NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Wind Turbine Aeroacoustic Noise – Measurement and Mitigation

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Why is noise an issue?

- Objectionable noise is an impediment to deployment
  - Complaints by residents threaten permitting
  - Projects must comply with established community noise standards (40 – 45 dBA is typical)
- Noise mitigation tools will enable more slender blades and higher tip speeds
  - 15% increase in tip speed yields 5-7% COE reduction
  - But 15% increase in tip speed = 3 dBA increase in sound emission

Sound Pressure Level

Most common noise measurement

$$SPL = 10\log_{10}\left(\frac{I}{I_{ref}}\right) = 20\log_{10}\left(\frac{p}{p_{ref}}\right)$$

$$I \propto \frac{1}{r^2} \qquad\qquad p \propto \frac{1}{r}$$

r = observer distance

Doubling distance = -3 dB in SPL

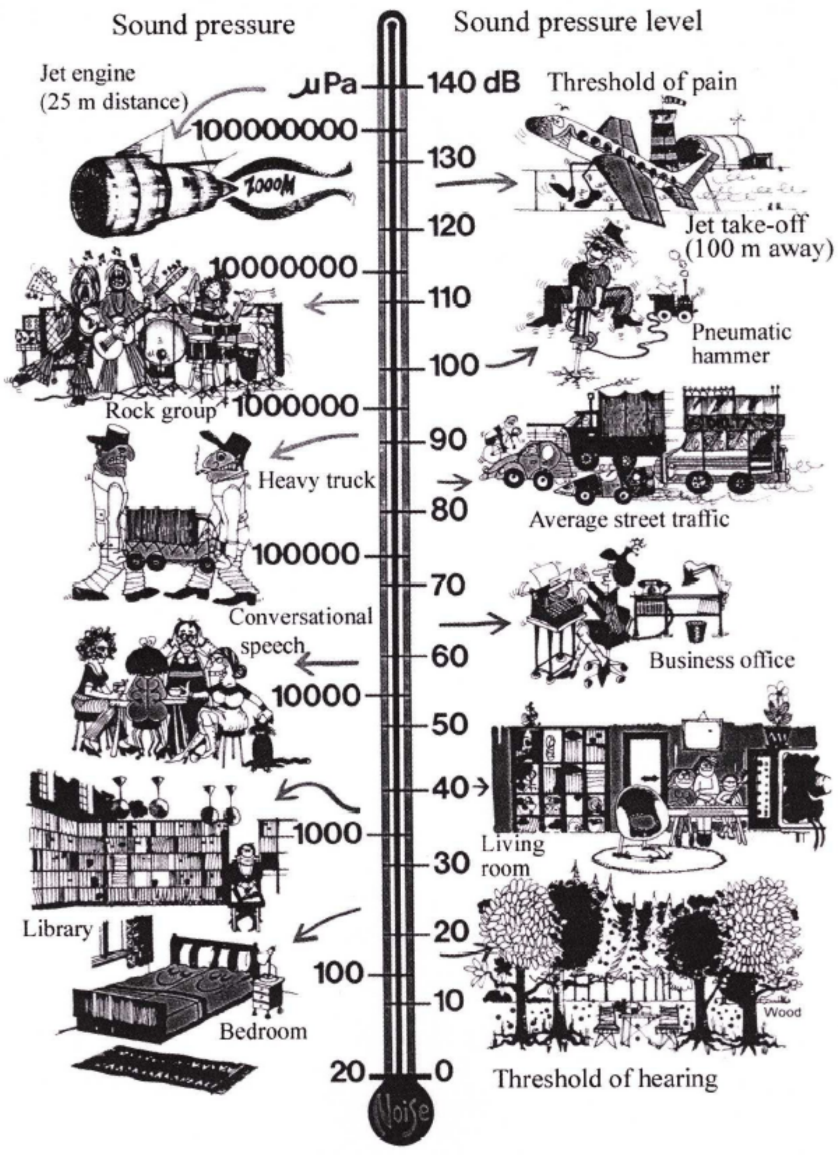
Human ear detects around 3 dB change

+10 dB = subjective doubling of perceived loudness

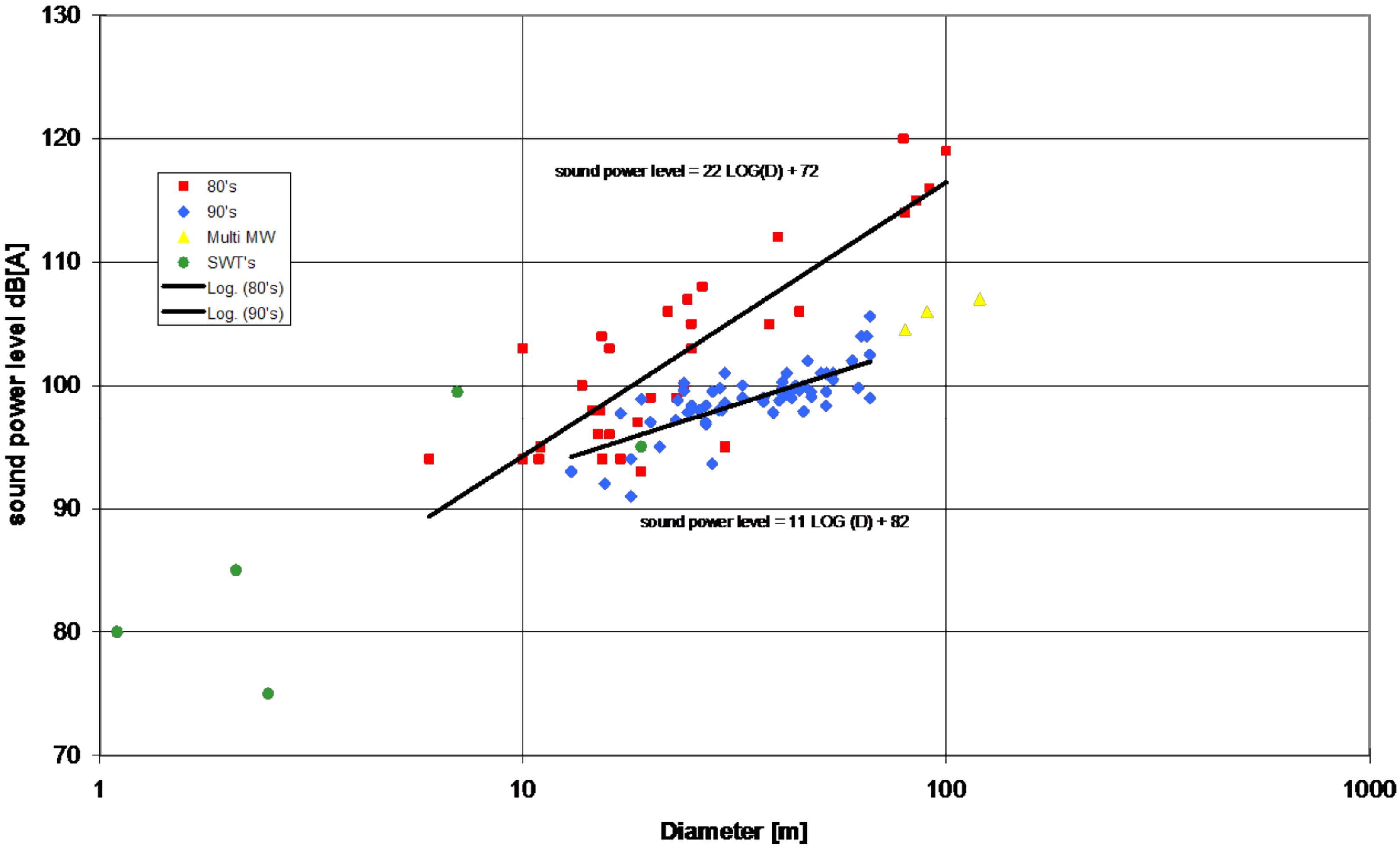
Sound Power Level

$$L_W = 10\log_{10}\left(\frac{W}{W_0}\right) \qquad\qquad SPL \approx L_W - 10\log_{10}(4\pi r^2)$$

