Aerodynamic Noise
from Wind Turbines

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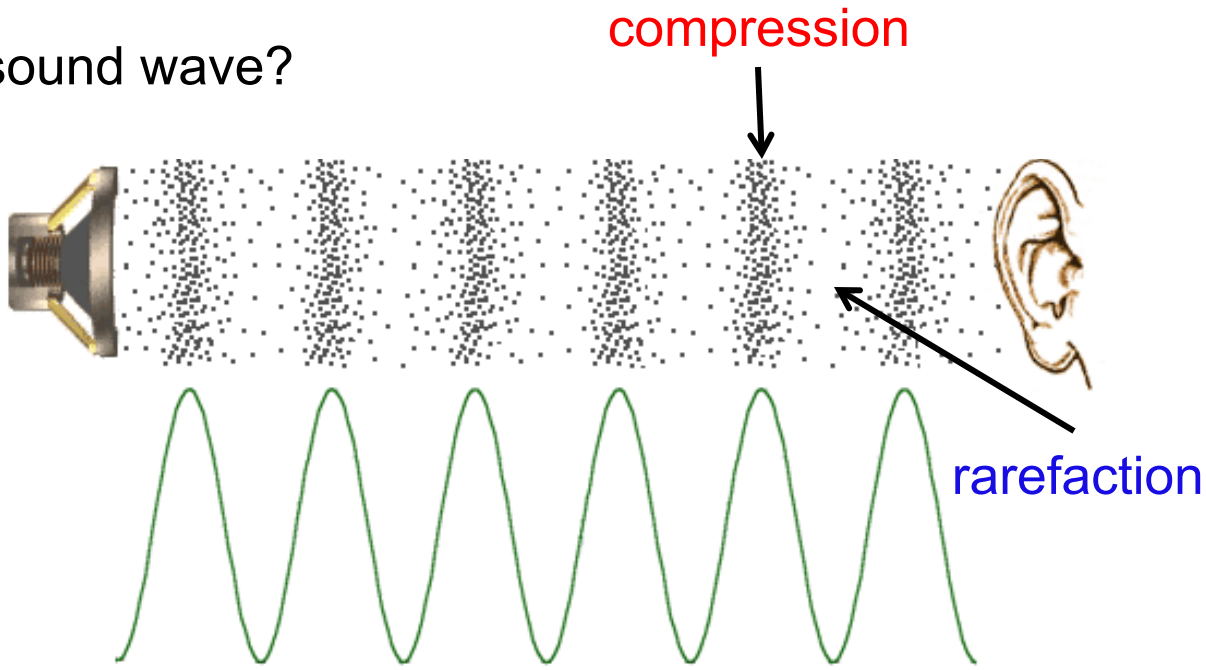
Agenda

- Basics of sound waves
  - What is sound?
  - Measurement units, energy in sound etc.
- Noise – what's all the fuss about?
- Wind Turbine Noise (Sources)
  - Generated by vibration → Mechanical (Gearbox)
  - Generated by flow → Aerodynamic
- Noise Prediction
- Noise Reduction – Some Methods

Sound Waves

- What is a sound wave?

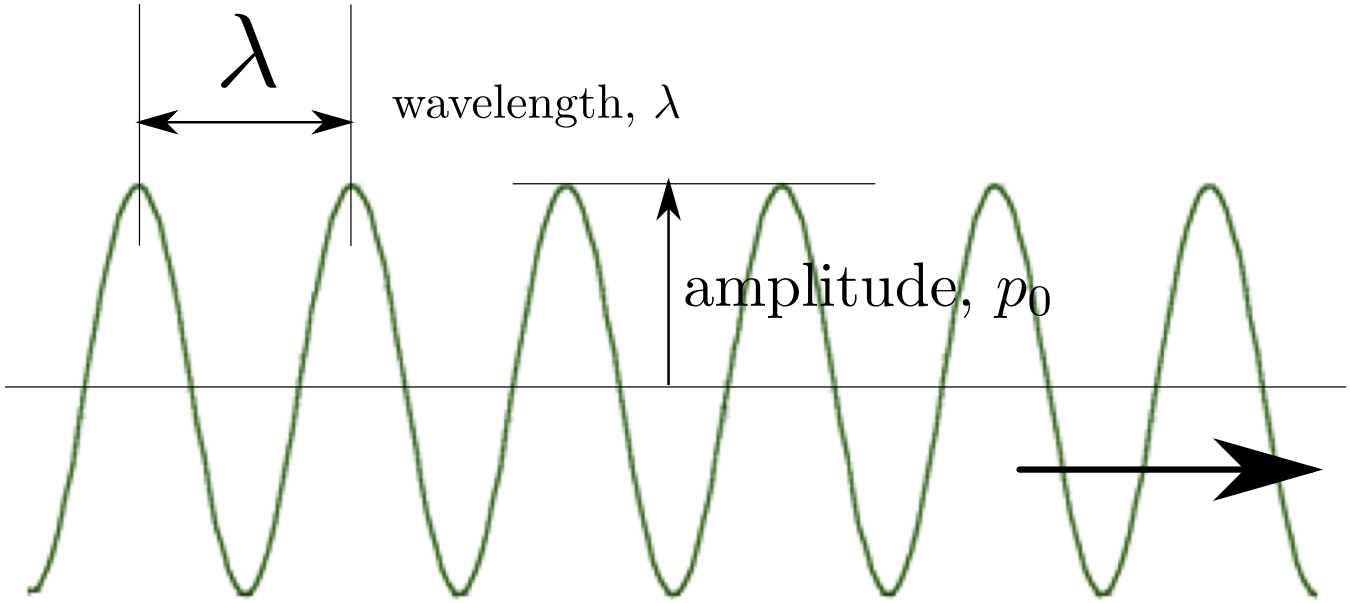


- "Longitudinal" – particle motion in the direction of wave motion
- Require a medium (air/water/solids) to propagate – unlike electromagnetic waves

