr}\phi_{pr}}{\omega_r^2 - \omega^2 + \mathrm{i}\omega 2\zeta_r\omega_r} S_{F_pF_p}(\omega) H_{np}^*$$

Near $\omega=\omega_r$,

$$S_{x_j x_n}(\omega) = \frac{\phi_{jr} S_{F_pF_p}\left(\phi_{pr}\right)^2 \phi_{nr}}{4\zeta_r^2\omega_r^4}$$

$$S_{\{x\}x_n}(\omega) = \{\phi\}_r \frac{S_{F_pF_p}\left(\phi_{pr}\right)^2 \phi_{nr}}{4\zeta_r^2\omega_r^4}$$

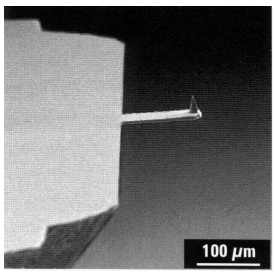
Atomic Force Microscopy

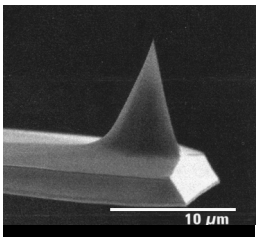


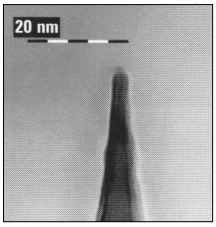
- AFM: A <u>mechanical</u> detection system for studying materials at the nanoscale.
  - Developed in 1986 by Binnig, Quate, and Gerber in a collaboration between IBM and Stanford University
- Laser based detection system:
  - Sub nanometer displacement resolution.
  - Sub nano-Newton force resolution.

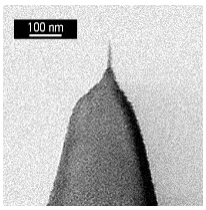
7

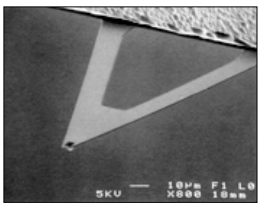
The AFM probe is a microfabricated cantilever (~100 μm) and tip (<50 nm radius)

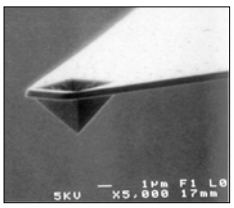






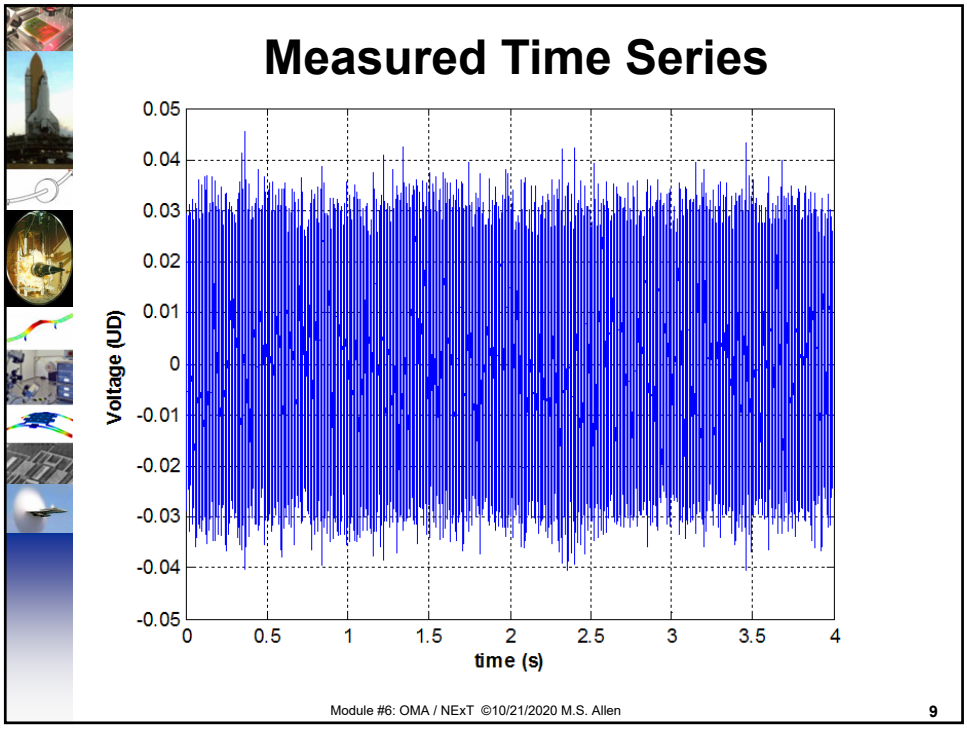






Images from NT-MDT, Inc, by J. VanLangendon, UW-Madison and from spmtips.com.