Noise and SPL



Noise Trends for Large Wind Turbines



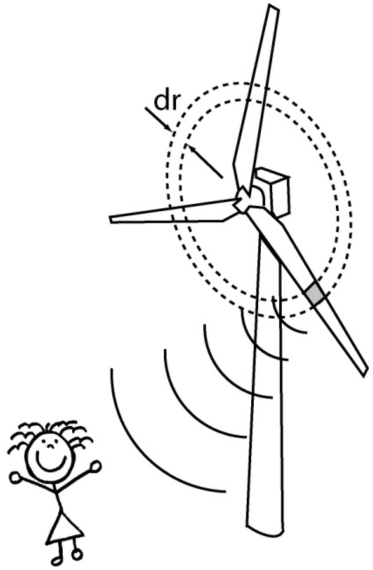
Types of wind turbine noise

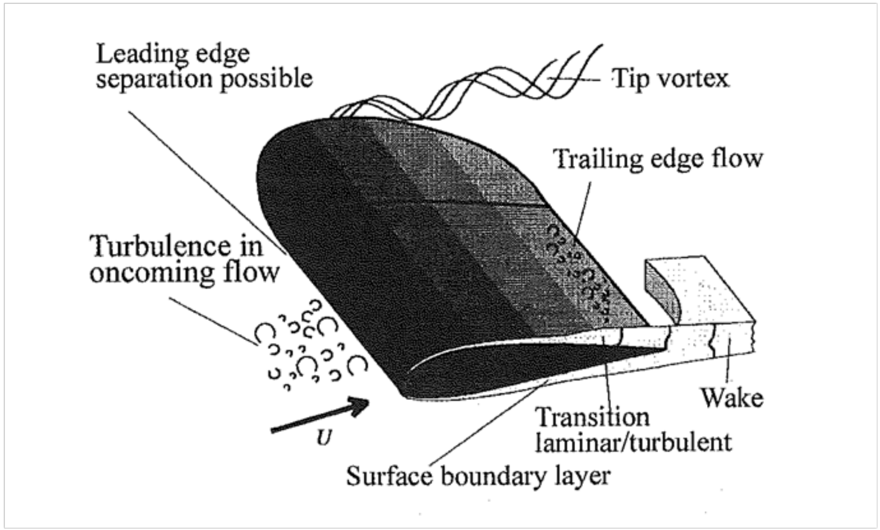
Mechanical

- Mostly tones
- Gearbox
- Generator
- Tower resonance
- Blade movement

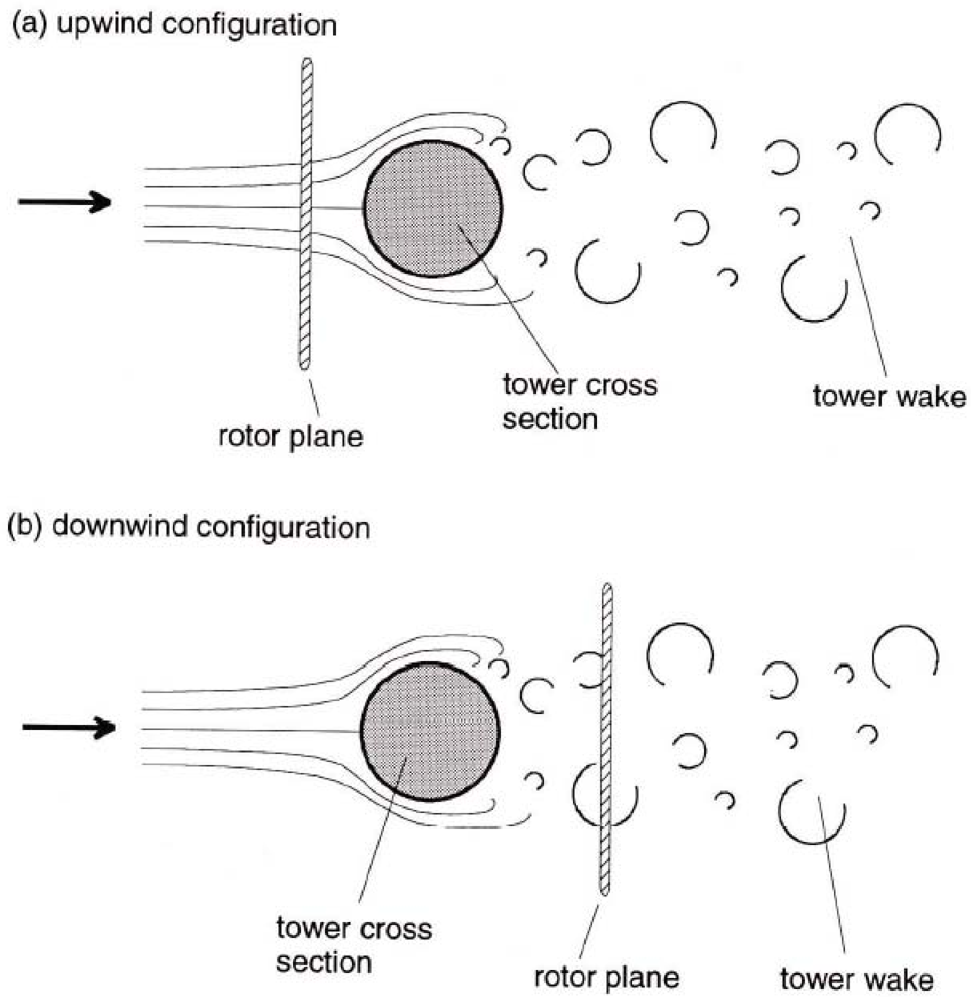
Aerodynamic

- Blades & tips
  - Proportional to M_{tip}^5
  - Higher frequency and broadband
- Tower wake
  - Rotational (low frequency)
  - 1-3 per rev



