Wind Turbine Acoustic Day 2018

Mogensen, Jesper; Søndergaard, Bo; Hunerbein, Sabine Von; Søndergaard, Lars S.; Hansen, Tomas R.; Hurault, Jérémy; Bertagnolio, Franck; Kelly, Mark C.; Shen, Wen Zhong; Bak, Christian; Fischer, Andreas

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Wind Turbine Acoustic Day 2018
Summary of the 3rd edition

Jesper Mogensen, Bo Søndergaard, Sabine von Hünerbein, Lars S. Søndergaard, Tomas R. Hansen, Jérémy Hurault, Franck Bertagnolio, Mark Kelly, Wen Zhong Shen, Christian Bak, Andreas Fischer
Edited by F. Bertagnolio
DTU Wind Energy
May 2018
Wind Turbine Acoustic Day 2018

Summary of the 3rd edition

May 2018

Author(s):
Jesper Mogensen, Bo Søndergaard, Sabine von Hünerbein, Lars S. Søndergaard, Tomas R. Hansen, Jérémy Hurault, Franck Bertagnolio, Mark Kelly, Wen Zhong Shen, Christian Bak, Andreas Fischer
Edited by F. Bertagnolio

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Title: Wind Turbine Acoustic Day 2018 - Summary of the 3rd edition

Department: DTU Wind Energy

Summary (max. 2000 characters):
The bi-annual event entitled Wind Turbine Acoustic Day dealing with wind turbine noise issues organized by DTU Wind Energy took place on May, 17th 2018 as its third edition. The abstracts and slides for the presentations are reported.
Preface

Since 2014, DTU Wind Energy has organized a bi-annual event, entitled the Wind Turbine Acoustic Day. Its goal is to give an overview of important activities and the current status of science based knowledge, as well as facilitate discussions on the needs for research and development in the future. The conference aims at an audience with interest in noise and acoustics from wind turbines and some of the presentations can be at a high technical level.

Speakers with different backgrounds (wind turbine manufacturers, consultants, technical and social researchers, and lawgivers) are invited, presenting a broad overview of wind turbine noise issues in Denmark and abroad.
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Summary

The bi-annual event entitled Wind Turbine Acoustic Day dealing with wind turbine noise issues organized by DTU Wind Energy took place on May, 17th 2018 as its third edition. The abstracts and slides for the presentations are reported.
1 Introduction

The aim of this report is to summarize the presentations which were given at the 3rd edition of the Wind Turbine Acoustic Day held by DTU Wind Energy on May, 17th 2018.

The presentations were organized in three successive sessions covering different topics: (1) Legal, technical and human issues regarding wind turbine noise, (2) Industry perspectives, and (3) Recent research advancements. The slides for the presentations, as well as abstracts for each of them, are provided in this document.
# Agenda of the Acoustic Day 2018

**ACOUSTIC DAY – Thursday, May 17th, 2018**

9:00-17:00
at DTU RISØ CAMPUS
Niels Bohr Auditorium, Building 112
Frederiksborgvej 399, 4000 Roskilde

**Agenda**

Chairman: Christian Bak, DTU Wind Energy

<table>
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<th>TIME</th>
<th>Activities</th>
<th>Speakers &amp; Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:30-9:00</td>
<td>Registration and coffee</td>
<td>Niels Bohr Auditorium - DTU Risø Campus (Bldg. 112)</td>
</tr>
<tr>
<td>9:00-9:10</td>
<td>Welcome</td>
<td>Peter Hauge Madsen, Head of Department, DTU Wind Energy</td>
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**Session #1: LEGAL, TECHNICAL AND HUMAN ISSUES REGARDING WIND TURBINE NOISE**

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<tr>
<th>TIME</th>
<th>Activities</th>
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<tr>
<td>9:10-9:35</td>
<td>Adjustments in the regulation of noise from wind turbines</td>
<td>Jesper Mogensen, Miljø- og Fødevareministeriet (Ministry of Environment and Food), Denmark</td>
</tr>
<tr>
<td>9:35-10:00</td>
<td>Low frequency sound insulation of buildings in relation to wind turbine noise</td>
<td>Bo Søndergaard, SWECO Danmark A/S</td>
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<tr>
<td>10:00-10:25</td>
<td>Annoyance from wind turbine noise? Review of wind turbine noise studies of the last two decades</td>
<td>Sabine Von Hünerbein, University of Salford, UK</td>
</tr>
</tbody>
</table>