8


Measured Time Series
Voltage (UD)
time (s)
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
0
0.5
1
1.5
2
2.5
3
3.5
4
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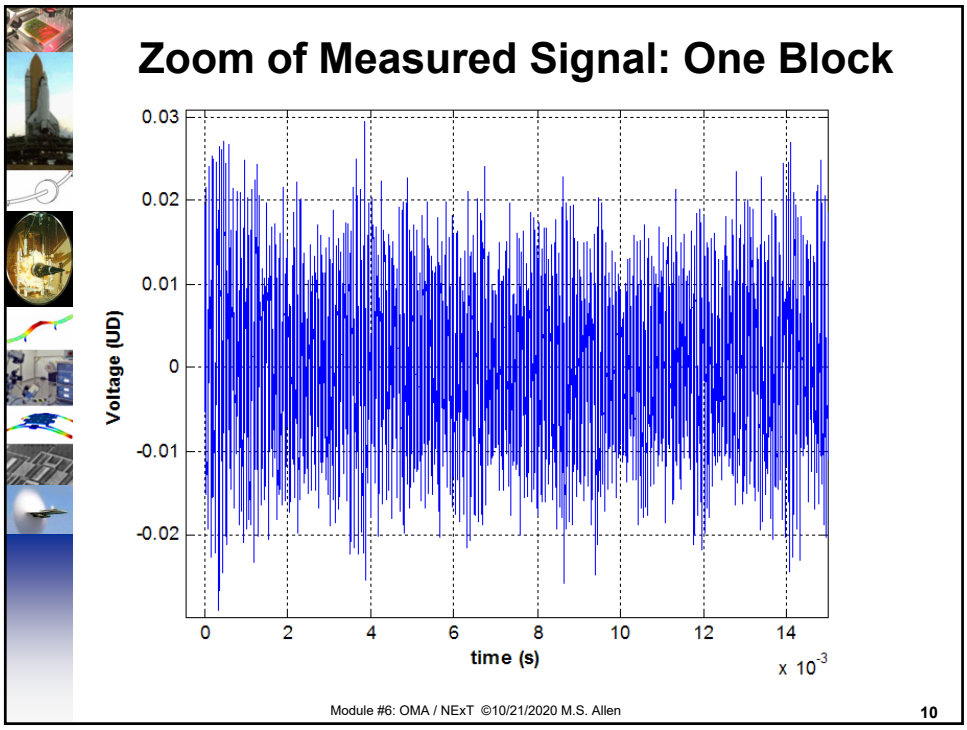
Zoom of Measured Signal: One Block
Voltage (UD)
time (s)
x 10-3
0.03
0.02
0.01
0
-0.01
-0.02
0
2
4
6
8
10
12
14
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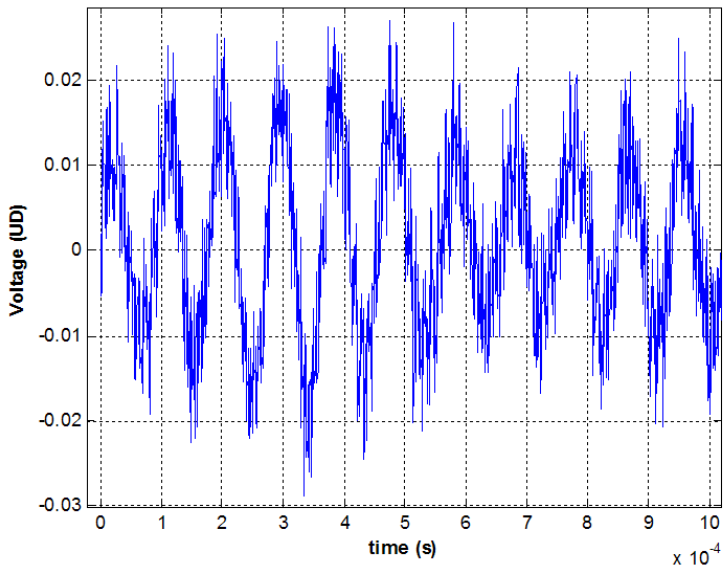
10