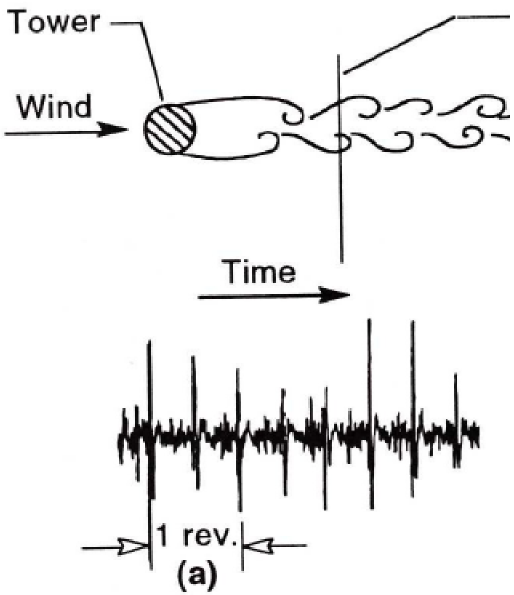


Tower influence

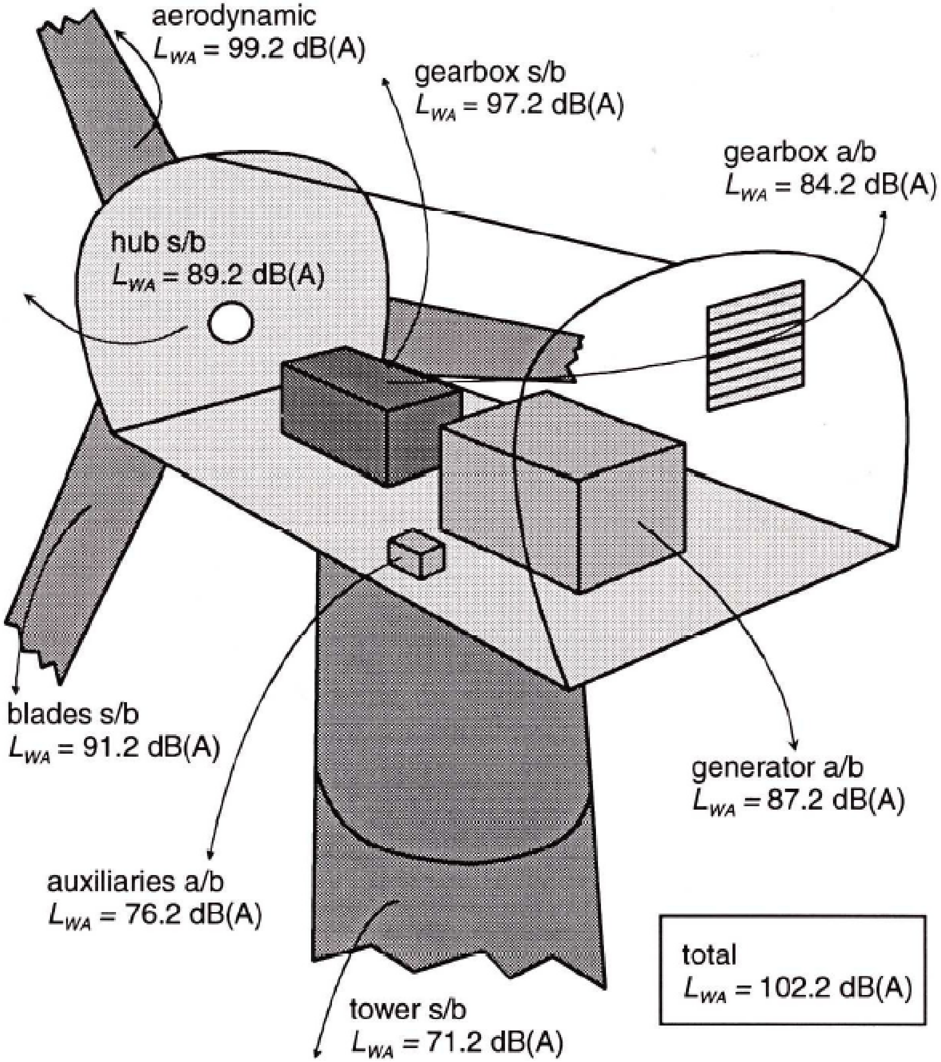


Multiple of rotor speed

Low Frequency



Relative noise contributions



Typical noise spectra

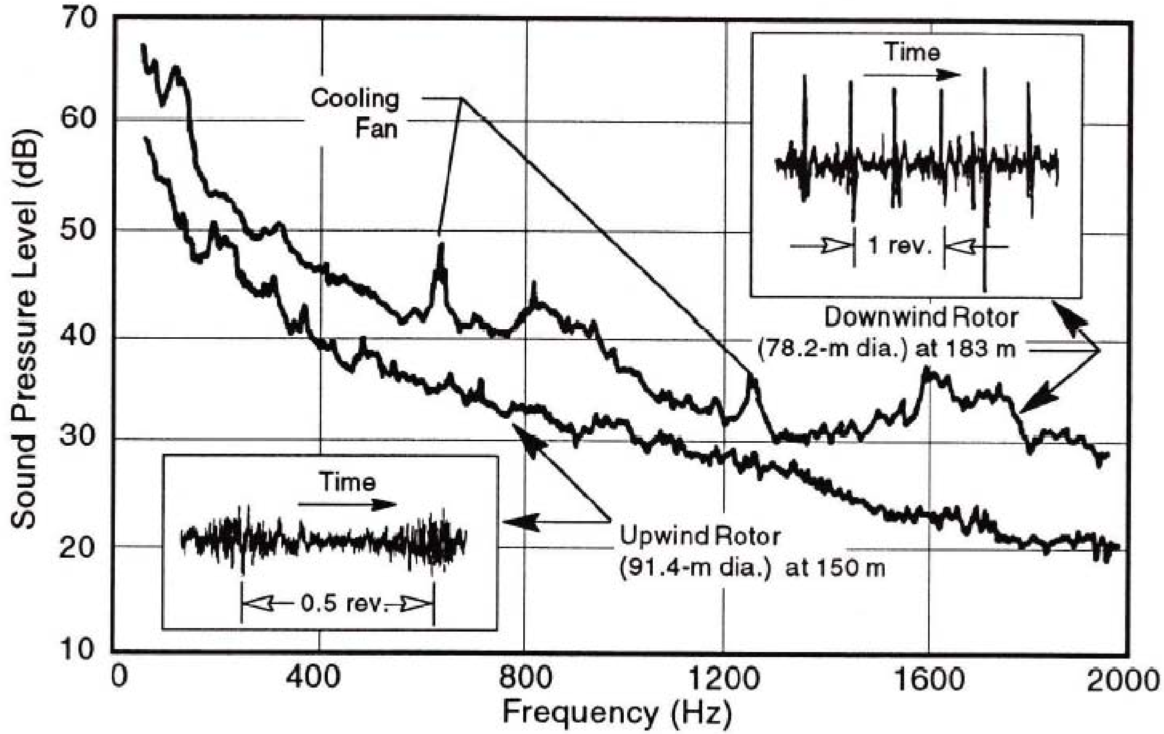
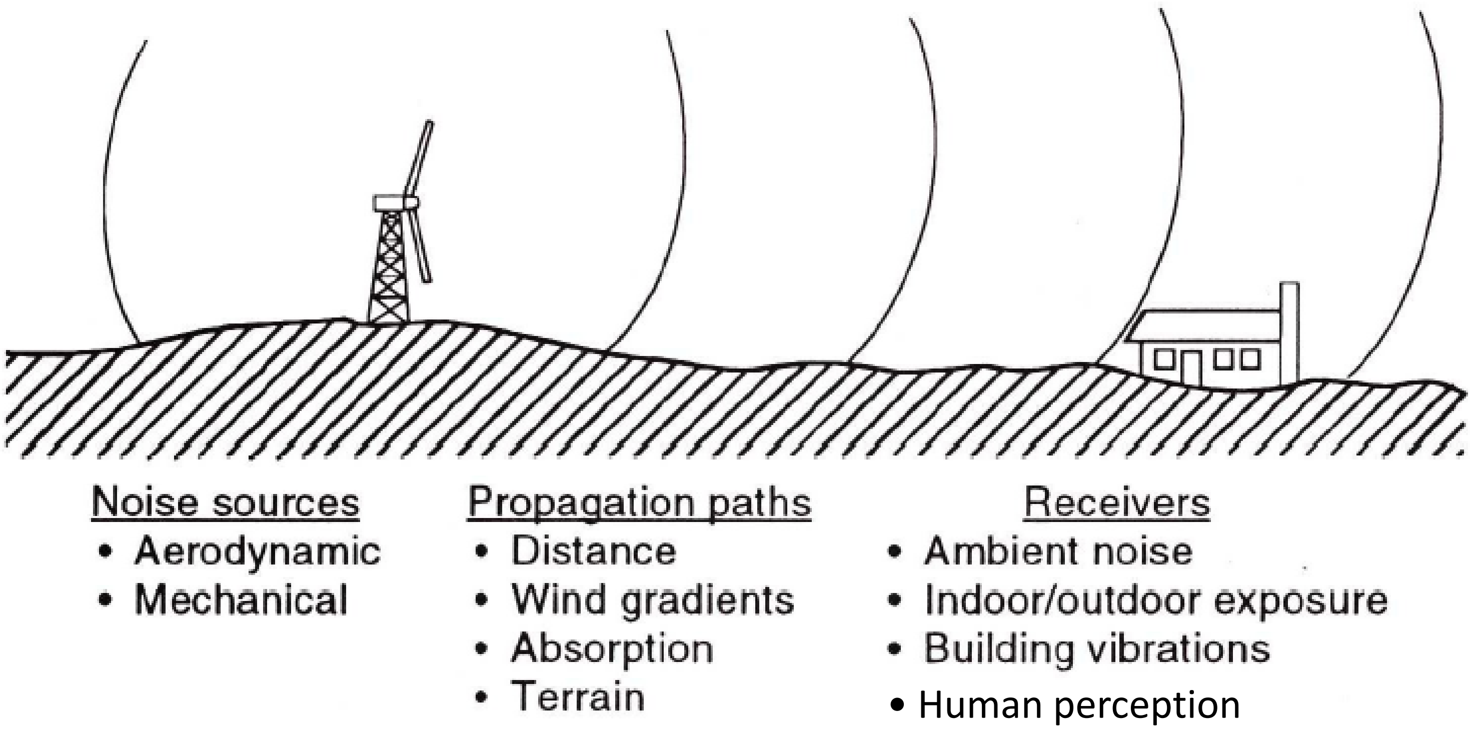


Figure 7-4. Narrow-band noise spectra from large-scale HAWTs with upwind and downwind rotors. (bandwidth = 2.5 Hz)

Noise Regimes

3 different regimes



Propagation

Humidity

Wind direction and speed

Wind Shear

Turbulence

Terrain

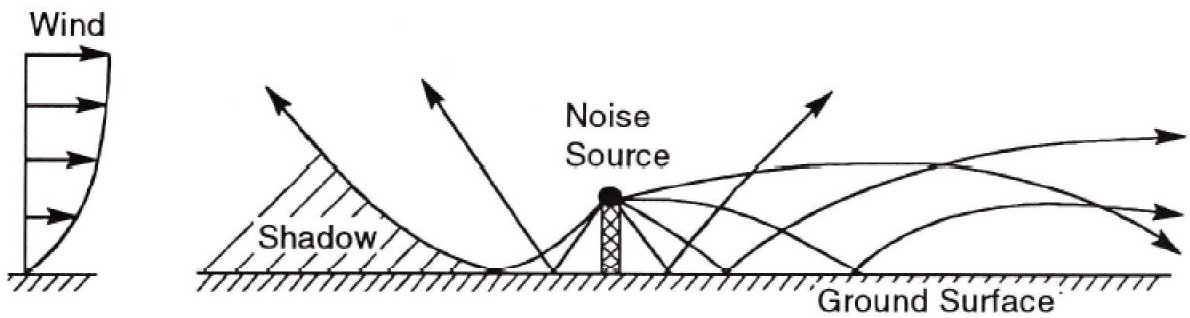


Figure 7-20. Effects of wind-induced refraction on acoustic rays radiating from an elevated point source. [Shepherd and Hubbard 1985]

Noise Ordinances

Varies by place and use

Table 2.4: Noise limits for equivalent sound pressure levels L_{Aeq} (dB(A)) in different European countries [75].

Country	*Commercial*	*Mixed*	*Residential*	*Rural*
Denmark			40	45
Germany				
– day	65	60	55	50
– night	50	45	40	35
Netherlands				
– day		50	45	40
– night		40	35	30

Human Response

Not as predictable as everything else

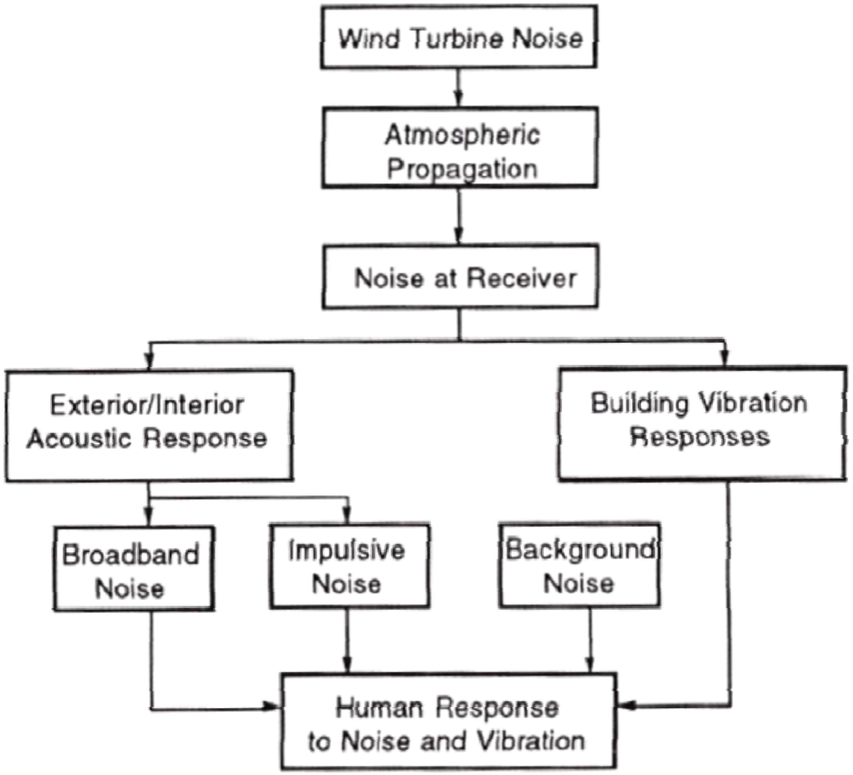


Table 7.1. Estimated Community Response to Noise (ISO 1971)

Amount by which received noise exceeds threshold level (dB)	Estimated community response	
	Category	Description
0	None	No observed reaction
5	Little	Sporadic complaints
10	Medium	Widespread complaints
15	Strong	Threats of community action
20	Very Strong	Vigorous community action