- **"Perturbation" of density/pressure that propagates with the speed of sound**

Sound Waves - Characteristics

Amplitude, frequency (pitch), speed, wavelength



$$p = p_0 \sin\left(2\pi(ft - x/\lambda)\right)$$

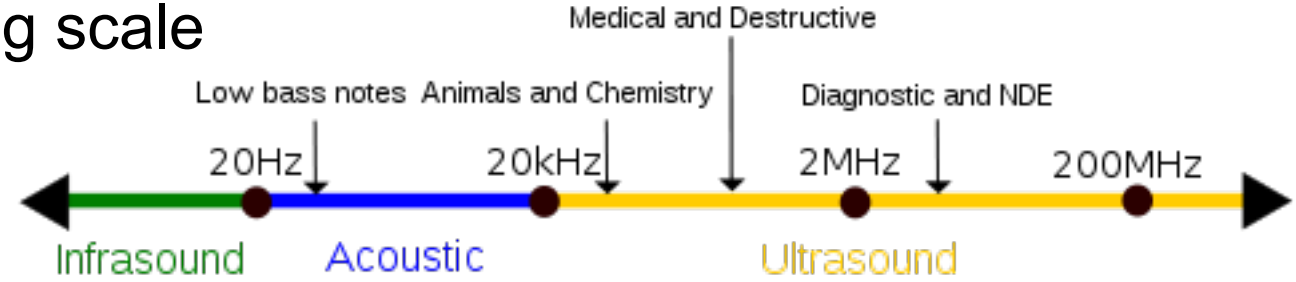
wavespeed, c

frequency, $f = c/\lambda$

Wave speed can be a function of frequency depending on the medium → dispersive media

Sound Waves - Characteristics

- Frequency (cycles per second or Hz) – log scale

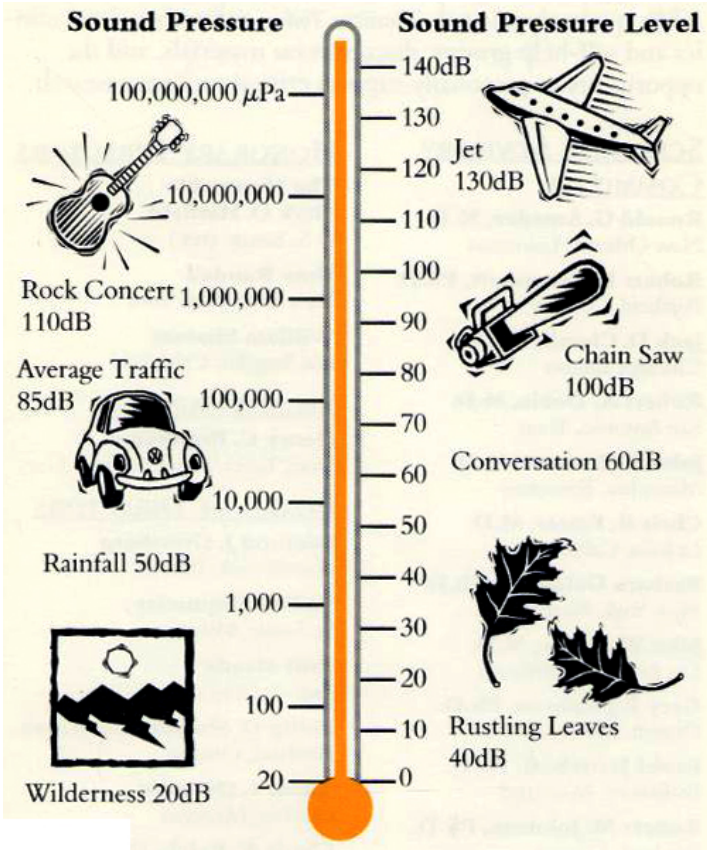


- Amplitude / energy measured in **decibels** – logarithmic scale

$$\mathrm{SPL} = 10 \log_{10} \left(p_{rms}^2 / p_{ref}^2 \right)$$

$$p_{ref} = 20\ \mu Pa$$

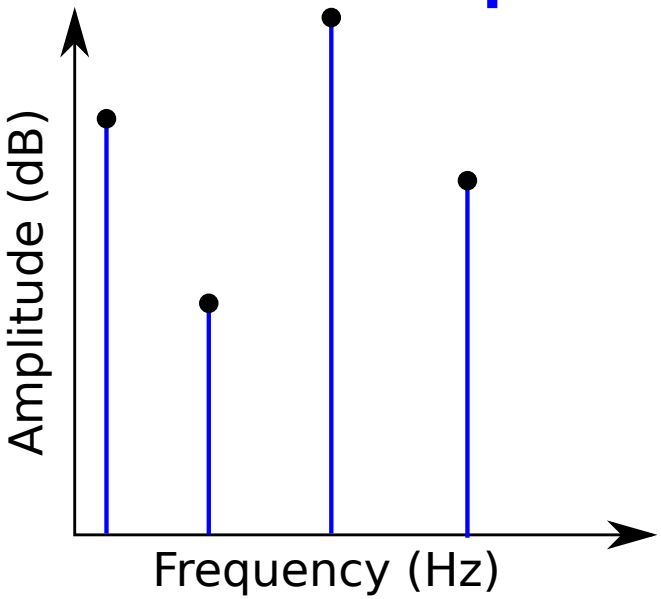
- Why logarithmic scale?