10

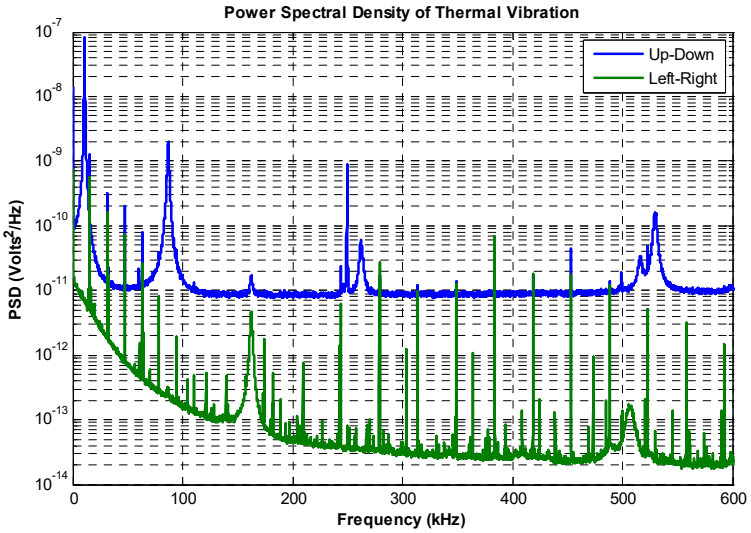
Zoom of Measured Signal



- **Period** of sinusoid seen in the signal:
- T = 91.1 μs
- **Frequency**:
- T^{-1} = f = 10976 Hz

11

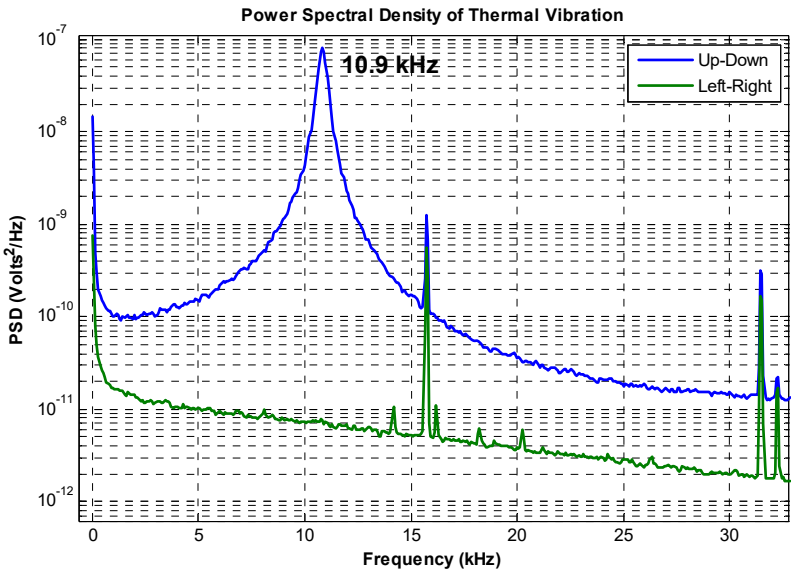
Power Spectral Densities of Signals



- Peaks in Up-Down signal probably correspond to the bending modes of the probe. Those in the Left-Right signal are probably torsion modes.

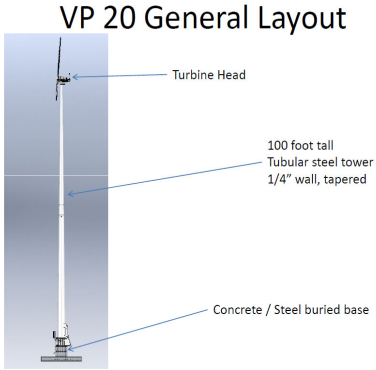
12

Zoom on 1st Resonant Peak



13

Case Study: Wind Turbine OMA



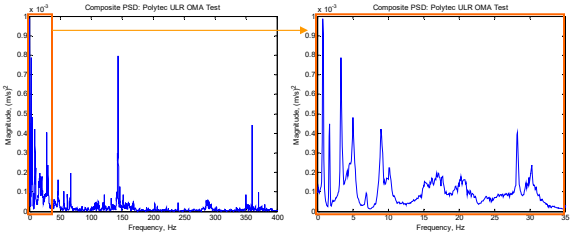
- 20 kW Wind Turbine
- Renewegy LLC, Oshkosh, WI
- 9.4m diameter rotor
- ~30m tower height