Noise descriptions

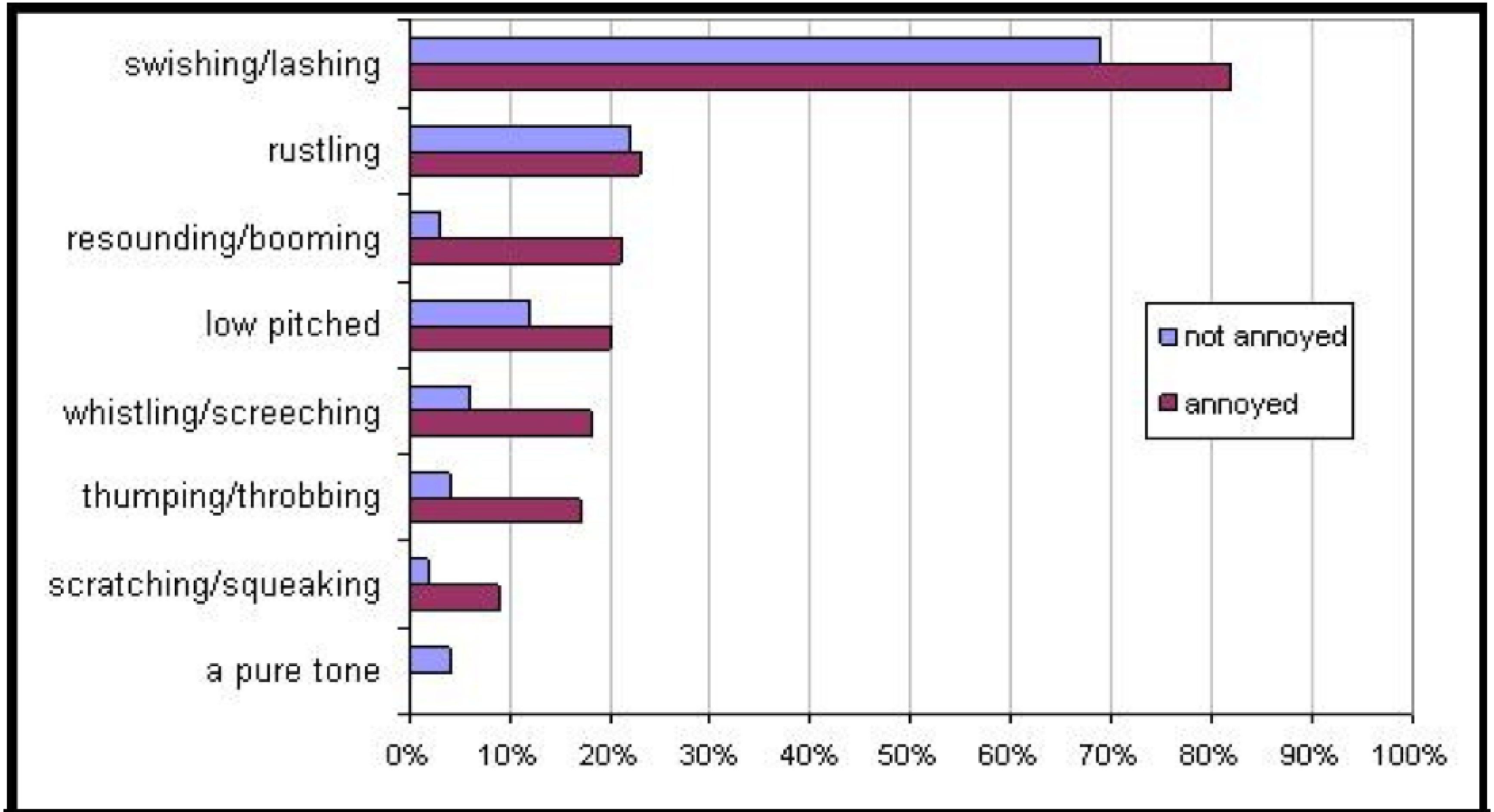


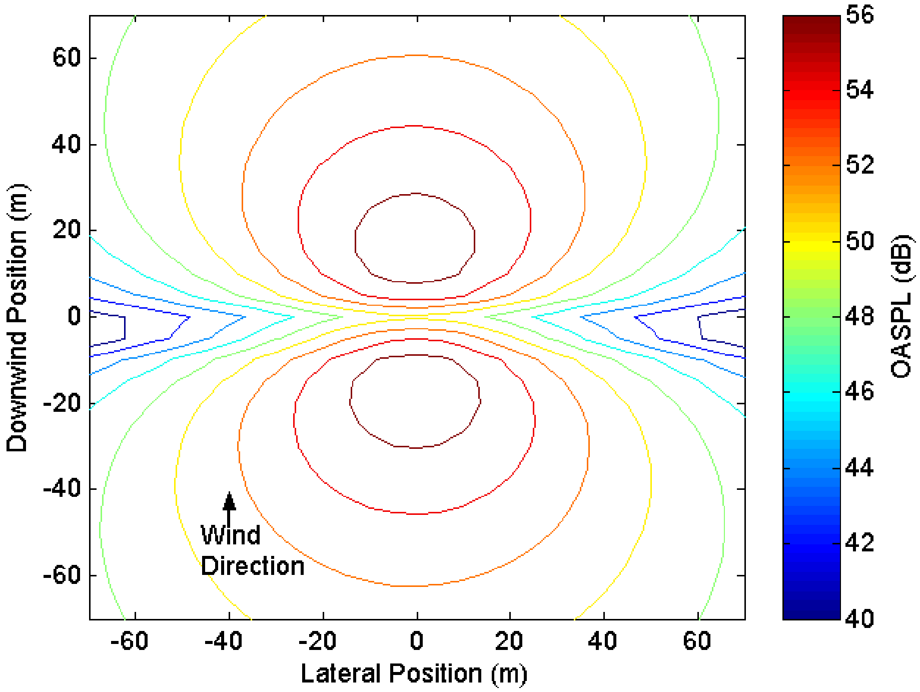
Figure 1: percentage of respondents that think the description fits the wind turbine sound they hear at home (based on [11])

Noise reduction

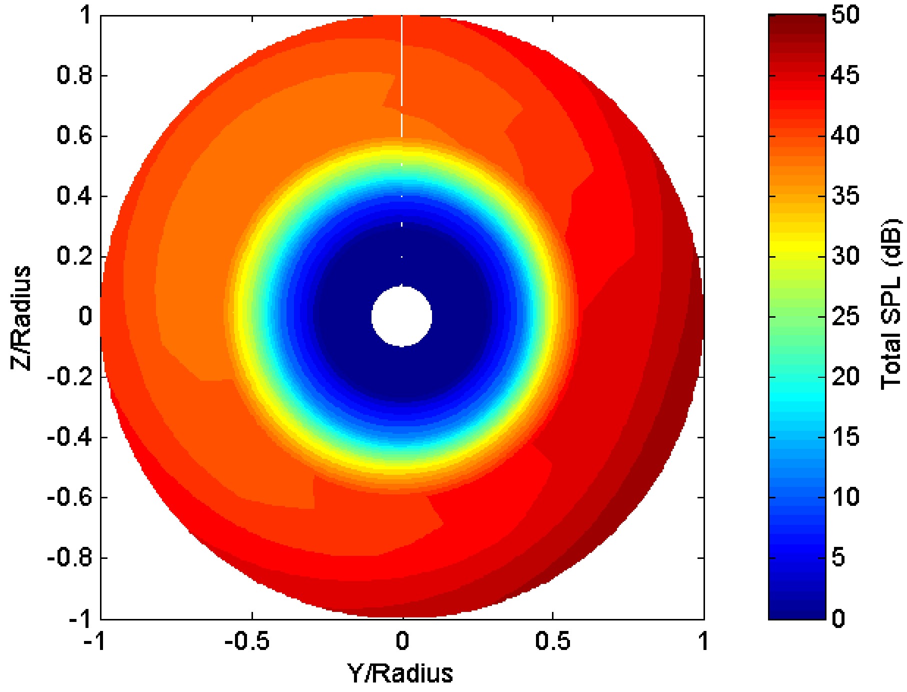
- Move turbines farther away
  - Offshore
  - Low frequencies travel farther
- Mechanical
  - Isolation
  - Insulation
  - Gear tooth design
- Aerodynamic
  - Lower tip speed
  - Modify trailing edge
    - Sharpen
    - Trailing edge serrations
  - Modify airfoil
    - Reduce TE boundary layer thickness
  - Modify blade shape
  - Modify tip shape

Observer location influence

Noise Footprint - Directivity

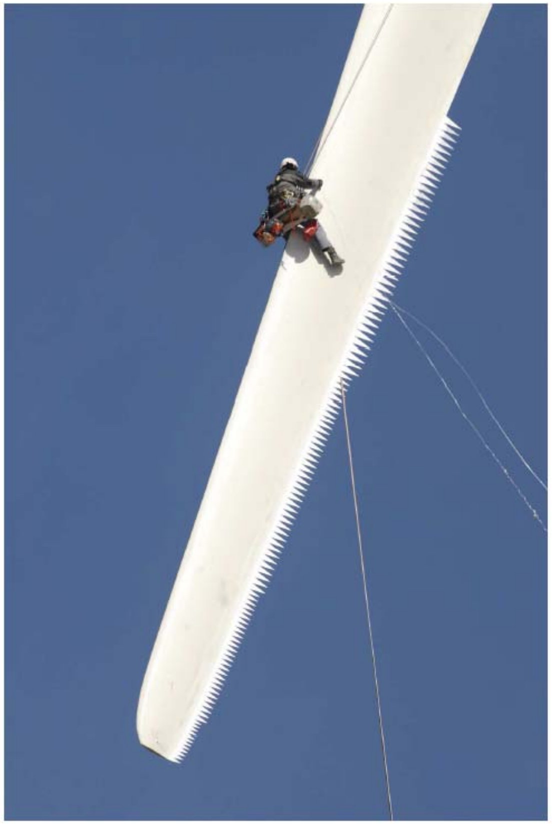


Rotor Plane – Doppler Amplification

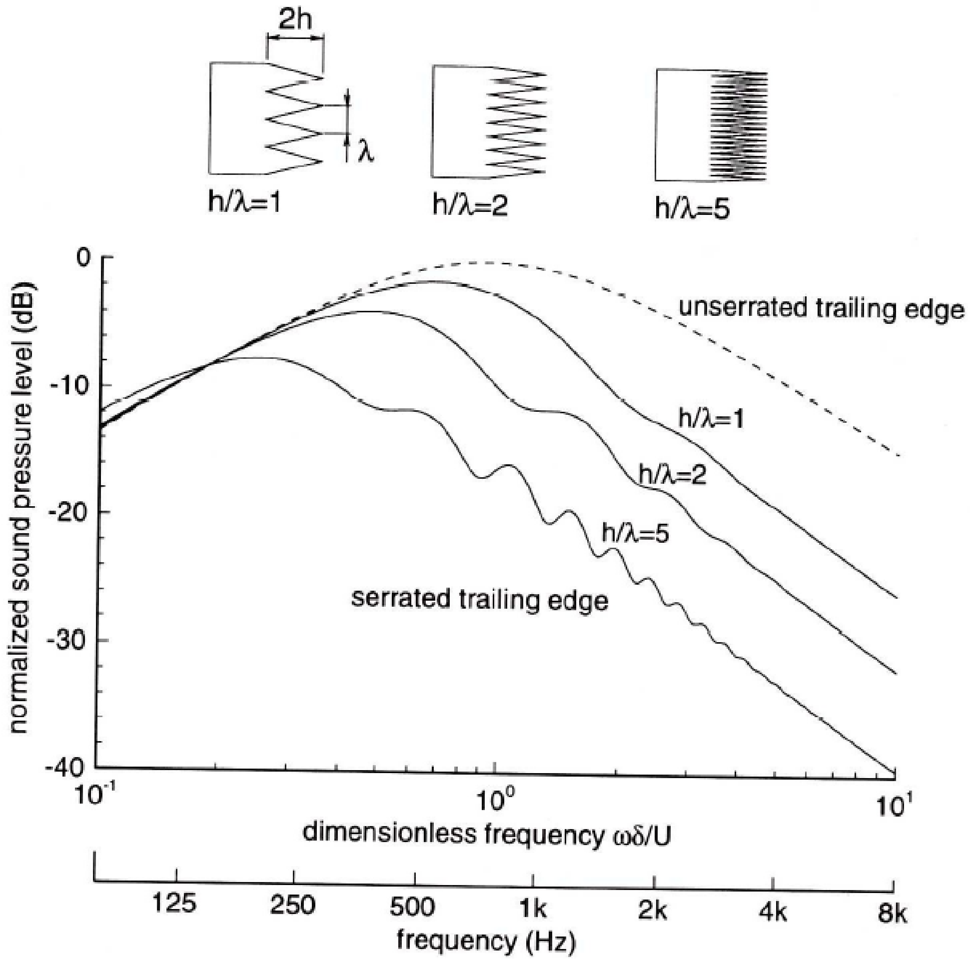


AOC 15/50

Trailing Edge Serrations



Serrated trailing edge for noise reduction (Oerlemans 2008)



