Aeroacoustic noise sources and their characterization

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Outline

☐ Part 1
  ▪ Overview of aeroacoustic noise sources
    ➢ The empirical Brooks Pope Marcolini model

☐ Part 2
  ▪ Measurement of high frequency surface pressure fluctuations for blade noise characterization
## Overview of aero acoustic noise sources

### Table 4.1: Survey of wind turbine aerodynamic noise mechanisms.

<table>
<thead>
<tr>
<th>Indication</th>
<th>Mechanism</th>
<th>Main characteristics/importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady thickness noise / steady</td>
<td>Rotation of blades / rotation of lifting</td>
<td>Frequency is related to blade passing frequency (BPF),</td>
</tr>
<tr>
<td>loading noise</td>
<td>surfaces</td>
<td>not important at current rotational speeds</td>
</tr>
<tr>
<td>Unsteady loading noise</td>
<td>Passage of blades through tower velocity</td>
<td>Frequency is BPF-related, small in case of upwind</td>
</tr>
<tr>
<td></td>
<td>deficit / wakes</td>
<td>turbines / possibly contributing in case of wind parks</td>
</tr>
<tr>
<td>Inflow turbulence noise</td>
<td>Interaction of blades with atmospheric</td>
<td>Contributing to broadband noise, not yet fully</td>
</tr>
<tr>
<td></td>
<td>turbulence</td>
<td>quantified</td>
</tr>
<tr>
<td>Airfoil self-noise</td>
<td>Interaction of boundary layer turbulence with</td>
<td>Broadband, main source of high-frequency noise</td>
</tr>
<tr>
<td>-Trailing-edge noise</td>
<td>blade trailing edge</td>
<td>$(750 , \text{Hz} &lt; f &lt; 2 , \text{kHz})$</td>
</tr>
<tr>
<td>-Tip noise</td>
<td>Interaction of tip turbulence with blade tip</td>
<td>Broadband, not yet fully understood</td>
</tr>
<tr>
<td>-Stall, separation noise</td>
<td>surface</td>
<td>Broadband</td>
</tr>
<tr>
<td>-Laminar boundary layer noise</td>
<td>Interaction of 'excess' turbulence with blade</td>
<td></td>
</tr>
<tr>
<td></td>
<td>surface</td>
<td></td>
</tr>
<tr>
<td>-Blunt trailing edge noise</td>
<td>Non-linear boundary layer instabilities</td>
<td>Tonal, can be avoided</td>
</tr>
<tr>
<td>-Noise from flow over holes, slits,</td>
<td>interacting with the blade surface</td>
<td></td>
</tr>
<tr>
<td>intrusions</td>
<td>Vortex shedding at blunt trailing edge</td>
<td>Tonal, can be avoided</td>
</tr>
<tr>
<td></td>
<td>Instable shear flows over holes and slits,</td>
<td>Tonal, can be avoided</td>
</tr>
<tr>
<td></td>
<td>vortex shedding from intrusions</td>
<td></td>
</tr>
</tbody>
</table>

Wagner et al. (1996)
The Brooks, Pope and Marcolini (BPM) model
- turbulent boundary layer trailing edge noise (*TBLTE noise*)

Sound pressure level

\[ L_{P,TBLTE} \approx \left( V_{rel}^5, \alpha \right) \]

Contributions from both the suction and pressure side

Figure 4.11: Principal mechanism of trailing-edge noise.
Turbulent inflow noise
- turbulent inflow noise (Amiet, Lowson)

\[ L_{P,II} \approx (U_\infty, TI, l, V_{rel}^5) \]

Figure 4.10: Turbulent eddies approaching the rotor blade.

Wagner et al. (1996)
Total noise computation

– BPM model + TI model (Amiet, Lowson)

Input data

- planform (chord and twist)
- rotor size
- rotational speed
- blade pitch setting
- inflow turbulence intensity
- inflow turbulence length scale
- directivity data

Aerodynamic model (BEM) computes:

- inflow angle along blade span
- relative velocity along blade span

Total noise found by summing up the different noise sources from all blade elements of the rotor
An example of contribution of the different aero acoustic noise sources

BPM+Amiet model -- 127m Rotor -- 6m/s -- TI=20%

Sound power level $L_W$ [dB]

FREQUENCY [Hz]

TE noise - pressure side
TE noise - suction side
TI noise
TOTAL NOISE
TOTAL NOISE A

HAa Madsen et al. -- Presentation at EWEA 2012 acoustic workshop
BPM model – a validation example

Total sound power level

- measured: 97.5 dB(A)
- BPM: 97.1 dB(a) tripped
- BPM: 98.1 dB(A) untripped

![Graph showing sound power level vs. frequency]

**Figure 4-7** Predicted sound power level in dB(A) compared to experimental results from Jacobsen & Andersen [14] for the Vestas V27 wind turbine at 8 m/s, tip pitch 0.5°.

Fuglsang and Madsen (1996)
BPM model – influence of tip pitch

Figure 4-12  Sound power level in dB(A) predicted for different tip pitch angles, compared with experiment for the Vestas V27 at 8 m/s.