- Gearbox between Generator and Rotor so both run at different speeds.
  - Nominal Rotor Speed:
    - 100 rpm = 1.67 Hz
  - Nominal Generator Speed:
    - 600 rpm = 10 Hz

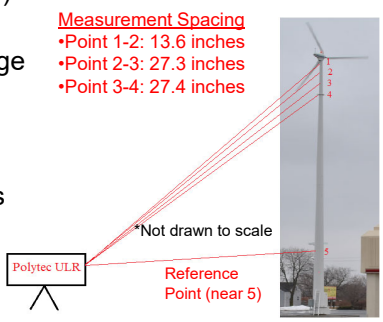
14

Operational Modal Analysis: Test Results

- OMA test performed March 21, 2011 at Renewegy in Oshkosh, WI.
- Data acquired using Polytec LDVs
  - PSV-400 (reference point)
  - Experimental Ultra Long Range Laser (roving point)
- Wind speed during measurements was 7-9 m/s (~16-20 mph).

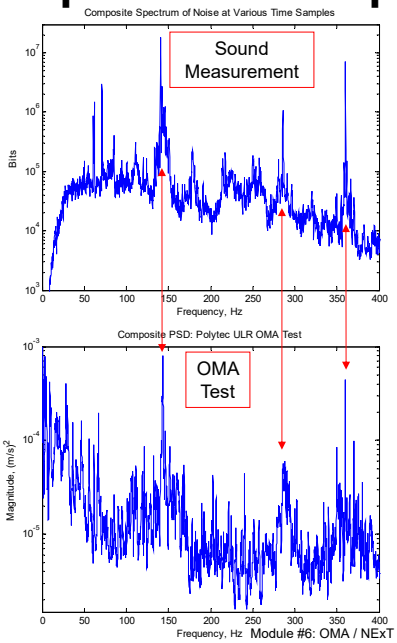


Measurement Spacing
- Point 1-2: 13.6 inches
- Point 2-3: 27.3 inches
- Point 3-4: 27.4 inches



15

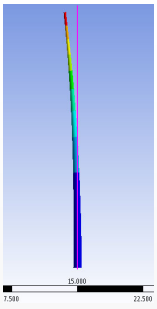
Spectrum Comparison: Sound/OMA



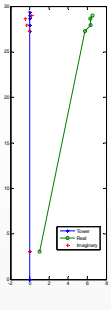
- Similar peaks in spectrum from the sound measurement and vibration test above 100 Hz.
  - 145 Hz
  - 290 Hz
  - 360 Hz
- Vibration of turbine shows the same frequencies that were present in the noise measurement.
- Mode shapes at each frequency extracted and compared in next slides.

16

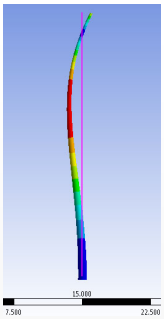
Low Frequency Mode Shapes: Test and FEM



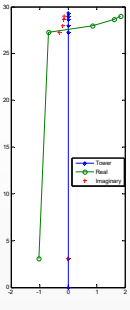
FEM Mode 1:
0.83 Hz



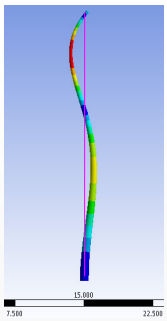
Test Mode 1:
0.78 Hz



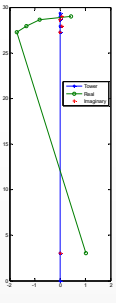
FEM Mode 3:
3.65 Hz



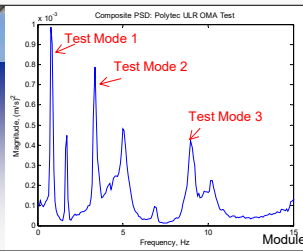
Test Mode 2:
3.34 Hz



FEM Mode 5:
9.14 Hz



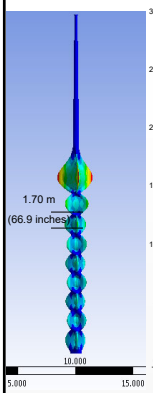
Test Mode 3:
8.98 Hz



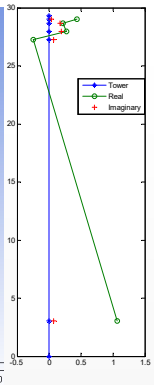
- Modes extracted using peak picking method.
- Measurements near top of tower resemble analytical mode shapes of a FEM model created from simplified tower geometry and known rotor mass and inertia.
- Additional peaks in PSD
  - 1.72 Hz (Rotating Frequency)
  - 5.00 Hz (Blade Pass Frequency)
  - 6.88 Hz (Harmonic of Rotation Freq.)
  - 10.16 Hz (2x Blade Pass Frequency)