10:25-10:50 Coffee break

**Session #2: INDUSTRY PERSPECTIVES**

10:50-11:15 Measurement at neighbor position | Lars Sommer Søndergaard, DELTA (FORCE Technology)

11:15-11:40 Developments in Acoustics at Vestas Wind Systems A/S | Jérémie Hurault & Kaj Dam Madsen, VESTAS Wind Systems

11:40-12:05 Developments in wind turbine noise: limitations and opportunities | Tomas Rosenberg Hansen, SIEMENS GAMESA Renewable Energy

12:05-12:55 Lunch

**Session #3: RECENT RESEARCH ADVANCEMENTS**

12:55-13:10 Cross-Cutting Activities and HAWC2-Noise | Franck Bertagnolio, DTU Wind Energy

13:10-13:25 Statistical prediction of far field wind turbine noise, with probabilistic characterization of atmospheric stability | Mark Kelly, DTU Wind Energy


13:55-14:10 The acoustic measurement setup in the Poul la Cour Wind Tunnel | Andreas Fischer, DTU Wind Energy

14:10-14:40 Coffee break

14:40-15:00 Walk or drive to the wind tunnel location (~700m from Niels Bohr auditorium)

**Session #4: VISIT OF THE POUL LA COUR WIND TUNNEL**

15:00-16:00 Visit of the wind tunnel facility | Poul la Cour Wind Tunnel - DTU Risø Campus (Bldg. 331)

16:00-17:00 Networking | Poul la Cour Wind Tunnel - DTU Risø Campus (Bldg. 331)

Good bye
3 Abstracts for the Presentations

The following abstracts can also be found in later sections in this document together with the slides for each individual presentation.

**Jesper MOGENSEN, Miljø- og Fødevareministeriet (Ministry of Environment and Food of Denmark)**

**Title:** Adjustments in the regulation of noise from wind

**Abstract:** The Danish EPA and the Ministry of Environment and Food are working on a number of adjustments to the statutory order on noise from wind turbines. The technical adjustments include a graduated penalty for clearly audible tones and differentiated sound insulation values for summerhouse areas and residences. The technical adjustments also include a correction to the calculation method for noise from offshore wind turbines and the corrected method takes into account a contribution from multiple reflections at sea. The adjustments also include a clarification of the transitional provisions applying if the wind turbine is altered and thus emitting more noise as well as the possibility for the authority to order the owner of an offshore turbine to make noise emission control measurements.

**Bo SØNDERGAARD, SWECO (DK)**

**Title:** Low frequency sound insulation of buildings in relation to wind turbine

**Abstract:** The Danish regulations for wind turbines includes noise criteria for low frequency noise. In the regulations a set of standard data for the insertion loss of typical Danish houses at frequencies from 8 Hz to 200 Hz are tabled for use in noise predictions. In 2016 and 2017 two new investigations were initiated by the Danish EPA on low frequency (LF) sound insulation in buildings at the countryside in Denmark. Both investigations are related to noise from wind turbines but the results can be used in general. The purpose with first investigation - to establish a more precise determination on LF sound insulation in typical houses - was fulfilled due to a mapping in 16 houses/24 rooms, roughly a doubling of the former data. The purpose...
of the second investigation was to establish new knowledge on how to improve LF sound insulation in existing Danish houses in areas with wind turbines. This investigation includes: (1) a literature survey to establish existing knowledge, (2) measurements and experiments on 23 building constructions to investigate how to improve sound insulation on heavy and lightweight facades by means of building elements and one experiment using a room acoustic approach. Some of the conclusions are that it – in some cases – is possible with traditional indoor sound re-isolation or by outdoor façade sound-isolation to improve the LF sound insulation significantly.