Fuglsang and Madsen (1996)
### BPM model – used in rotor optimization

#### Baseline rotor

<table>
<thead>
<tr>
<th></th>
<th>Bonus Combi 300 kW</th>
<th>1) Optimized for min. noise constrained production</th>
<th>2) Optimized for max. production constrained noise</th>
<th>3) Optimized for max. production</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production (MWh)</strong></td>
<td>838</td>
<td>838</td>
<td>855</td>
<td>860</td>
</tr>
<tr>
<td><strong>Noise (dB(A))</strong></td>
<td>98.0</td>
<td>94.9</td>
<td>98.0</td>
<td>101.2</td>
</tr>
<tr>
<td><strong>Tip speed (m/s)</strong></td>
<td>56.8</td>
<td>50.1</td>
<td>57.0</td>
<td>65.2</td>
</tr>
<tr>
<td><strong>Tip pitch (deg)</strong></td>
<td>-1.8</td>
<td>1.2</td>
<td>0.8</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Fuglsang and Madsen (1996)
Outline – Part 2

Measurement of high frequency surface pressure fluctuations for blade noise characterization

- Why using high frequency surface pressure measurements?
- The measurement technique
- Measurements on a full scale 80m diameter rotor
- Perspectives for application of the technique
Why using high frequency surface pressure (SP) measurements for aeroacoustic characterization?
- SP is the source of trailing edge (TBLTE) noise
- SP is the source of turbulent inflow (TI) noise
- SP has a high intensity compared with ambient noise (an example will be shown)
Measuring SP enables correlation with detailed inflow data from inflow sensors on the blade, resolving 1p variations causing amplitude modulation (an example will be shown).

Measuring SP provides more accurate aeroacoustic characterization during design and testing of new low noise airfoil designs.

Measuring SP provides detailed noise source information, enabling continuous, optimal input to the turbine control system for operation within noise constraints.
Drawbacks with the SP technique compared with traditional far field measurements

- It is measurements at a cross section of a blade
- Uncertainty in converting the SP to the far field noise
- ......
SP in the turbulent boundary layer has a high intensity compared with the far field sound.

Based on set-up in the Virginia-Tech Wind Tunnel 2011 – NACA64-618 airfoil at 1.5 mill Re

Far field sound measured about 2m from the airfoil section.
The inflow to the blade is varying considerably in time, in particular over 1p - the same is the noise source

Measured inflow angle at radius 30m on a 2MW turbine
The measurement technique
SURFACE PRESSURE – Meas. Technique

Flush-mounted HF microphones
Calibration of microphones in cooperation with B&K

(a) reference microphone and pinhole  
(b) Sennheiser headphone HD650 source

Figure 4: High-Frequency Microphones Deviations [Figure courtesy of Brüel & Kjær]
Measurements on a full scale 80m diameter rotor
- From the DAN-AERO project -
Measurement of SP on a full scale rotor blade, 80m diameter rotor, 2MW - - DAN-AERO MW project

- surface pressure and inflow measured at 4 radial stations
- the outboard station also instrumented with around 60 microphones for high frequency surface pressure measurements
- high frequency measurements of the inflow
- measurements from June to September 2009
Installation of the 38.8m instrumented blade in May 2009
Campaign measurements from June to September 2009

Microphone holes

Pressure holes

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Pressure and inflow measurements on the NM80 turbine in the Tjaereborg wind farm

- High frequency inflow sensors
- Five hole pitot tubes

HAa Madsen et al.

DTU Wind Energy, Technical University of Denmark
Measurement of SP on a full scale rotor blade, 80m diameter rotor, 2MW

Wind shear measured in a met mast

SP spectra derived for each red dot

MEASUREMENT ON NM80 2MW TURBINE

AOA radius 30m
MIC. MEAS

AOA radius 30m
AOA radius 19m
MIC. PSD

DTU Wind Energy, Technical University of Denmark

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TE spectra measured during free inflow at 9-11 m/s -- amplitude modulation

Each spectrum is based on 0.5 sec
TE + LE spectra measured during free inflow at 9-11m/s

Each spectrum is based on 0.5sec
Perspectives for application of the technique
A blade mounted sensor system for aeroacoustic noise source monitoring and control

Objectives of blade mounted monitoring system:

- continuous monitoring of the noise source by measuring HF SP at a few points on each blade
  - derive total noise of turbine based on numerical modelling and experimental calibration
  - derive details of noise source variation as function of blade position

Advantages of system

- Detailed and continuous source monitoring enables changes of turbine control system only when necessary
- Detailed source monitoring can provide input to the control system on an azimuth level, e.g. for individual pitch control to reduce/avoid amplitude noise modulation
Proposed system

Surface mounted microphones from B&K

Data processing and analysis system

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One output screen from the system could be continuously updated PSD spectra of surface pressure fluctuations and a noise constrain line.
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- DTU Wind Energy
Thank you for your attention