Basic Principles and Evidences of Wind Turbine Noise Generation Mechanisms

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Basic Principles and Evidences of Wind Turbine Noise Generation Mechanisms

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Outline

Two main parts:

- **Physics of Sound Generation**
  - Basic mechanisms of sound generation
  - Using analogies - No equations :-)
  - Mechanisms responsible of wind turbine noise

- **Characterization of wind turbine noise sources**
  - Using surface pressure microphones
  - Measurements performed on a 2MW wind turbine

- **Conclusions**
WIND TURBINE NOISE

Noise generation mechanisms

Aerodynamic and/or Mechanical noise

Wind turbine noise

As it can be measured in the direct vicinity of the wind turbine & As used for WT noise assessment

Propagation of sound

Atmospheric conditions, Orography, Vegetation, Refraction, Diffraction

Perception of sound by receiver

More subjective, Sensitivity of individual, Quality of noise, Home insulation
The Physics of Sound Generation

Analogy:
➢ The AIR is **compressible** = acts as a **SPRING!**
The Physics of Sound Generation

Analogy:

➢ The AIR has a MASS! (it is light but still...!!!)

➢ Two important consequences:
  ➢ Energy is required to push the air
  ➢ Air has inertia

Energy is stored = Compressed air!
The Physics of Sound Generation

Analogy: ➢ The AIR = MASS + SPRING

Energy is released pushing contiguous air mass!

Travelling wave at $C_0 \approx 340 \text{ m/s} = \text{SPEED OF SOUND}$
The Physics of Sound Generation

**Working principle of a loudspeaker:**

- **Very fast:** 1000 times/second = 1000 Hertz = Frequency
- **Very efficient loudspeaker only converts 5% of the energy into sound energy (dB)**

\[ \text{SPEED} = C_0 \approx 340 \text{ m/s} \]
The Physics of Sound Generation

Wind turbine mechanical noise

Nacelle components act as loudspeakers!

Shaft+Gear+Generator rotate and may be slightly unbalanced or misaligned generating (eigen-)modal structural vibrations = pushing!
The Physics of Sound Generation

Wind turbine mechanical noise is tonal:

Narrow band noise

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Energy Level [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td></td>
</tr>
</tbody>
</table>

Harmonics

Energy Spectrum
The Physics of Sound Generation

Wind turbine noise visualization:

Oerlemans and Schepers, NLR [2009]
The Physics of Sound Generation

Wind turbine noise visualization:

Mechanical noise from nacelle is NOT dominant!!!
The Physics of Sound Generation

There are no loudspeakers on wind turbine blades! Then...

... WHO IS PUSHING?
The Physics of Sound Generation

... WHO IS PUSHING?

TURBULENCE!
What is **turbulence**? Flow convection induces **CHAOS**

**Boundary layer**

**Thermal effects can induce turbulence**

1. **Flow convection induces CHAOS**
2. **Boundary layer**
3. **Thermal effects can induce turbulence**
The Physics of Sound Generation

Flow turbulence is characterized by **turbulent vortices!!!**
The Physics of Sound Generation

*Turbulent vortices* are the pushers... they provide the *energy*!
The Physics of Sound Generation

Aerodynamic noise is broadband:

Narrow Band Energy Spectrum
The Physics of Sound Generation

Aerodynamic noise is broadband:

Narrow Band Energy Spectrum

Large & Slow vortices produce low frequencies

Small & Fast vortices produce high frequencies

Broadband Energy Spectrum

Noise Level [dB(A)] = Energy Level

Frequency [Hz]
The Physics of Sound Generation

Where is turbulence for wind turbine noise?

1. From atmosphere
The Physics of Sound Generation

Where is turbulence for wind turbine noise?

2. Self-generated - Turbulent boundary layer

Airfoil relative speed near blade tip

# 300 km/h = 190 mile/h !!!
The Physics of Sound Generation

Where is turbulence for wind turbine noise?

3. Self-generated – Stalled flow

For high angles of attack
The Physics of Sound Generation

Where is turbulence for a wind turbine?

4. Self-generated - Tip vortex

Blade tip speed # \( 300 \text{ km/h} = 190 \text{ mile/h} \)!
The Physics of Sound Generation

Turbulent vortices are the pushers...

BUT it is **bad** quality stuff: *Not efficient!*

Jet engine noise... is helped by **combustion**

adding **ENERGY** and **SPEED** to the turbulent flow
The Physics of Sound Generation

Why turbulence alone is not efficient?

Turbulent vortices are pushing... *air against air!!*

Analogy: like pushing something in space..
The Physics of Sound Generation

Turbulent vortices are pushing... air against air!!
The Physics of Sound Generation

**Analogy:** Air mass + spring against mass + spring
The Physics of Sound Generation

**Analogy:** Air mass + spring against mass + spring

Turbulent vortices push in one direction, but energy redistributed not only in one direction, but in *all directions* (air medium)

Therefore turbulence alone is *VERY inefficient* to produce noise!
The Physics of Sound Generation

No combustion

No loudspeaker on blades...

Then.. how is wind turbine noise generated?

There are hidden loudspeakers!!!
The Physics of Sound Generation

One hidden loudspeaker...

... is the blade **hard surface**!
The Physics of Sound Generation

One hidden loudspeaker...

... is the blade **hard surface**!
The Physics of Sound Generation

**Analogy:**

➢ The **AIR is compressible** = acts as a **SPRING**!