Trailing Edge Serrations

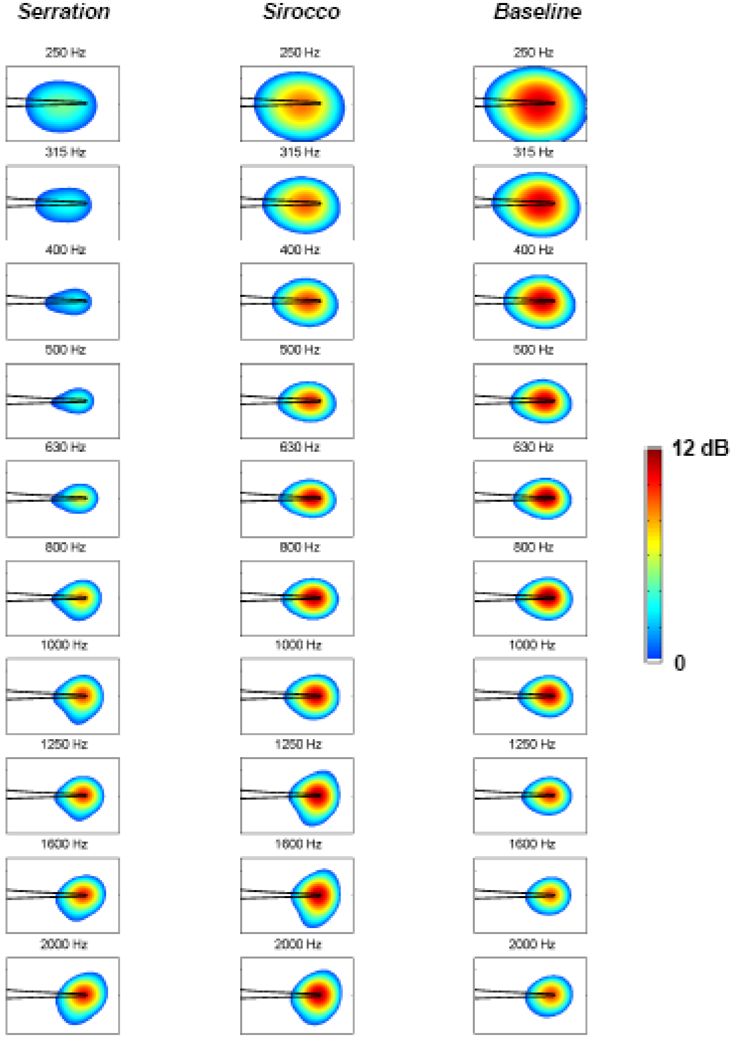
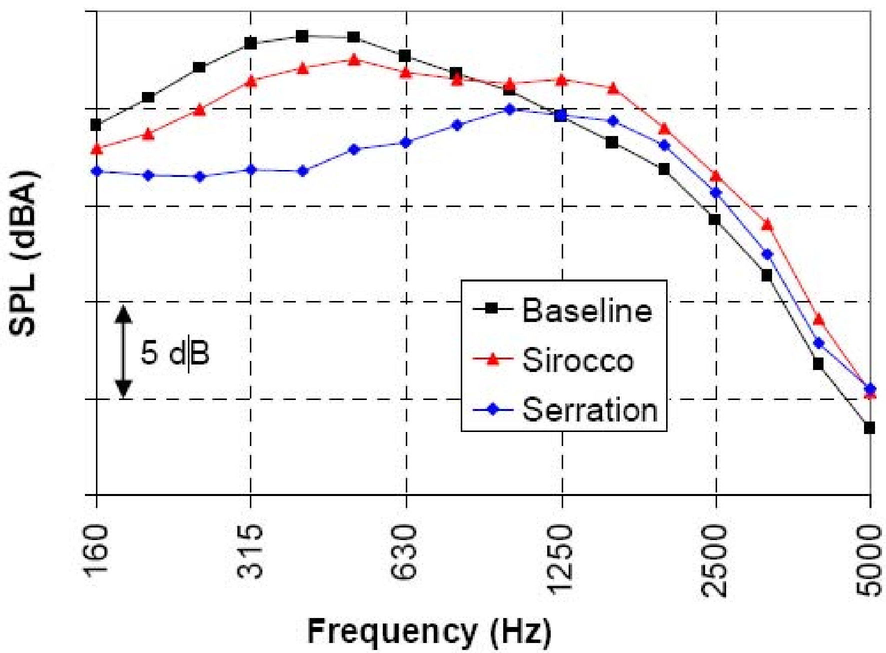
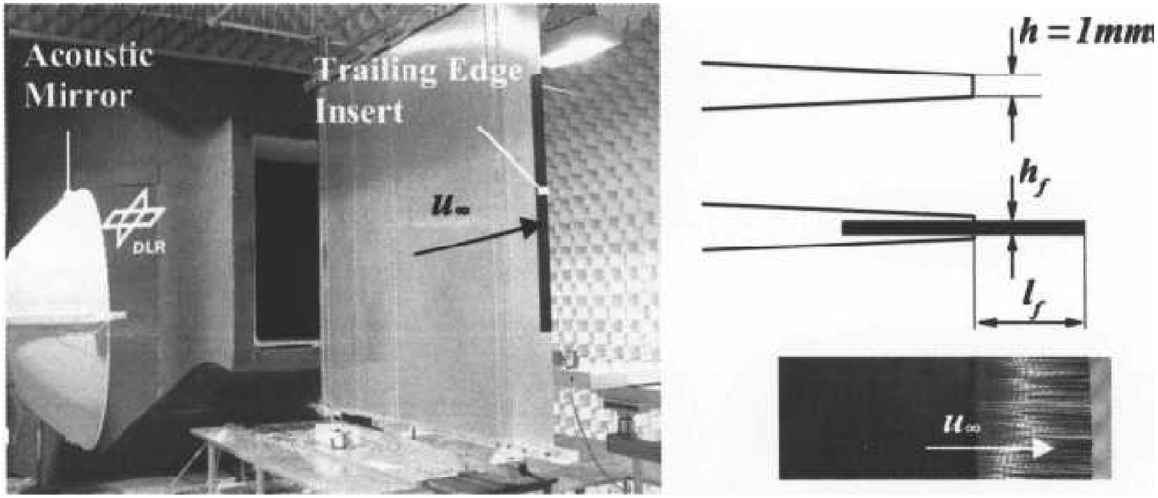


Figure 8-11: Average rotating source maps for individual blades in State 2a, as a function of frequency. The range of the color scale is 12 dB and the maximum is the same within each row.



Oerlemans 2009

Trailing Edge Brushes



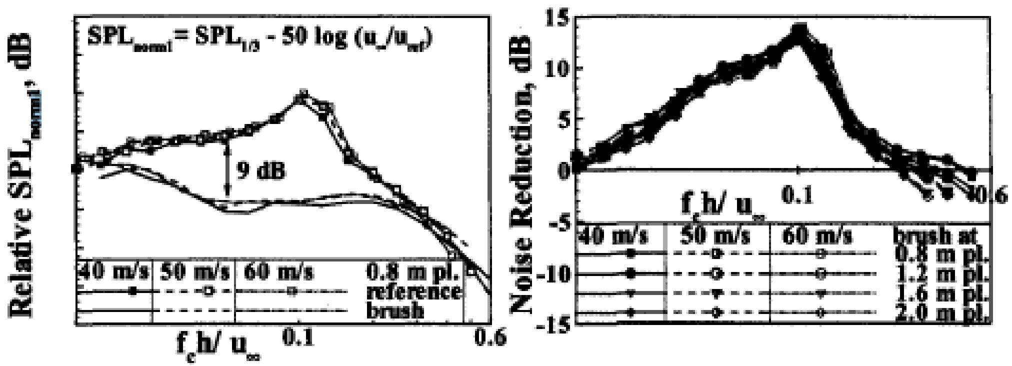


Figure 7 *(left)* Trailing edge noise reduction by means of brush edges (fibre diameter: 0.4 mm, length: 30 mm), comparison with solid trailing edge reference configuration.
Figure 8 *(right)* Influence of plate chord length and flow velocity on the noise reduction potential (same brush configuration as in Figure 7).

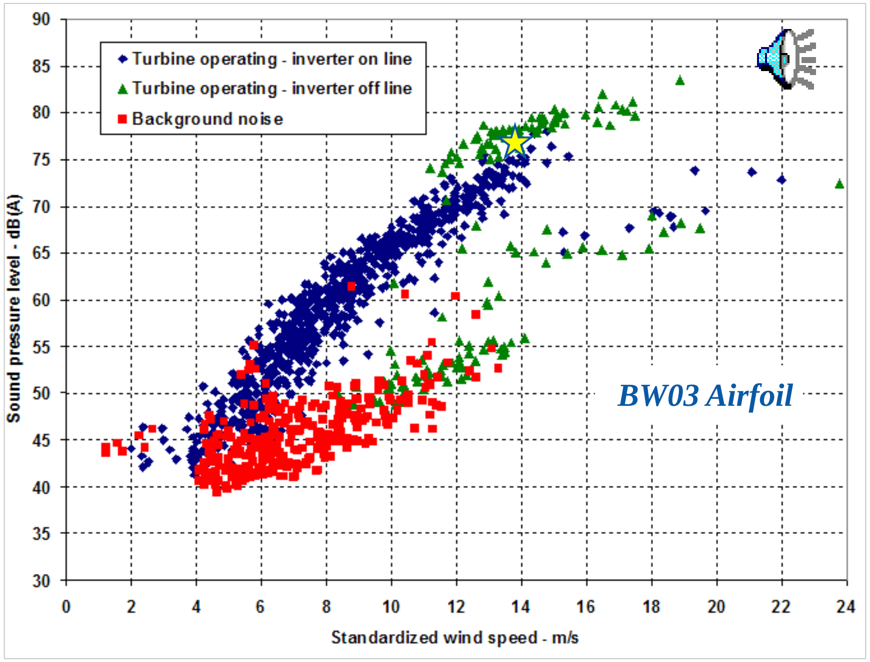
Herr, 2004 “Experimental Study on Noise Reduction through Trailing Edge Brushes.”