Sabine VON HÜBERNEIN, University of Salford (UK)

Title: Annoyance from wind turbine noise? Review of wind turbine noise studies of the last two decades

Abstract: In agreement with other environmental noise literature, most work on the annoyance from wind turbines has focussed on noise. Notable work has been carried out in Sweden, the Netherlands, Japan, China, Canada and the US. Their results seem to show that the noise from wind turbines starts to annoy at sound levels that are much lower than that of other sources such as road or rail traffic. At the same time other factors are identified that also correlate highly with annoyance ratings. The presentation will critically review the evidence and raise the question whether it is time to shift the focus from noise annoyance to a much broader view on the factors affecting the acceptance of wind energy installations.

Lars Sommer SØNDERGAARD, DELTA (FORCE Technology, DK)

Title: Measurement at neighbor position

Abstract: Project for the Danish EPA to investigate whether the current guidelines for measurement of noise emission and noise propagation calculation from wind turbines described in the Danish Statutory Order give an accurate noise contribution at residents and to make measurements under conditions other than the Danish Statutory Order prescribes.

Jérémie HURAULT & Kaj Dam MADSEN, VESTAS Wind Systems (DK)

Title: Developments in Acoustics at Vestas Wind Systems A/S

Abstract: The presentation will hold a short introduction on the perspectives and then a more detailed presentation on aero-acoustic developments.
Tomas Rosenberg Hansen, Siemens-Gamesa (DK)

Title: Developments in wind turbine noise: limitations and opportunities

Abstract: Noise from wind turbines is one of the constraining factors for how many wind turbines will be built in the future and thereby how much clean energy we can produce by use of onshore wind turbines. What will be the important factors to ensure turbines also in the future? Which are the limitations Siemens-Gamesa sees in the market related to noise and how do we react to this?

Franck Bertagnolio, DTU Wind Energy (DK)

Title: Cross-cutting activities and wind turbine noise

Abstract: In this presentation, self-financed research activities (so-called CCA) currently conducted at DTU Wind Energy on a Vestas V52 test turbine are described with focus on measurements related to noise. Furthermore, some measurements are compared with the HAWC2-noise model which combines the well-known aeroelastic and load prediction code with a recently implemented noise module. Some features of the software are also presented.

Wen Zhong Shen, DTU Wind Energy (DK)

Title: Recent developments in noise propagation modelling

Abstract: Wind turbine noise from source to receiver is a complicated process, which is influenced by atmospheric conditions and turbine operation conditions. This talk summarizes the recent developments at DTU in modelling the noise propagation process which include the coupling modelling of atmospheric flow, wind turbine wake flow, noise source and noise propagation, as well as the moving source strategy.

Mark Kelly, DTU Wind Energy (DK)

Title: Statistical prediction of far-field wind turbine noise, with probabilistic characterization of atmospheric stability

Abstract: Here we provide statistical low-order characterization of noise propagation from a single wind turbine, as affected by mutually interacting turbine wake and environmental conditions. This is accomplished via a probabilistic model, applied to an ensemble of atmospheric conditions based upon atmospheric stability; the latter follows from the basic form for stability distributions established by Kelly and Gryning (2010). For each condition, a parabolic-equation acoustic propagation model is driven by an atmospheric boundary-layer
("ABL") flow model; the latter solves Reynolds-Averaged Navier-Stokes equations of momentum and temperature, including the effects of stability and ABL depth, along with the drag due to the wind turbine. Sound levels are found to be highest downwind for modestly stable conditions not atypical of mid-latitude climates, and noise levels are less elevated for very stable conditions, depending on ABL depth.

The probabilistic modelling gives both the long-term mean and rms noise level as a function of distance, per site-specific atmospheric stability statistics. The variability increases with the distance; for distances beyond 3 km downwind, this variability is the highest for stability distributions that are modestly dominated by stable conditions. However, mean noise levels depend on the widths of the stable and unstable parts of the stability distribution, with more stably-dominated climates leading to higher mean levels.

Christian BAK, DTU Wind Energy (DK)

Title: Status of the National Wind Tunnel

Abstract: n/a.