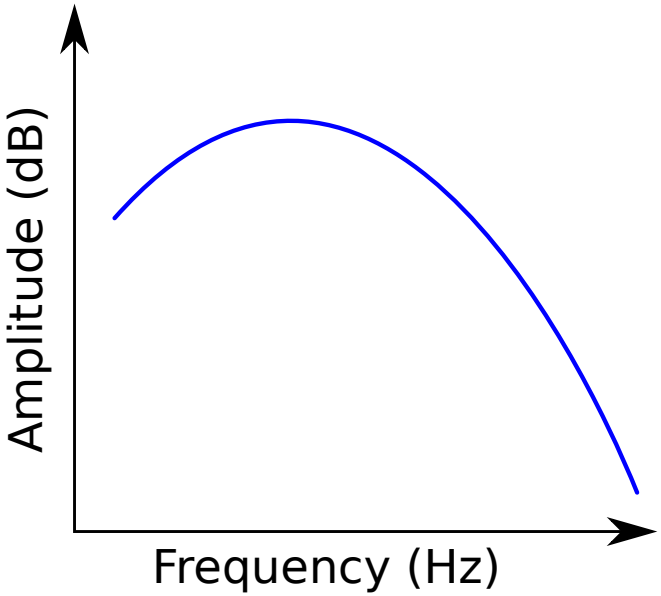
Sound Waves - Characteristics

Frequency domain

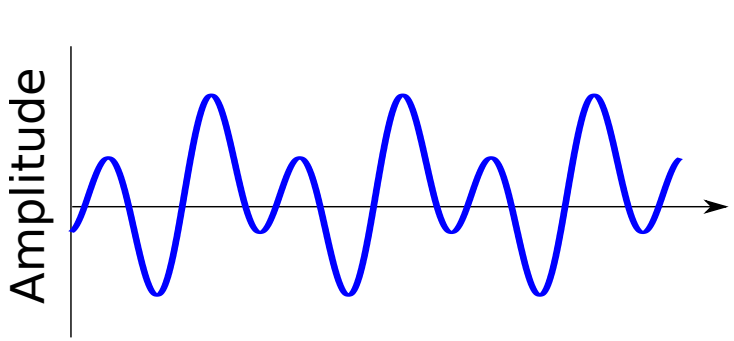
Tonal noise - discrete frequencies

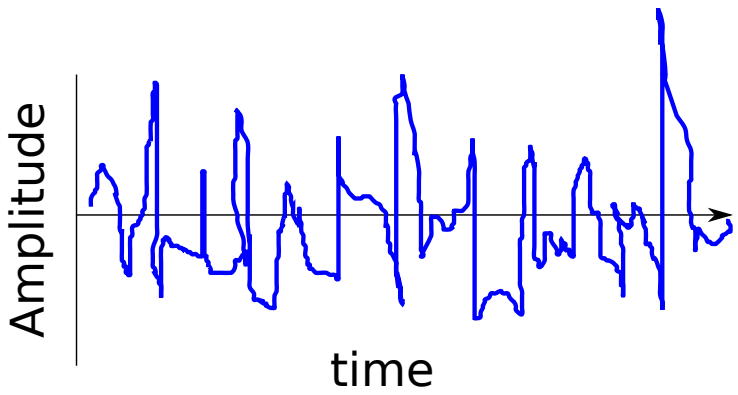


Broadband noise -



Time domain

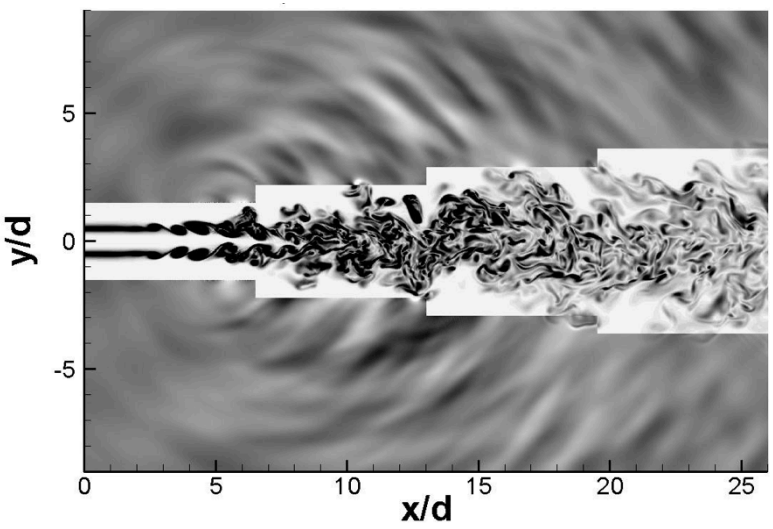




Sound Waves - Energy

Jet Engine:

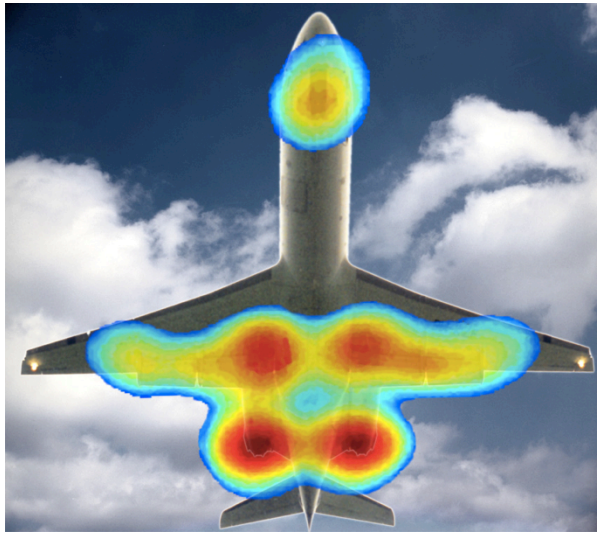
- 130 dB ~ 10 watts/sq. m of power density
- 10 KW of net acoustic power
- Contrast with ~ 100 MW of power generated by the engine (factor of 10^4)
- "Needle in a haystack"

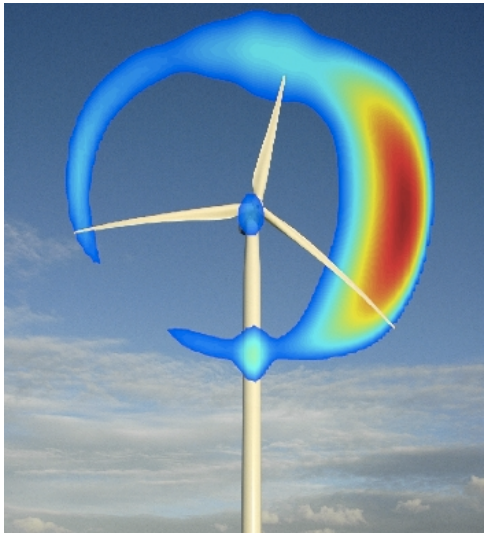


- Noise generation in jets is very inefficient … *thank God for that!*
- I often tell my daughter "screaming does not work!"