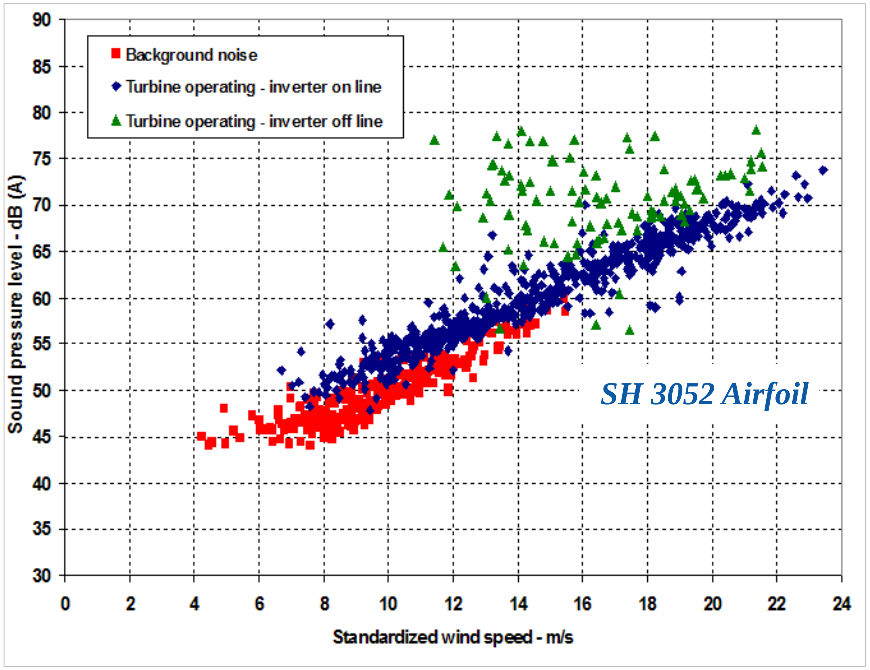
Blade Shape

Spread out blade loading change through tower shadow - Computer fans

Blade tip shape changes tip vortex interaction

Rotor Modification – Bergey Excel





☆ Unloaded turbine and/or furling cause considerable noise.

Rotor modifications (airfoil and diameter/tip speed) significantly reduce noise.

Low Frequency Noise and Infrasound

Low Frequency Sound
- 20 Hz < f < 200 Hz

Infrasound
- f < 20 Hz

Important for large scale downwind turbines

Can resonate with building structural frequencies

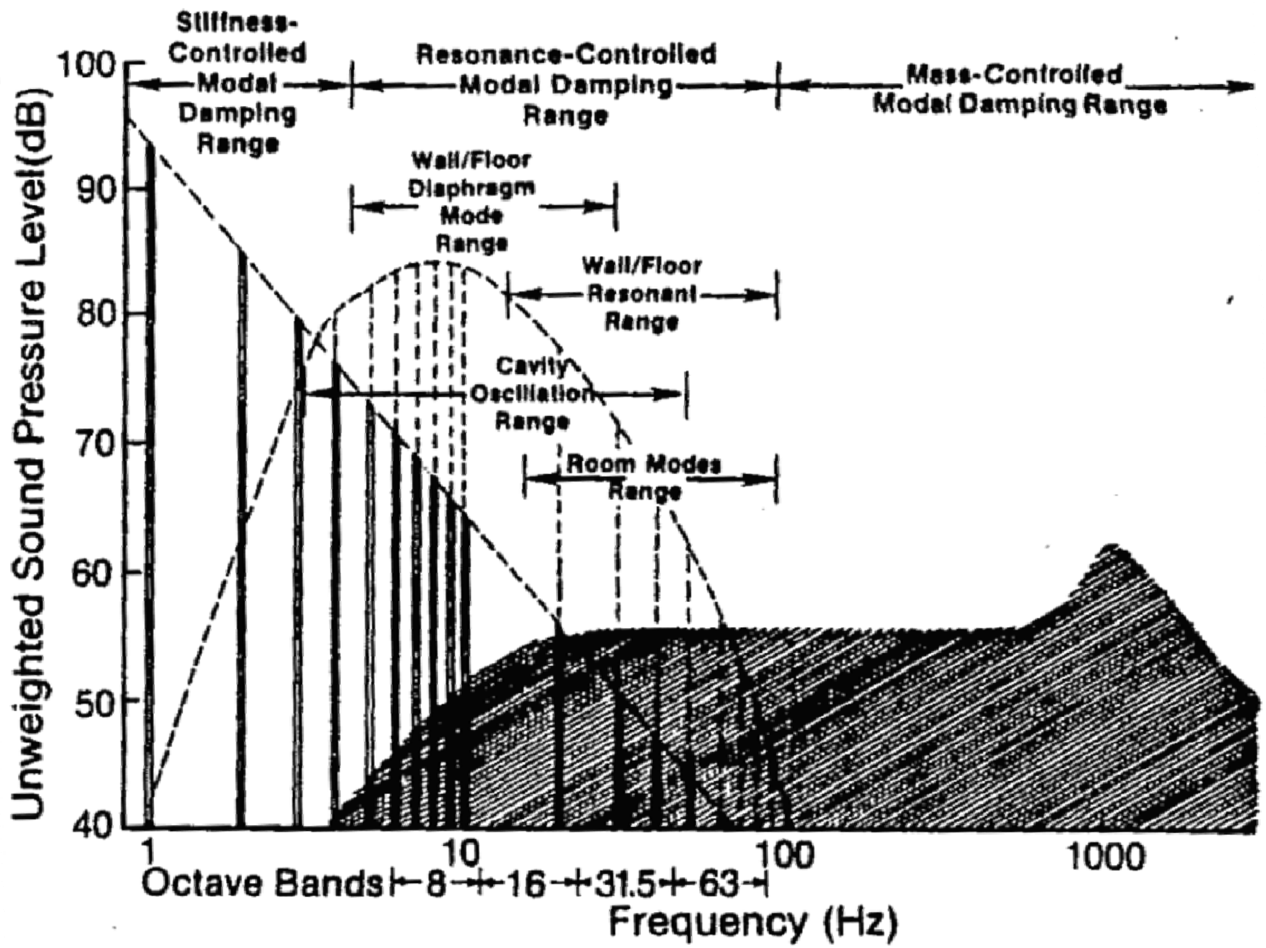
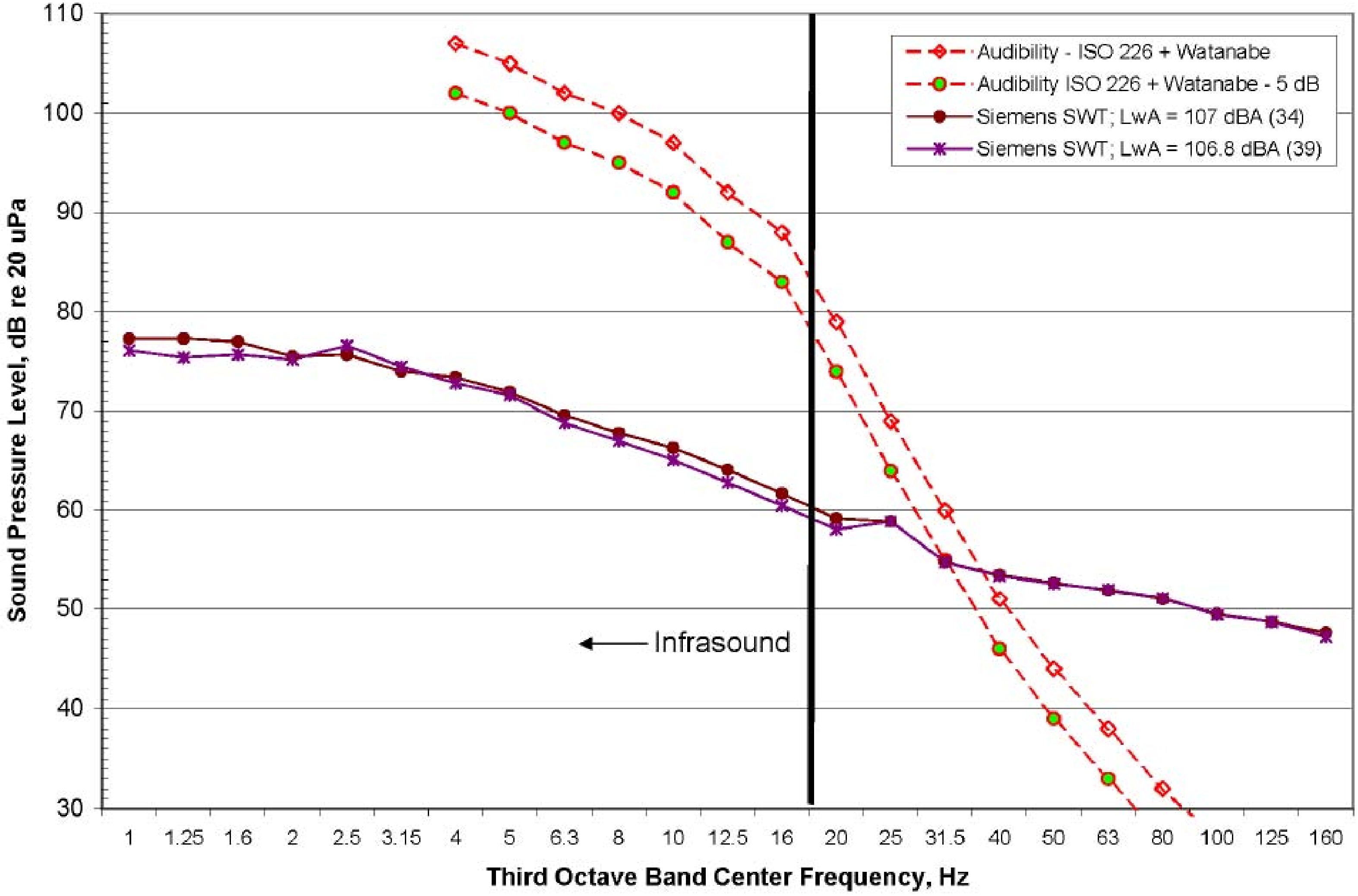


Figure 2. SCHEMATIC SOUND SPECTRUM OF FIGURE 1, WITH RESIDENTIAL VIBRATION AND ACOUSTIC MODES ADDED

Low Frequency Noise and Infrasound

Figure 8.1-1 Siemens SWT-2.3-93 Wind Turbine Outdoor Sound Levels at 1000 feet compared to Audibility Criteria