Andreas FISCHER, DTU Wind Energy (DK)

Title: The acoustic measurement setup in the Poul la Cour Wind Tunnel

Abstract: The Poul la Cour Wind Tunnel provides the possibility to test aerofoils at high Reynolds numbers. It can be configured in two different set-ups: the aerodynamic and the acoustic setup. This talk focuses on the acoustic set-up which is similar to the one developed at Virginia Tech. It consists of large Kevlar walls that allow the sound to propagate, but contain the flow. The test section is surrounded by a large anechoic chamber where an 84 channel Brüel & Kjær microphone array is located. Array data processing techniques to extract the aerofoil noise will be presented.
4 Session #1
Legal, Technical and Human Issues Regarding Wind Turbine Noise

This session is about various aspects of wind turbine noise which directly impact the residents and how they experience noise.
4.1 Adjustements in the regulation of wind turbine noise

Speaker: Jesper Mogensen, Ministry of Environment and Food of Denmark

Abstract:
The Danish EPA and the Ministry of Environment and Food are working on a number of adjustments to the statutory order on noise from wind turbines. The technical adjustments include a graduated penalty for clearly audible tones and differentiated sound insulation values for summerhouse areas and residences. The technical adjustments also include a correction to the calculation method for noise from offshore wind turbines and the corrected method takes into account a contribution from multiple reflections at sea. The adjustments also include a clarification of the transitional provisions applying if the wind turbine is altered and thus emitting more noise as well as the possibility for the authority to order the owner of an offshore turbine to make noise emission control measurements.

Slides:
Outline

Technical adjustments
• Graduated penalty for clearly audible tones
• Differentiated sound insulation values for summerhouse areas and residences.
• Correction in the calculation method for noise from offshore wind turbines taking into account a contribution from multiple reflections at sea

Legal adjustments
• Clarification of the transitional provisions
• Possibility for the environmental authority to order the owner of an offshore turbine to make noise emission control measurements

The Statutory order – 1736 December 21, 2015
• Mandatory provisions
• Noise limits at 6 and 8 m/s for the total noise from all turbines
  • Calculated noise levels
  • Broadband noise
  • Low frequency noise
• Annex with mandatory methods
  • Emission measurement methods (in general agreement with IEC 61400-11)
  • Calculation methods (broadband and low frequency noise)
  • Downwind propagation from all turbines
  • Calculation of low frequency level indoor using general sound insulation values for typical Danish houses in open country
  • 5 dB penalty for clearly audible tones
• Transparent system, identically same procedure used for application and for control
Graduated penalty for clearly audible tones

- Well known Danish method made into a standard:

- Measurement for wind speeds 5 – 9 m/s for at least 1 hour
- At least 1 spectrum below 6,0 m/s and 1 above 8,0 m/s
- At least 5 spectra 5,5 – 7 m/s
- At least 5 spectra 7 – 8,5 m/s

Sound insulation of dwellings at low frequencies – current values

- 14 different dwellings, 26 measurements
- The chosen level implies that 67% of typical dwellings in Denmark have a better sound insulation and 33% have a lower sound insulation
• Sound insulation at low frequencies – new measurements

• New measurements in 16 houses - doubling the total data set
• More precise determination of average and standard deviation for the low frequency sound insulation for Danish houses

• Results:
• The sound insulation for lightweight summer houses are in the order of 5 dB lower than the average of all other measurements
• Houses in the countryside do not have a lower sound insulation at low frequencies than Danish houses in general

• Differentiated sound insulation values for summerhouse areas and residences.
• 67%-percentile will give calculated low frequency levels for summer house areas in the order of 4.5 dB lower than for other residences.

• Differentiated sound insulation values – Consequences ?

• Turbines 100 m total height or more within 1000 m from summerhouse area: 1
• Turbines 100 m total height or more within 1500 m from summerhouse area: 11

• Existing smaller turbines emitting low frequency noise:
• 750 kW turbines in Denmark: 697
• Only 7 within 500 – 1,000 m from summerhouse areas

• Big offshore windfarms close to the coast (+ 4km): small impact possible.
• Correction for multiple reflections at sea

• Swedish measurements by Mathieu Boué at 10 km distance for 80, 200 and 400 Hz. Source height 30 m. 10 dB correction in 10 km distance

• Swedish method for offshore turbines:
  