![Diagram of sound wave generation](image)

**Travelling wave in opposite direction**
The Physics of Sound Generation

Turbulent vortices pushing **against the wall** do make **more noise!!!
The Physics of Sound Generation

Explains **directivity** effects:
The Physics of Sound Generation

Explains directivity effects:

![Dipole Pattern Diagram]
The Physics of Sound Generation

Explains directivity effects:

Direction of maximum radiation

Silence zone

Directions of null radiation
The Physics of Sound Generation

Aerodynamic noise source mechanisms

Two mechanisms were identified:

1. Turbulence alone … Inefficient \( \sim M_a^8 \)!

2. Hard surfaces … Not efficient either \( \sim M_a^6 \)!

Still *cannot explain* wind turbines noise generation!?
The Physics of Sound Generation

**Aerodynamic** noise source mechanisms

Two mechanisms were identified:

1. Turbulence alone … *Inefficient!*
2. Hard surfaces … *Not very efficient either!*

*Still cannot explain* why WT noise generation!? 

The *really efficient* noise source mechanism:

**EDGE SCATTERING NOISE!!!**
The Physics of Sound Generation

*Trailing edge noise*  
= *Scattering phenomenon*
The Physics of Sound Generation

Conveacting with the flow

Trailing edge scattering noise
The Physics of Sound Generation

Trailing edge scattering noise

Air accelerated due to edge singularity

Very efficient noise generator!!
The Physics of Sound Generation

Trailing edge scattering noise

Cardiod directivity pattern
The Physics of Sound Generation

Trailing edge noise

Turbulent Inflow Noise

Leading edge noise
The Physics of Sound Generation

Directivity of stall noise

**Large vortices produce low frequencies**

**Small vortices produce high frequencies**

- Frequency [Hz]
The Physics of Sound Generation

Wind turbine noise source mechanisms:

Four main mechanisms were identified:

1. **Trailing edge noise**
   
   *From self-generated turbulent boundary layer*

2. **Leading edge noise**
   
   *From atmospheric turbulence*

3. **Stall Noise**
   
   *From separated flow over airfoil at high AoA*

4. **Tip Noise**
   
   *Still unclear if tip vortex interacts with tip or edge?!
Outline

Two main parts:

➢ Physics of Sound Generation
  ▷ Basic Mechanisms
  ▷ Using analogies - No equations :-)

➢ Characterization of wind turbine noise sources
  ▷ Using surface pressure microphones
  ▷ Measurements performed on a 2MW wind turbine

➢ Conclusions
Characterizing Wind Turbine Noise

Difficult to characterize in the far-field!

Individual noise generation mechanisms cannot be identified!!!
Characterizing Wind Turbine Noise

Using surface pressure microphones
Characterizing Wind Turbine Noise

Surface pressure spectra = pseudo-sound is **NOT** far-field noise!!

- Directivity / Doppler effects / Convective amplification ...
  ... alter pseudo-sound in near field (=1/2 rotor diameters)

- Atmospheric sound propagation effects including wind direction / shear-veal / stratification / etc ...
  ... alter pseudo-sound in far field (=10/100+ rot. diameters)
Characterizing Wind Turbine Noise

Using surface pressure microphones

Using mathematical formula

Far-field noise can be inferred
Characterizing Wind Turbine Noise

Surface Pressure Microphones
Characterizing Wind Turbine Noise

Surface pressure microphones mounted on wind turbine
Characterizing Wind Turbine Noise

Surface Pressure (SP) turbulent fluctuations have been measured at 1 single section.

HF microphones
Characterizing Wind Turbine Noise: AM

Periodic inflow wind speed!
Characterizing Wind Turbine Noise: AM

Periodic angle of attack!

SP measured at Trailing Edge

SP spectra binned according to Angle of Attack
Characterizing Wind Turbine Noise: **AM**

Flow periodicity results in **Amplitude Modulation**!
Characterizing Wind Turbine Noise: **Wake**

*Wind turbine Wake is turbulent!*
Characterizing Wind Turbine Noise: **Wake**

**Turbulent inflow from Wake!**

Wind Turbine Noise 2015, INCE/Europe

Glasgow, Apr. 2015
Characterizing Wind Turbine Noise: Wake
Turbulent inflow NOISE from Wake!
Characterizing Wind Turbine Noise: Stall noise!
Characterizing WT Noise: Conclusions

Surface pressure measurements showed:

- Trailing edge noise + Wind shear = Amplitude Modulation

- Wind turbine wake = Higher turbulent inflow noise

- Stall noise increases noise in range 50-200 Hz

- Tip noise... Could not be assessed with our experimental set-up
Mitigation of Wind Turbine Noise

What can be done...?

➢ Food for thought...
Mitigation of Wind Turbine Noise

What can be done...?

➢ Wind turbine farm design and siting
  Good understanding of the *noise propagation* is the key!

➢ Deal with actual noise sources
  In the perspective of the mechanisms introduced in this presentation...

➢ However, remember that the two aspects may interact (farm)... It can get really complicated!!!
Mitigation strategy of WT noise

What can be done...?

Hard surface and sharp edge scattering effect

Turbulence as noise energy source
Mitigation strategy of WT noise

Cure #1: Reducing the turbulence intensity

- Alter BL development using specific airfoil design (e.g. by decambering – but associated with loss of energy efficiency / lift)

- Alter BL turbulence with active control (micro-jets, actuators) or passive ones (vortex generators for postponing stall)

- Reduce rotor speed or reduce blade pitch (de-rating or other WT control strategies)

Turbulence as noise energy source
Mitigation strategy of WT noise

Altering the scattering effect

➔ Serrated airfoil

➔ Porous surface...

Hard surface

or

sharp edge

scattering effect
Conclusions

➢ 4 main noise generation mechanisms have been identified

➢ Evidence of these mechanisms on wind turbines using surface pressure measurements

➢ Some considerations on WT noise mitigation

➢ Thank you!