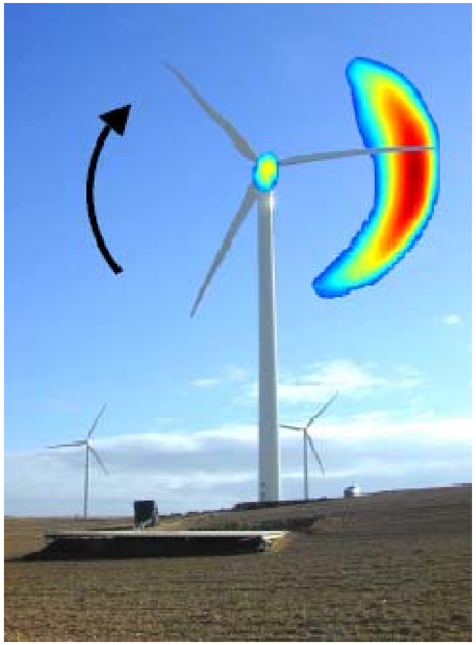
Measurement Techniques

Single Microphone

- Relatively simple setup
- No ability to interpret location of noise
- Can't get below background noise

Acoustic Array

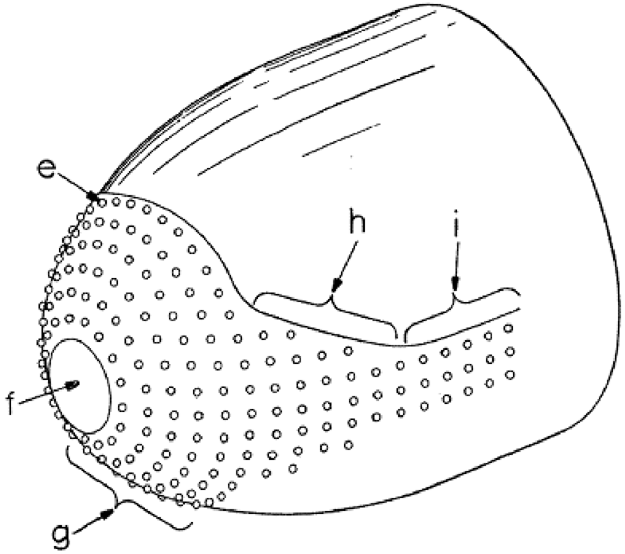
- Reduce background noise relative to turbine noise
- Identify source locations



Background – What is an Acoustic Array?

- An acoustic array is a phased array of microphones
- Time (or phase) delay between signals received at each sensor used to determine direction of the source(s)
- Electromagnetic phased arrays used in radar, radio astronomy
- Acoustic array examples are SONAR applications (submarines) and investigation of aircraft noise

The VLA in New Mexico: a phased array for radio astronomy



Phased microphone array on torpedo

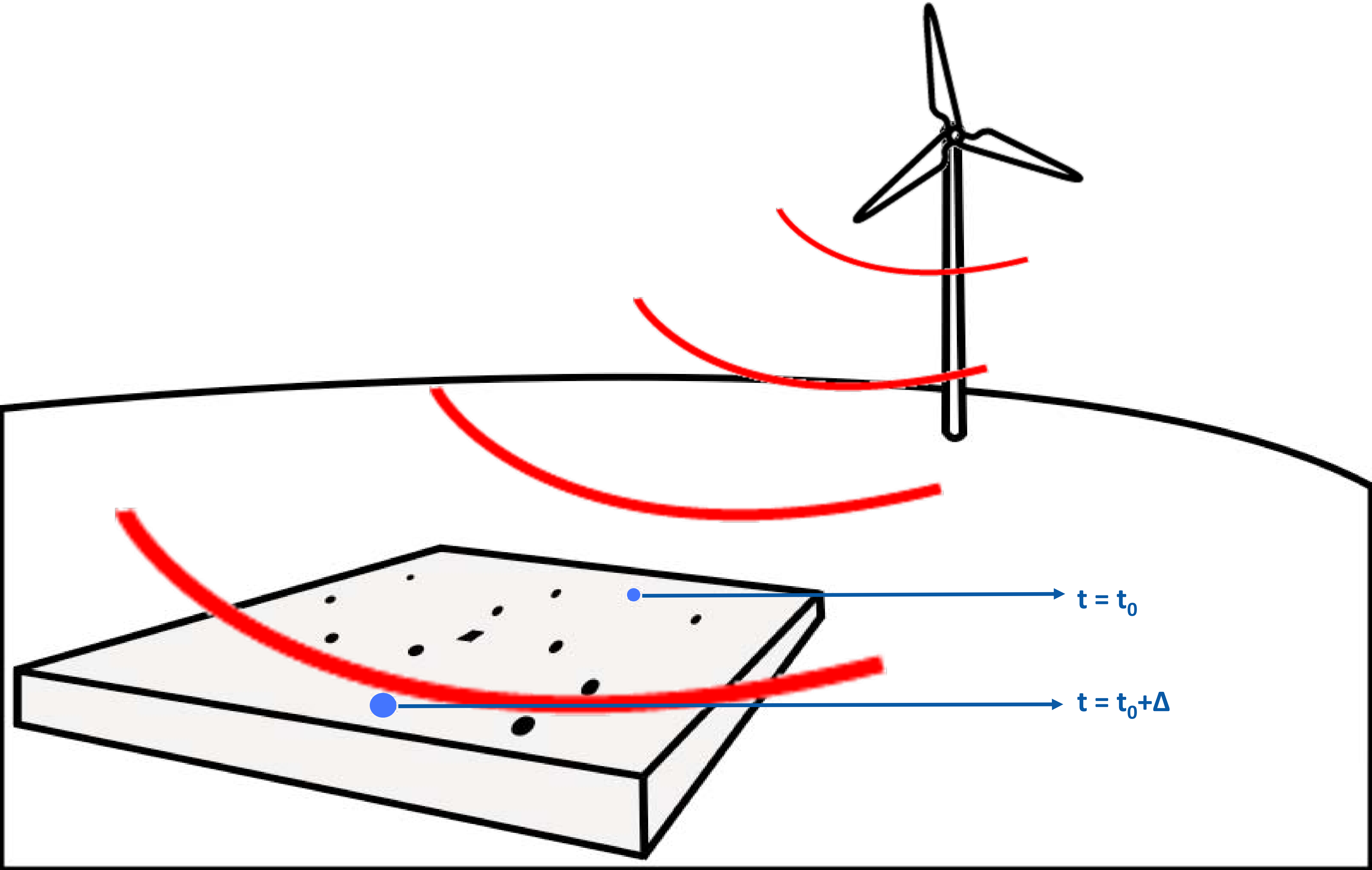
Background – Acoustic Arrays for Aeroacoustic Analysis

- Arrays used for aeroacoustic analysis beginning in the mid 1970's.
- Key innovators: NASA, NLR (The Netherlands), DLR (Germany), Boeing
- Wind tunnel measurements
- Flyover measurements
- Goal to reduce airframe and engine noise by identifying acoustic sources

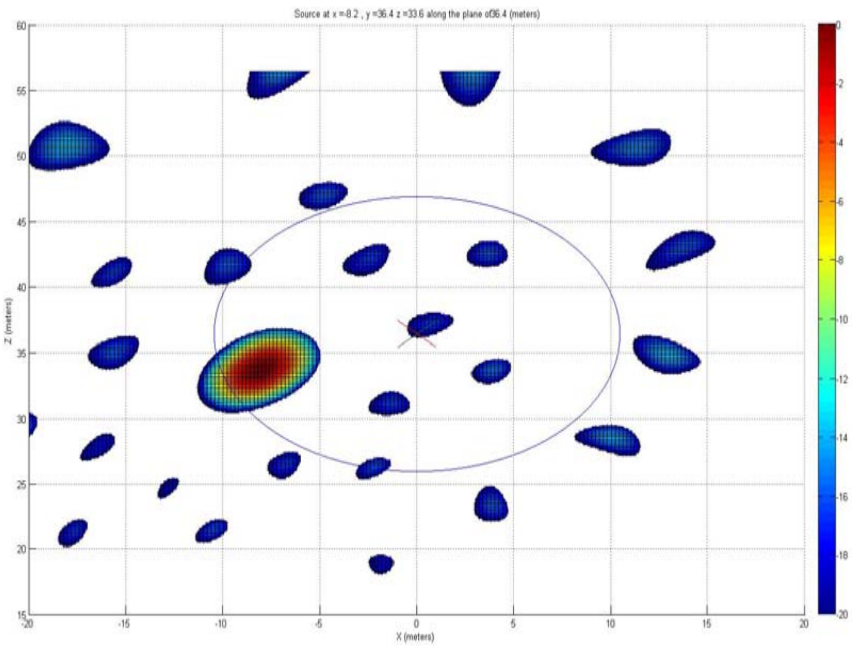
Acoustic array in German-Dutch Wind Tunnel

A 600-microphone array used by Boeing

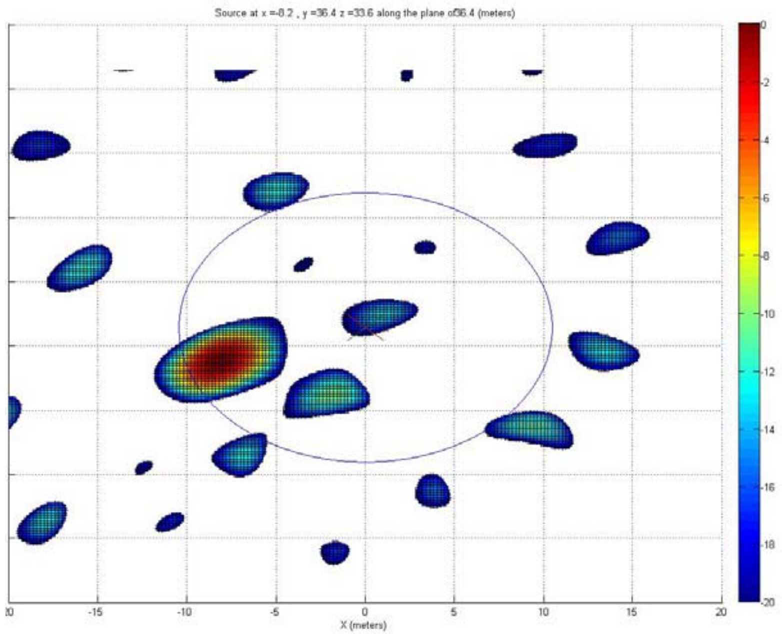
How does it work?



