Basic Principles and Evidences of Wind Turbine Noise Generation Mechanisms

Bertagnolio, Franck; Aagaard Madsen, Helge; Fischer, Andreas; Bak, Christian

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Basic Principles and Evidences of Wind Turbine Noise Generation Mechanisms

Franck BERTAGNOLIO, Helge Aa. MADSEN, Andreas FISCHER and Christian BAK
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
  - \( \approx 1000 \text{ Hertz} \)
  - \( = \text{Frequency} \)

- **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

Noise Level [dB(A)]

= Energy Level

Harmonics

Energy Spectrum

Frequency [Hz]

Narrow band noise
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!
The Physics of Sound Generation

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

Boundary layer

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!

Generating Aerodynamic Noise
The Physics of Sound Generation

**Aerodynamic noise is broadband:**

![Graph showing narrow band energy spectrum](image-url)
The Physics of Sound Generation

Aerodynamic noise is broadband:

- **Narrow Band Energy Spectrum**
  - Noise Level [dB(A)]
  - Energy Level
  - Frequency [Hz]

- **Broadband Energy Spectrum**
  - Large & Slow vortices produce **low frequencies**
  - Small & Fast vortices produce **high frequencies**

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!!

Analogy:

Push
The Physics of Sound Generation

*Analogy:* \( \text{Air mass} + \text{spring} \) against \( \text{mass} + \text{spring} \)
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 showing the analogy between air compressibility and a spring]
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
The Physics of Sound Generation

Explains directivity effects:

Directions of null radiation

Silence zone

Direction of maximum radiation

Silence zone
Aerodynamic noise source mechanisms

Two mechanisms were identified:

1. Turbulence alone ... Inefficient ~ $M_a^8$!

2. Hard surfaces ... Not efficient either ~ $M_a^6$!

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

Convekting with the flow
The Physics of Sound Generation

Conveying 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**
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

PSEUDO-SOUND
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-vear / 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

Measured spectrum
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!

Inflow Wind Shear

Altitude

Bin #1

Bin #2

Bin #3

Bin #4
Characterizing Wind Turbine Noise: \textit{AM} Periodic \textit{angle of attack}!

SP spectra binned according to Angle of Attack

SP measured at Trailing Edge
Characterizing Wind Turbine Noise: **AM**

Flow periodicity results in **Amplitude Modulation**!

![Diagram showing Amplitude Modulation](image)

- **Surface pressure PSD** (Pa² Hz⁻¹)
- **Flow periodicity**
- **Low frequency range**
- **High frequency range**

**Bin: -π/8 < θ < π/8**
- θ: Angle of Attack

- **100** Hz
- **1000** Hz
Characterizing Wind Turbine Noise: **Wake**

Wind turbine Wake is turbulent!
Characterizing Wind Turbine Noise: \textit{Wake}

Turbulent inflow from \textit{Wake}!
Characterizing Wind Turbine Noise: **Wake Turbulent inflow NOISE from Wake!**

Blade UP

Blade GOING UP

Blade GOING DOWN

Blade DOWN
Characterizing Wind Turbine Noise: 

**Stall noise!**

![Diagram showing stall noise patterns in wind turbines.](Image)

Below are various images illustrating the surface pressure PSD (Pressure in Pa^2/Hz) for different AoA (Angle of Attack) and x/C (normalized chord length) values. The graphs depict the frequency (in Hz) across a range from 100 to 1000 Hz, with separate curves for different Re (Reynolds number) values (e.g., Re=3.0M, Re=4.0M, Re=5.0M, Re=6.0M). Each graph highlights the effect of stall noise under varying conditions, showing how the noise is distributed across different frequencies and how it changes with different AoA and x/C values.
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
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!