  Correction term: \( \Delta L_{\text{re}} = 10 \log (r/1000) \)
  
  for \( r > 1000 \text{ m} \)

  Independent of wind speed and source height

• Correction based on PE-modeling of sound propagation at sea

• PE – calculations:
  
  • Distances: 0 - 10 km
  
  • Source height: 10, 20, 30, 50, 70, 100 m
  
  • Receiver height: 1.5 m
  
  • Wind speed 1 – 10 m/s
  
  • Temperature 15º C
  
  • Temperature gradient: 0
  
  • Surface impedance: infinite
• Suggested correction for multiple reflections

• Threshold distance \( t_0 \)

\[
L_0 = 2000 \cdot \frac{h}{30} \cdot \sqrt[\gamma_{ref}]{\frac{6}{v_{ref}}}
\]

- \( h \): hub height
- \( v_{ref} \): wind speed component

• Rated distance \( t' = \frac{1}{t_0} \)

• \( \Delta L_{in} = \begin{cases} 
0 & \text{for } t' \leq 1 \\
10 \cdot \log t' & \text{for } 1 < t' < 2,512 \\
N \cdot \log_{2,512} t' + 4 & \text{for } 2,512 \leq t' \leq 5 \\
10 \cdot \log t' + (N - 10) \cdot \log_{2,512} t' & \text{for } t' > 5 
\end{cases} \)

N:  
- 20 for \( f \leq 400 \) Hz  
- 10 for \( f \geq 800 \) Hz

\[
- 20 - 10 \cdot \frac{\log f}{\log 2} \text{ for } 400 < f < 800
\]
Adjustments legal provisions

- Possibility to order noise control measurements
- Wind turbines on land and offshore
  - When a turbine is put into operation
  - Environmental supervision
  - In connection with complaints
- Transitional provisions
  - For turbines regulated by earlier issued statutory orders a new application in compliance with the newest statutory order must be submitted if the turbine is changed in a way that results in an increase in noise emission.
  - The date of transition for offshore turbines is defined by the permit to establish the turbines issued by the Danish Energy Agency
4.2 Low Frequency Sound Insulation (8-200Hz) - Mapping and Improvement of Existing Houses

Speaker: Bo Søndergaard, SWECO Denmark A/S
Co-authors: Claus Møller Petersen and Bo Søndergaard

Abstract:
The Danish regulations for wind turbines include noise criteria for low frequency noise. In the regulations, a set of standard data for the insertion loss of typical Danish houses at frequencies from 8 Hz to 200 Hz are tabulated for use in noise predictions. In 2016 and 2017, two new investigations were initiated by the Danish EPA on low frequency (LF) sound insulation in buildings at the countryside in Denmark. Both investigations are related to noise from wind turbines but the results can be used in general. The purpose of the first investigation was to establish a more precise determination on LF sound insulation in typical houses - was fulfilled due to a mapping in 16 houses/24 rooms, roughly a doubling of the former data. The purpose of the second investigation was to establish new knowledge on how to improve LF sound insulation in existing Danish houses in areas with wind turbines. This investigation includes: (1) a literature survey to establish existing knowledge, (2) measurements and experiments on 23 building constructions to investigate how to improve sound insulation on heavy and lightweight facades by means of building elements and one experiment using a room acoustic approach. Some of the conclusions are that it – in some cases – is possible with traditional indoor sound re-isolation or by outdoor façade sound-isolation to improve the LF sound insulation significantly.

Slides:
LOW FREQUENCY SOUND INSULATION (8-200HZ) – MAPPING AND IMPROVEMENT OF EXISTING HOUSES

Claus Møller Petersen and Bo Søndergaard
Sweco Denmark A/S – Acoustica Department

2 projects for the Danish Environmental Protection Agency

Reports:
1. “Enhanced data basis for Danish houses insulation against low frequency noise”
   by Bo Søndergaard
2. “New knowledge on low frequency sound insulation of houses in areas near wind turbines”
   by Claus Møller Petersen

Other participants:
- Dan Hoffmeier/ Delta – Force technology
- Birgit Rasmussen/ AAU – SBI
1. Mapping – building materials

New measurements (6-200 Hz)

- Older/typical farmhouses
  (heavy walls and double-pitch roof, most with attics used for living).