“Displeasing” Sound Waves - Noise

- Generate quite a bit of it when I “play” guitar!
- Engineering machines make noise:
  - Aircraft, aircraft engines, energy turbomachines, **wind turbines**, fans, your laptops … you name it

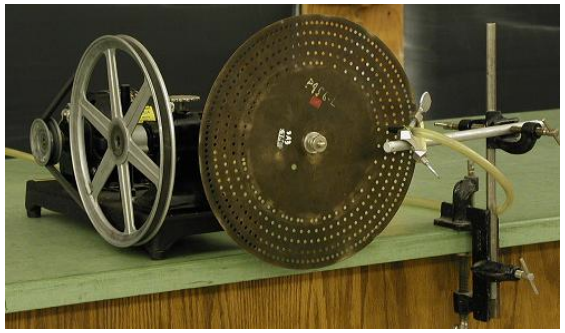




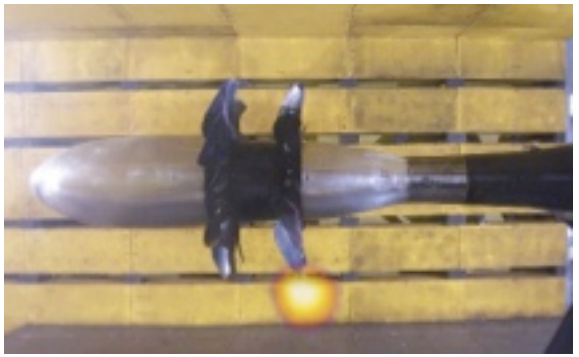
- Vibration generated noise – tuning fork, vibrating plate, etc.

Sound generated by Aerodynamics

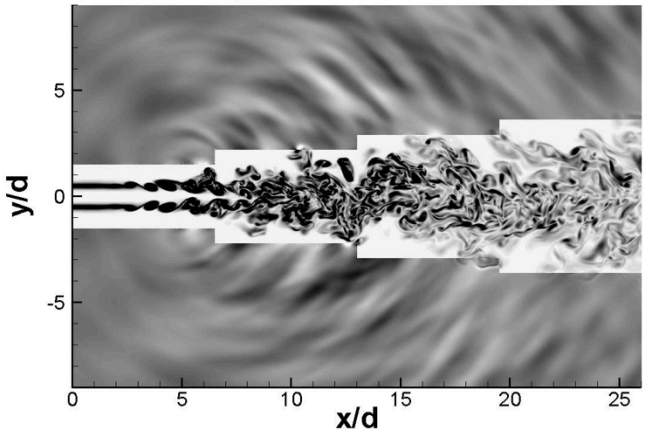
- Siren: (unsteady mass)



- Propeller: (unsteady force)



- Jet: (unsteady stress)



Heat (combustion): (unsteady heat)

  - http://www.youtube.com/watch?v=WBblqoVKO4w

Noise – What's All the Fuss About?

- Annoyance: sleep disturbance, "psycho"acoustics, deafness, etc
- $$ impact → Dept of Veteran Affairs spends ~ USD 1B / year on hearing loss!
- Regulations: can't operate if exceed limits
- Limits use of Green Technologies – noise & efficiency trade
- In a wind turbine, noise limits rotor diameter, speed and number of turbines in a farm

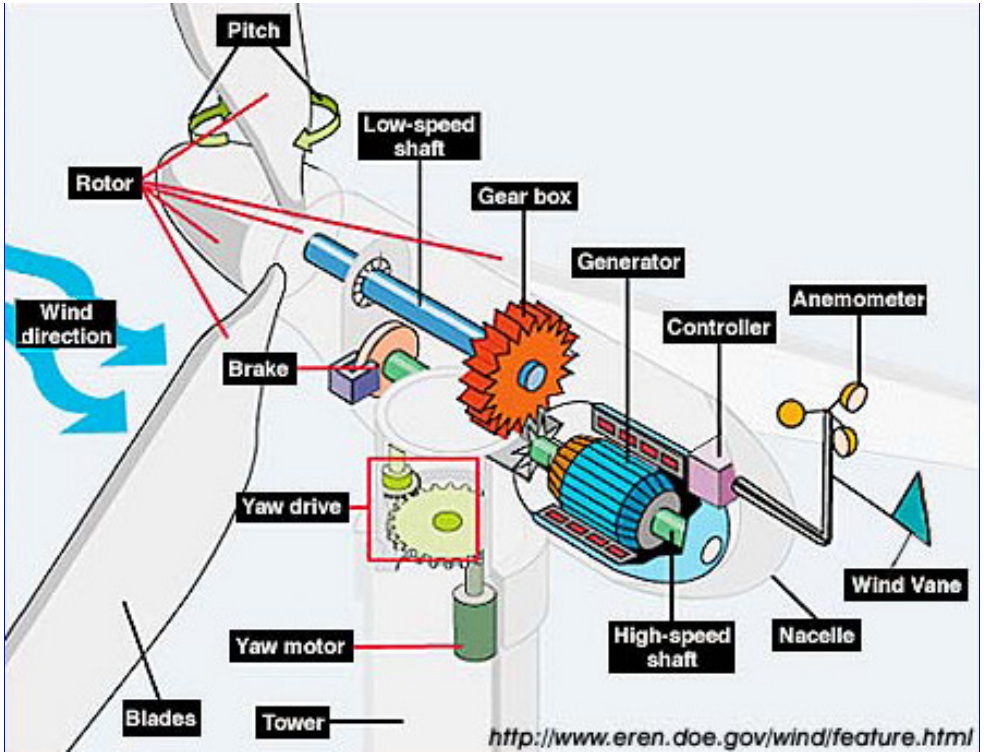
Understanding / prediction of noise generation is a must before designing for "low" noise