17

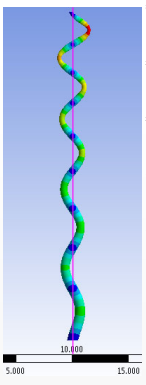
High Frequency Mode Shape? ~145 Hz



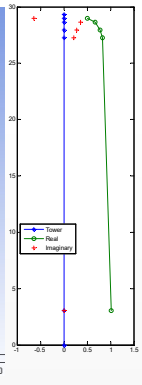
FEM Mode 74:
144.9 Hz



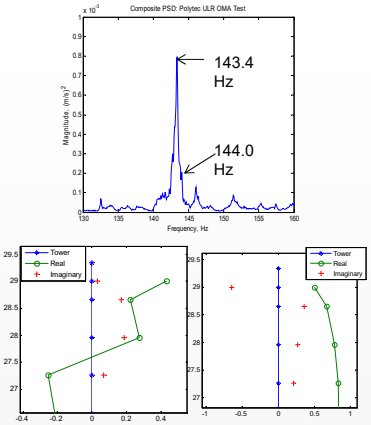
Test Mode:
143.4.0 Hz



FEM Mode 75:
144.92 Hz



Test Mode:
144.0 Hz



- Two shapes extracted from test data (143.4 Hz and 144.0 Hz).
- 143.4 Hz Shape: Too few measurement points to draw firm conclusion.
- 144.0 Hz Shape: Displacement at top of tower resembles the shape of the FEM bending mode near that frequency.
  - Operating shapes are complex, possibly be due to other nearby modes with similar natural frequencies.

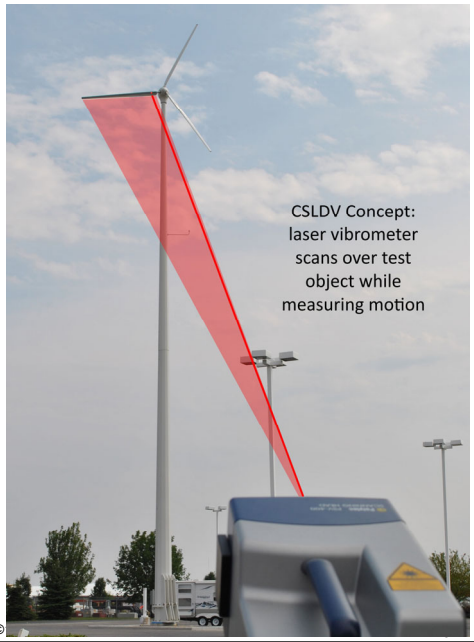
18

- The following slides were covered previously.