Theory vs. Field Test



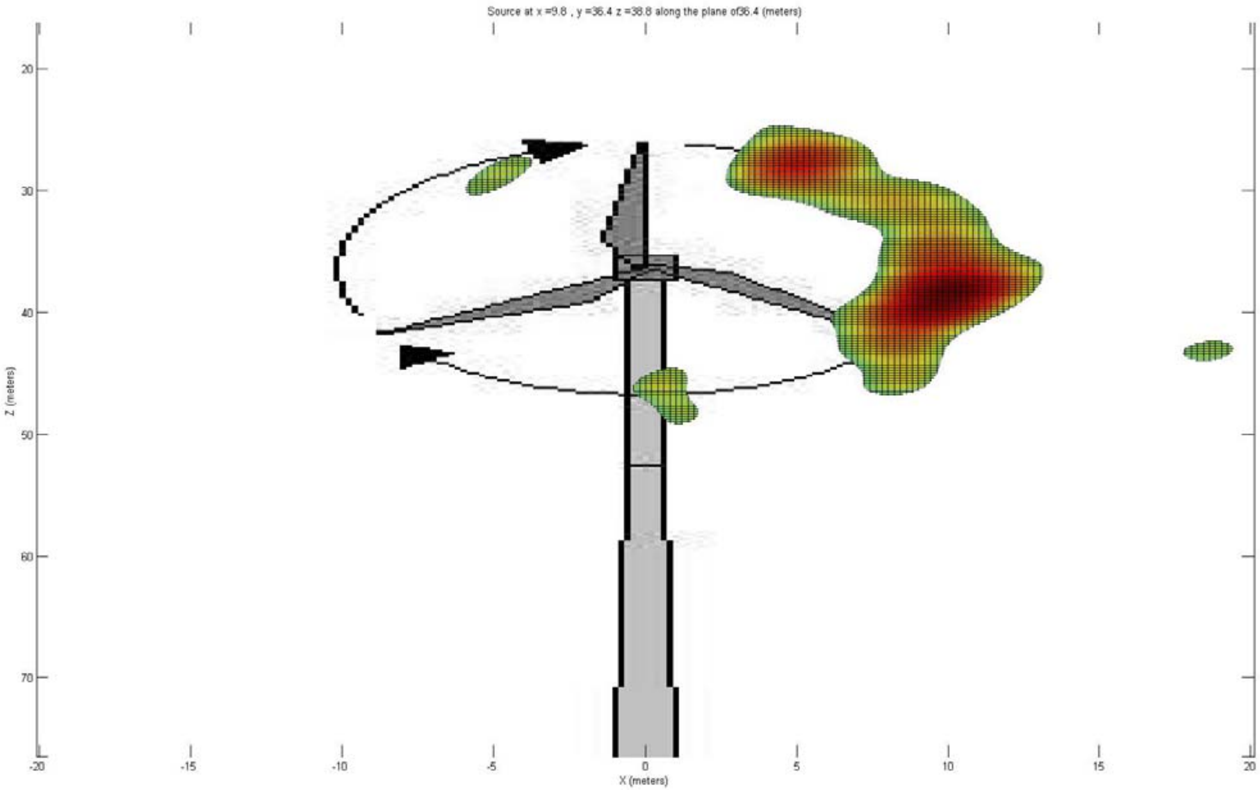
Simulation using 1kHz



Field Testing with 1kHz Tone

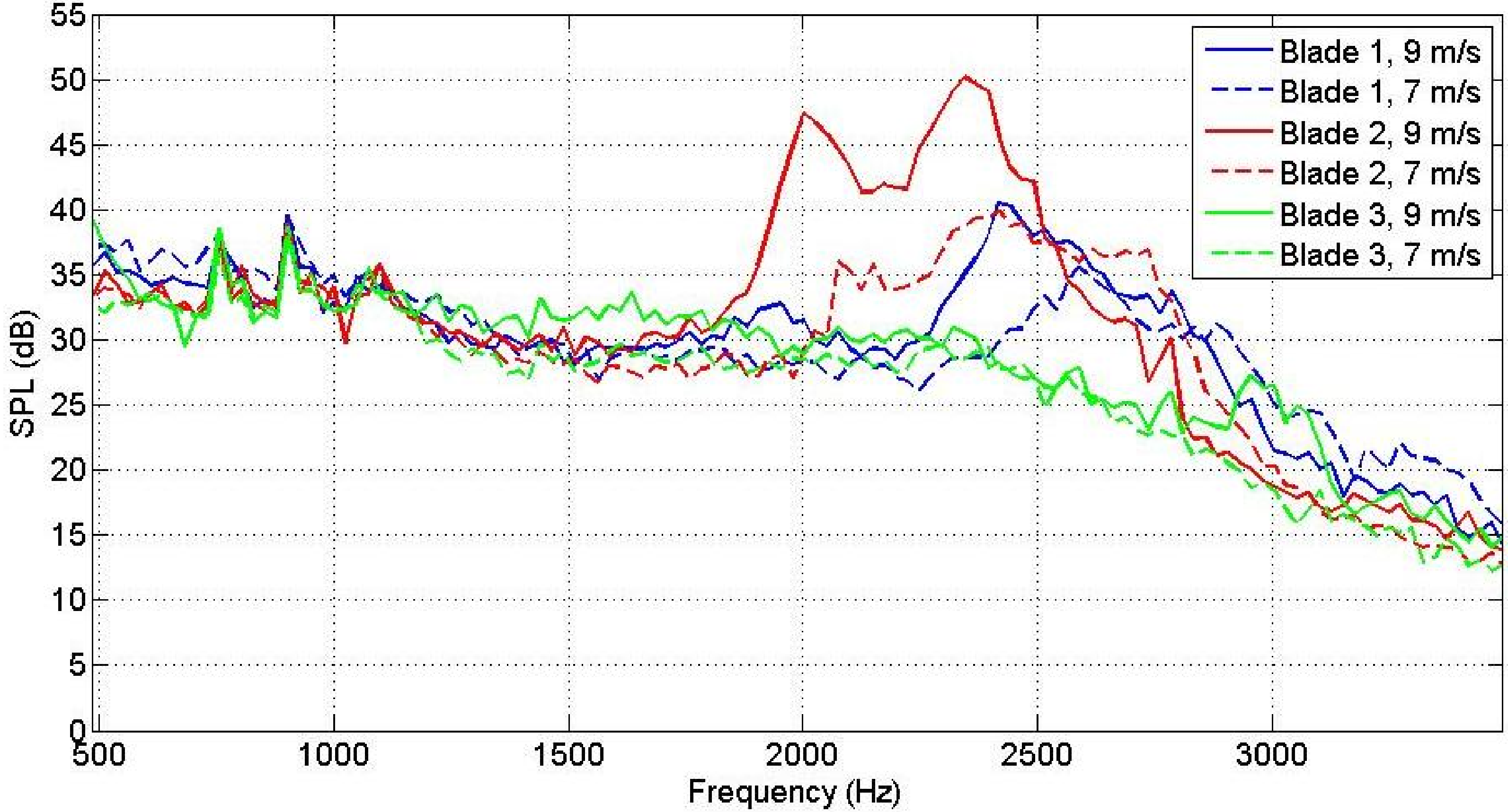
Actual Turbine

Northwind100B



4kHz Beamforming, averaged over 1.5sec (one period of the rotor). Only highest 10dB of noise is visible. Data from July, 2008

Individual Blades



- Two blades cause significant high frequency noise (1.75 kHz – 2.75 kHz)

Background – CU-NREL Array

- 32 microphone array
- Frequencies of interest: 125 Hz – 8 kHz
- Regions of interest: blade tip regions, inboard blade regions (for "flatback" blades)
- Array used for field measurements of 100 kW turbine in Bushland, TX since summer 2009
- Upcoming tests of CART3, Siemens, GE (?)

21 meter rotor diameter turbine used for array development at NREL

Upcoming Acoustic Array Project

Acoustic Array Development

- New array with 64 microphones
- New spiral shape
- Improved weatherproofing

Baseline Measurements

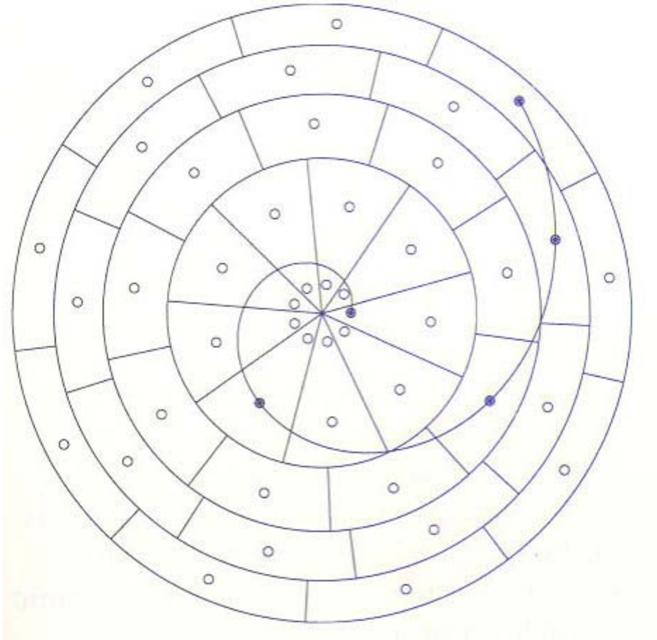
- Background
- Individual microphones around turbine perimeter
- Acoustic array of original blades

Constructing trailing edge modifications

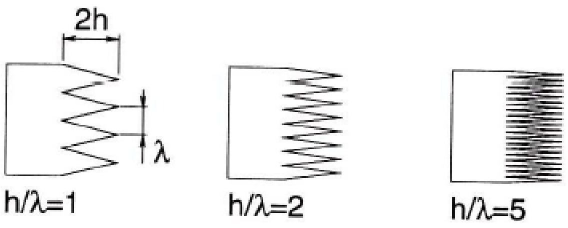
- Serrated trailing edges
  - Variable aspect ratios
  - Variable chord lengths
- Brushes
- Easily attached/removed

Noise mitigation testing

- Individual microphones around turbine perimeter
- Acoustic array of original blades



Multi-arm spiral array shape (Underbrink, 2002)



Questions?