WIND TURBINE NOISE

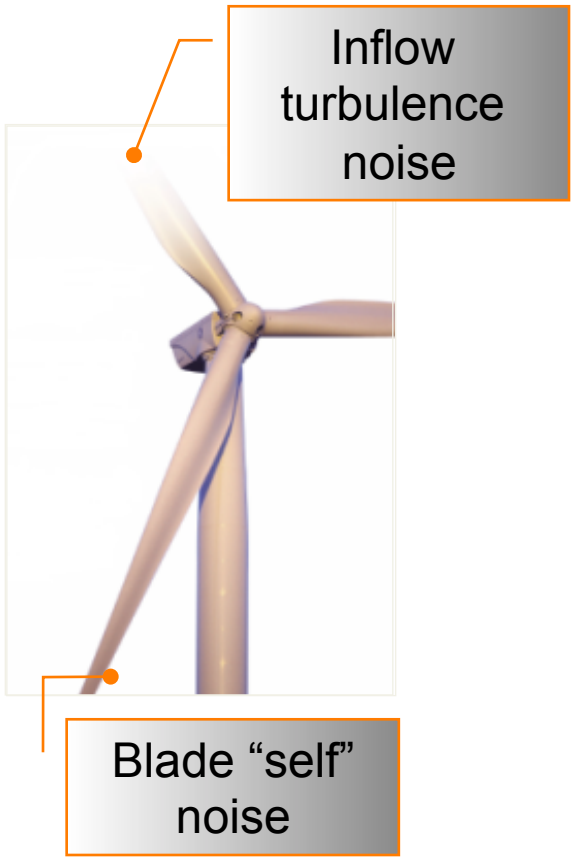
Wind Turbine Noise - Mechanical

Sources: Gearbox, generator, yaw/pitch drives, & cooling system

- Gearbox: Teeth do not match exactly – periodic impact → vibration → noise
- Generator: vibration due to coil flexure
- Drives: noise from hydraulic compressors
- Cooling system: fan



Aerodynamic Noise – Wind Turbines

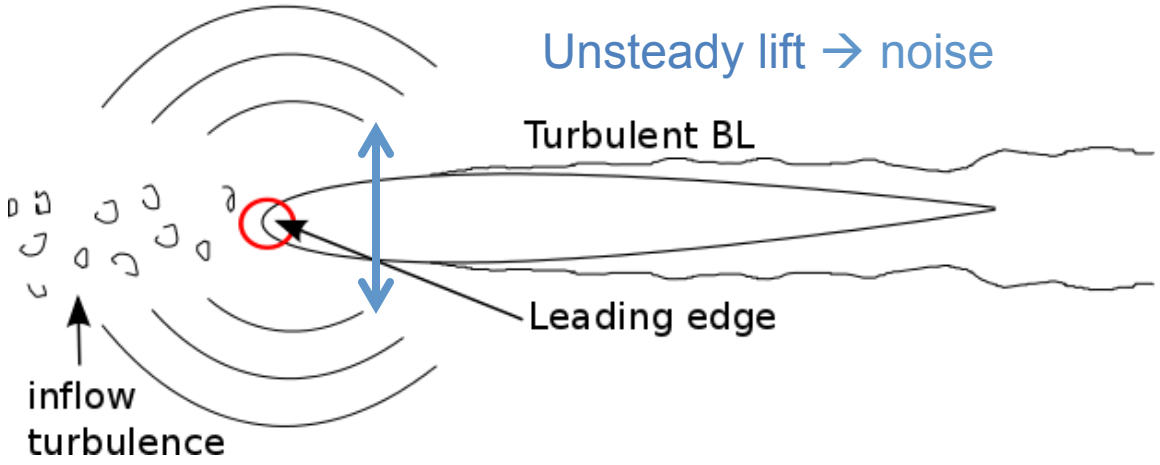


- Airflow over the turbine blades → aerodynamic noise
- Primarily broadband – caused by turbulence:
  1. Inflow turbulence noise
  2. "Self" generated turbulence noise

Wind Turbine Aerodynamic Noise

1. Inflow turbulence noise

- Atmospheric / other turbine wake turbulence interacting with blade
- Broadband at low frequencies (< 1KHz)

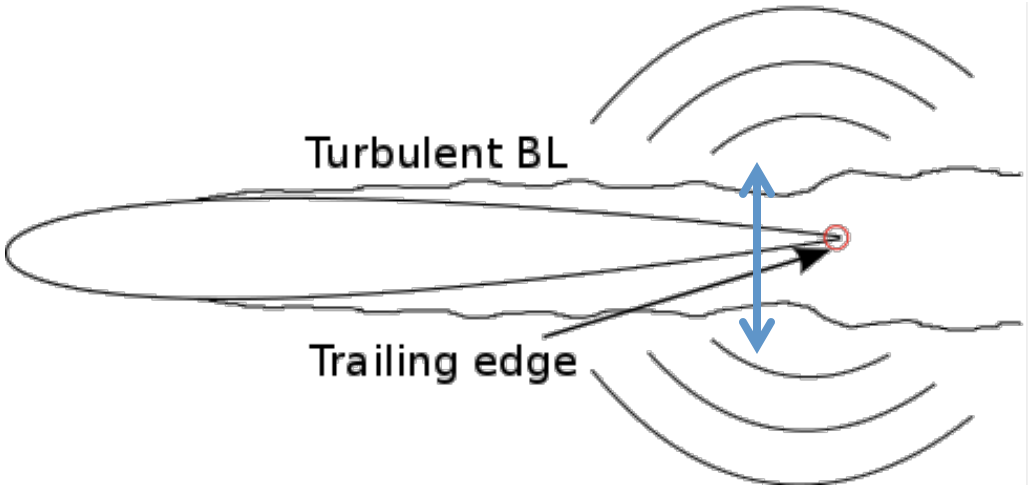


2. "Self" noise: turbulence generated by blade it"self"

1. Trailing edge noise
2. Separation / stall noise
3. Tip vortex noise
4. Other: laminar vortex shedding / trailing edge bluntness