19

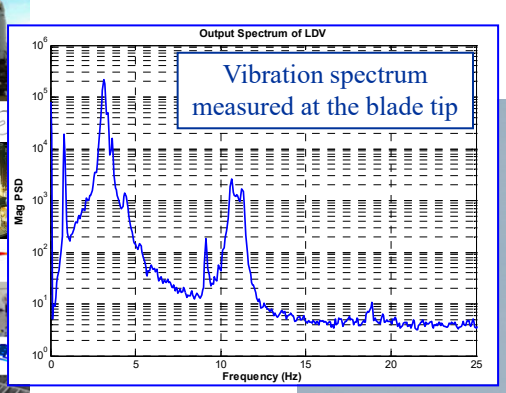
OMA-CSLDV on Wind Turbine Blade

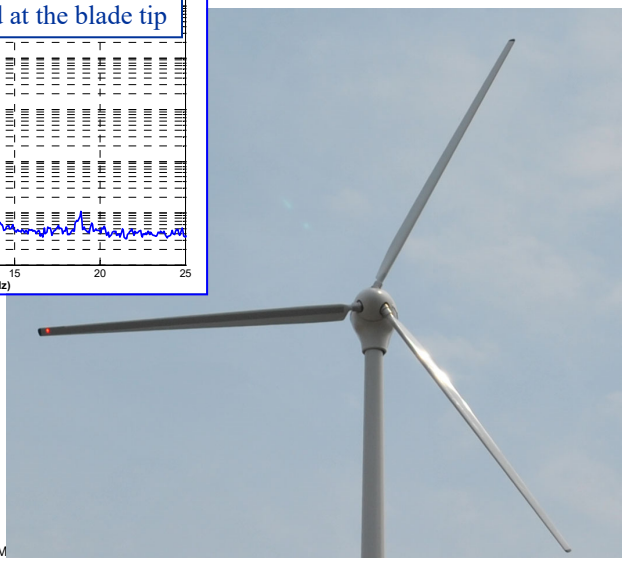
- Alternative to obtain more detailed mode shape measurements:
  - Allen, Sracic & Yang recently extended operational modal analysis to continuous-scan measurements.
  - Laser sweeps across the surface of interest while acquiring measurements.
  - Has the potential to obtain spatial resolution that is hundreds of times better in the same amount of time.



20

Conventional OMA (Tip Measurement)





- Laser positioned at a fixed point at the tip of the blade as shown.
- Power spectrum shows several peaks.

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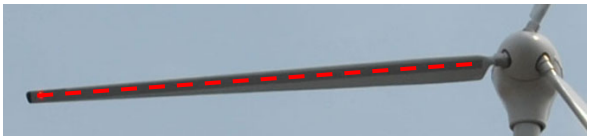
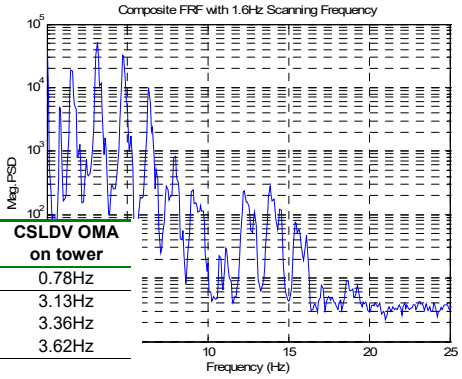
OMA-CSLDV Measurement



Laser scanned along the length of the blade for CSLDV measurement.

- Several modes identified in the harmonic power spectrum.

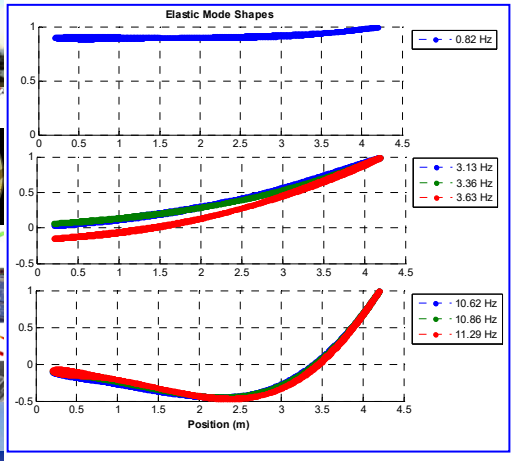


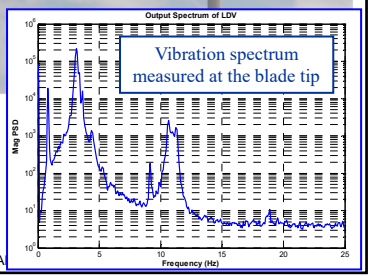
Mode	Conventional test in stiff fixture	Fixed point OMA on tower	CSLDV OMA on tower
-	-	0.81Hz	0.78Hz
Flap Wise Bending 1	3.36Hz	3.13Hz 3.37Hz 3.63Hz	3.13Hz 3.36Hz 3.62Hz
Edge Wise Bending 1	5.24Hz	4.38Hz	-
-	-	9.13Hz	-
Flap Wise Bending 2	11.40Hz	10.63Hz 10.94Hz 11.25Hz	10.62Hz 10.86Hz 11.29Hz

22

22

Mode Shapes Identified by OMA CSLDV





- CSLDV reveals the deformation shape of the structure associated with each frequency.

23

Comparison with Conventional Methods

- Conventional Test Methods:
  - OMA with accelerometers (fixed sensors)
    - Requires attaching sensors to the points of interest and running cables to data acquisition (or wireless transmitters).
- OMA with conventional scanning LDV
  - At least two measurement points needed to obtain mode shapes.
  - Cost per LDV: $80,000+
  - Each pair of points must be observed for at least 10 minutes.
- The results presented here were acquired with one ground based laser and two 10-min time records!

24