Wind Turbine Aerodynamic Noise

Trailing edge noise – dominant



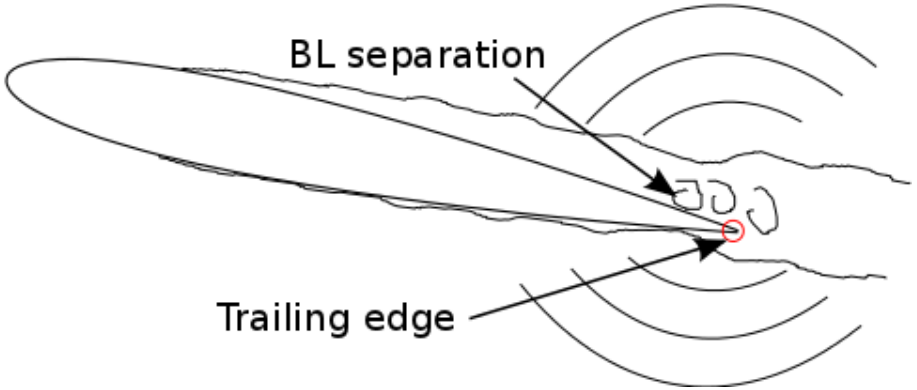
- Eddies in turbulent boundary layer (BL) – noise source in itself
- However, eddies radiate more efficiently (as dipoles) in the vicinity of the trailing edge
- “Scattering” from TE → alter TE geometry to reduce noise

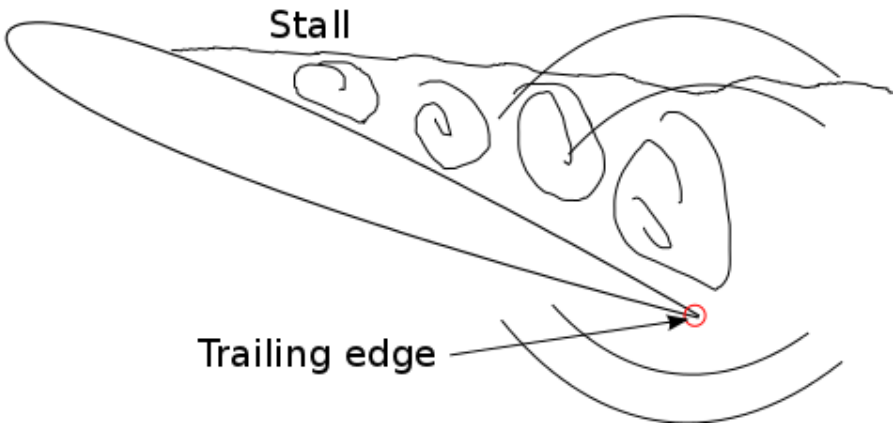
Wind Turbine Aerodynamic Noise

Separation / Stall noise:

- HAWTs often operate in a very transient, high angle-of-attack (Aoa) environment
  - Finite time for pitch change to adapt to AoA change
  - → BL separation and stall commonly observed

- Noise generation mechanism is the same – turbulence interacting with the **blade** (not just the trailing edge)





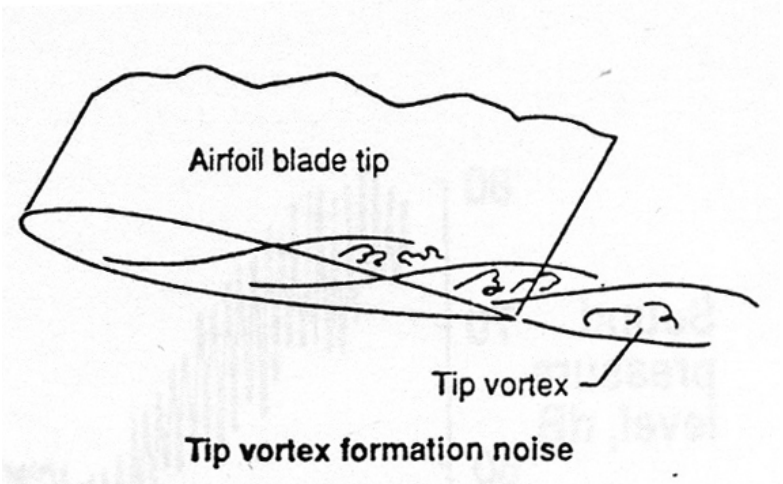
Wind Turbine Aerodynamic Noise

Tip Vortex Noise

- Prandtl's lifting line theory can be applied to study HAWT aero
  - Large vorticity shed near blade tip
  - Tip shape significantly affects noise

- **Turbulence** in blade vortex interacting with the tip (edge)

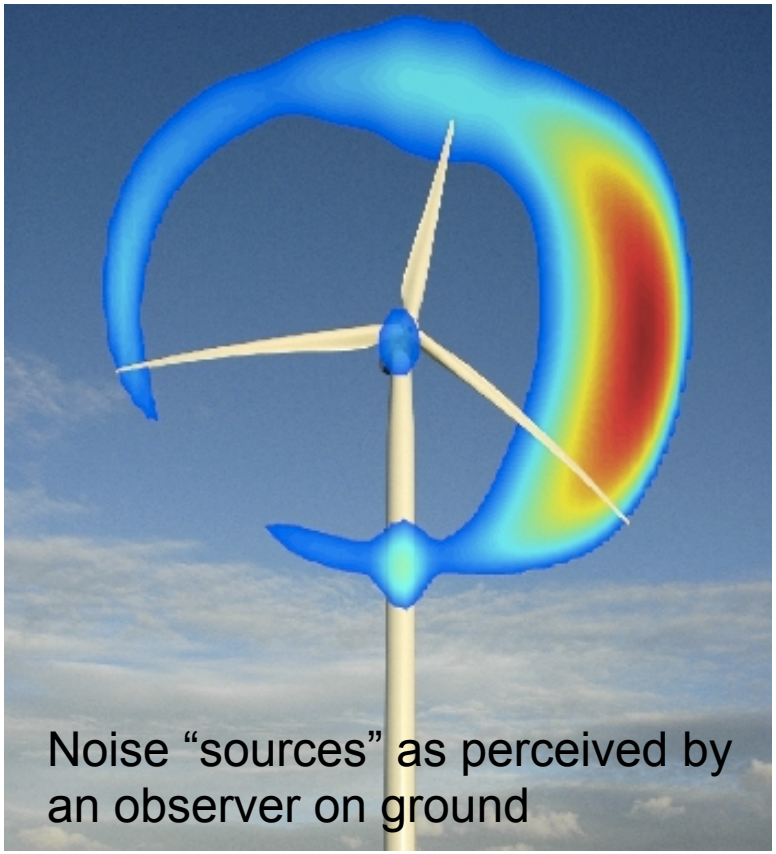
Tip vortices from aircraft wings



Tip vortex formation noise

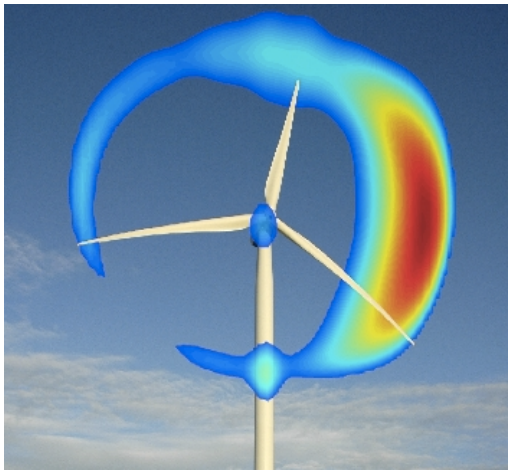
M^5 noise scaling limits rotor size … energy capture

HAWT Aerodynamic Noise – “Swishing”



- “Picture” developed using an “acoustic telescope”
- Noise from a turbine appears as “Swishing” noise (once per blade passing)

What's with the "Swish"?



Stand right below a HAWT (when running)
You will hear a "swishing" noise

It is not a blade passing tone

It is due to "**amplitude modulation"**

Approaching train …
Doppler "shift" & "amplification"

Now imagine a Ferris wheel where there is a siren on each car
… stand right below it …
you will hear a "swish" as each car goes by!

Amplitude Modulation - AM

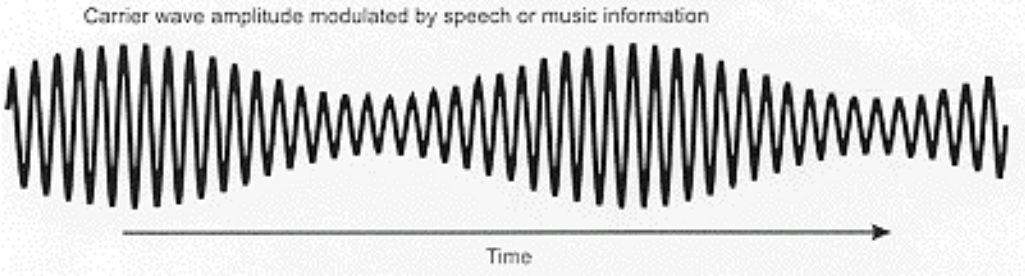
1

Signal to be transmitted

2

Carrier signal

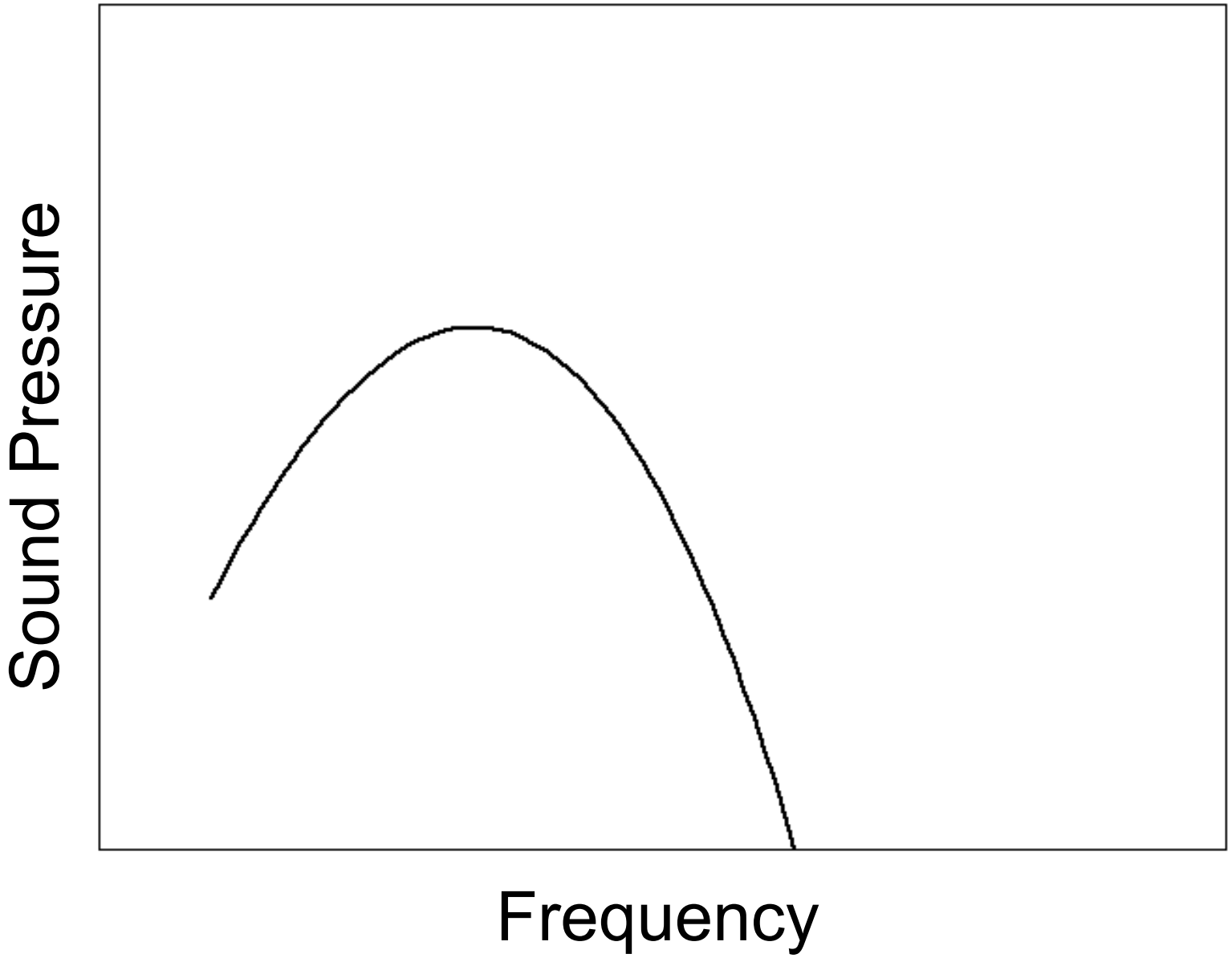
3



Amplitude modulated signal

- Amplitude modulation (AM) for radio waves … now frequency modulation (FM) is more commonly used
- HAWT:
  1. Blade passing time signal
  2. Turbulence generated noise
  3. Observer perceived signal

Amplitude Modulation in a HAWT

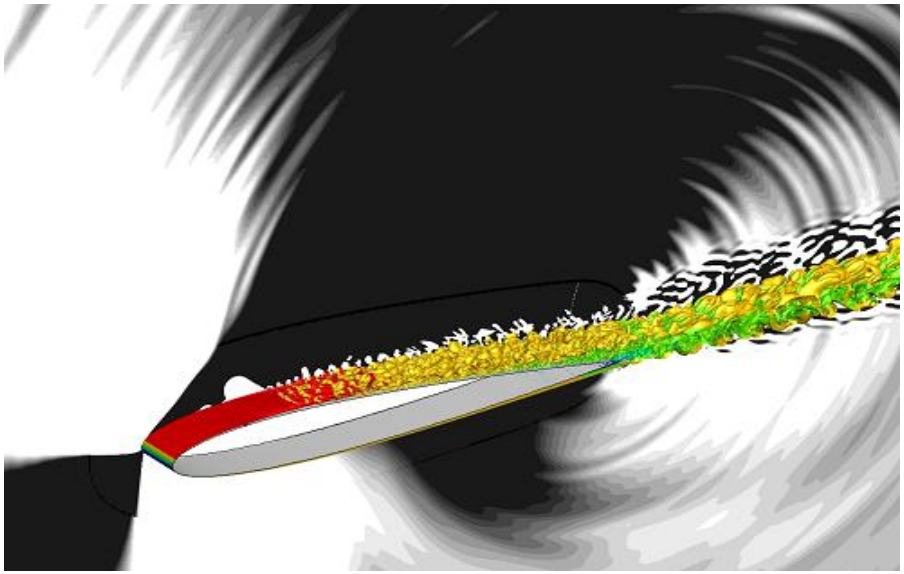


Noise Prediction Approaches

- Empirical: a/f correlations, strip theory
  - Discretize blades into small span airfoils → sum contribution from each airfoil

- Modeling: RANS TKE → model sources; scattering from TE using analytical (Green's functions) and numerical (BEM/LEE) methods

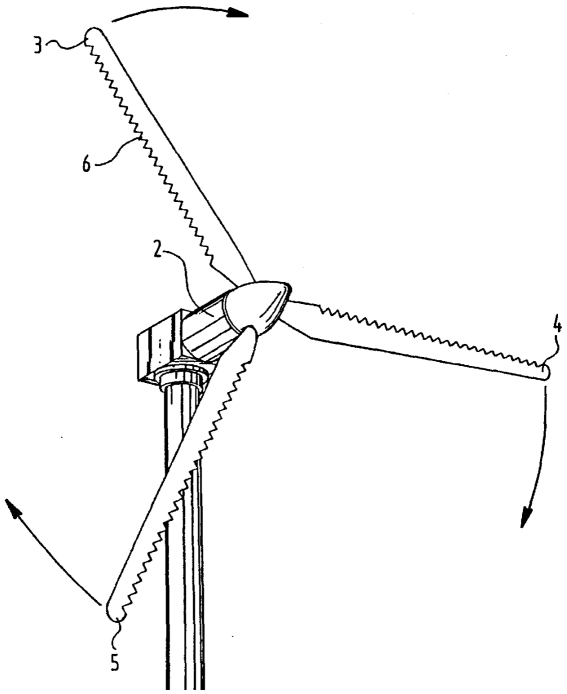
- Direct computation :: compute turbulence, scattering – all in one! EXPENSIVE!!



Source: Stanford flow gallery

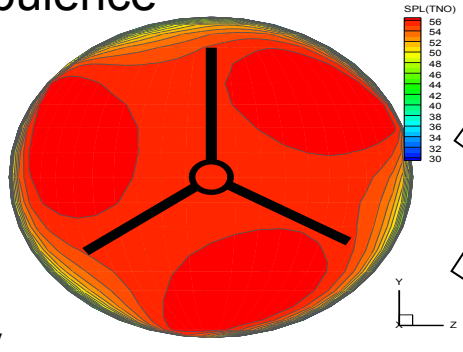
Noise Reduction – Some Concepts

- Trailing edge noise:
  - “sawteeth”, “brushes”, porous trailing edges
- Tip noise:
  - Tip shapes that reduce turbulence close to blade tip
- Inflow turbulence noise:
  - Ideas? … tubercles leading edge



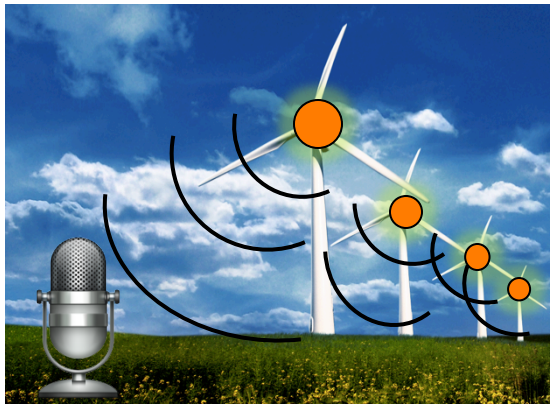
Farm Aero/Acoustics → Future

- Single turbine aero/noise reasonably well understood
- How turbines work in a farm?
  - Persistent wakes/vortices
  - Unsteady loads, aero, & inflow turbulence noise
- Noise
  - Noise regulations on a farm level
  - Long range noise propagation: ray acoustics, LEE, etc.
- Optimize:
  - layout (micrositing) & operations



Farm aerodynamics

Farm noise



Hope You Now Feel Familiar with …

- Basics of acoustics … aerodynamic noise
- Wind turbine aerodynamic noise sources
- Why the turbine produces a “swishing” noise
- General idea of how one can predict HAWT noise
- Concepts being tried to reduce noise

Thank you for your attention

Questions?