- Summer houses (lightweight constructions)

Roofs: Heavy tiled roofs, Eternit (fibre cement)-plates and more lightweight thin metal plates.
Windows: Double-glazed in all buildings
1. Mapping - results

Expected Indoor Wind Turbine noise

Lₜₓ=44 dB is the limit for outdoor Wind Turbine noise at 8 m/s for houses at the country side.
1. Mapping. Changes in indoor LF WT noise

Indoor noise $L_{	ext{A,LF}}$ (18-160 Hz) calculated using:

- Existing fare insulation data compared to the new data
- Standard Wind Turbine noise spectrum with $65 = 44$ dBA at the facade of a farm house which equals the noise limits at the countryside.

*) This applies for 50% calculated at 50 dB in distance from the houses and hub - height 50 m at 5 m/s wind speed 10 m above ground.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Noise Level (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earlier measurements</td>
<td>0.0 dB</td>
</tr>
<tr>
<td>Farm houses (all measurements)</td>
<td>-1.6 dB</td>
</tr>
<tr>
<td>Farm houses used attics</td>
<td>0.5 dB</td>
</tr>
<tr>
<td>Farm houses – other rooms</td>
<td>-3.7 dB</td>
</tr>
<tr>
<td>New houses</td>
<td>0.6 dB</td>
</tr>
<tr>
<td>Lightweight summer houses</td>
<td>4.5 dB</td>
</tr>
<tr>
<td>All new measurements</td>
<td>-1.1 dB</td>
</tr>
<tr>
<td>All measurements</td>
<td>8.5 dB</td>
</tr>
<tr>
<td>All measurements excl. light</td>
<td>-8.4 dB</td>
</tr>
</tbody>
</table>

2. New knowledge - project content

- Background
  - Why f <= 20 Hz?
  - Can you hear it – and can you do anything by the buildings?

- Literature
  - Sparser output of 57 reports, articles, papers (only 14 on sound insulation; 18-160 Hz and 14 on f>50 Hz, All the about windows

- Experiments in typical building type(-s)
  - Heavy (groundfloor)
  - Lightweight (1st floor)
Experiments heavy facades

- Freestanding
- Unlined and heavy attached window
- Outdoor facade insulation

All results – heavy constructions characteristics

- Thermo-panel, C
- Facade-window visible from inside
- Floor-mode, S,1,4

Amenities
- Heavy window movable window and heavy outdoor facade isolation
Heavy constructions — cavity and attachment

Effect of indoor linings 3 x 15 mm over lamine with heavy insulating wall compared to existing heavy construction

- A. Existing façade with fenestration
- B. Effect of free-standing linings (180 mm cavity) with heavy insulating wall
- C. Effect of attached linings (150 mm cavity) with heavy insulating wall

Heavy constructions — indoor vs. outdoor insulation

Effect of indoor vs. outdoor lining — heavy construction (all with removable window)

- D. Indoor attachment (150 mm cavity + 100 mm glass wool)
- E. Outdoor insulation (200 mm glass wool) + 2 layers of plaster
- F. Outdoor insulation (200 mm glass wool) + plaster
Detailed results – lightweight constructions

Effect of number of layerplates (independent ceiling) compared to existing-lightweight construction

Number of
Building
is
Insulation (dB) insertion (dB)

L1: Existing roof and window
L2: As L1 plus layer ceiling w/ 1 layer
L3: As L2 plus layer ceiling w/ 1 gas separators
L4: As L3 plus layer ceiling w/ 3 gas separators

Detailed results – TAKE CARE on open windows

Effect of partly open window - lightweight construction

Window 5 cm open
Existing conditions
Experiments - room acoustics

Effect lowfrequency absorbents - heavy construction

Indoors windturbine-noise - heavy facade

Existing Building

Linehood - heavywindow

Outdoor facade insulation with plates

A

B

C

D

E

L_{A,eq} =

15 dB

22 dB

2 dB

5 dB

3 dB

5 dB

7 dB

8 dB

OK if L_{A,eq} <

threshold limiting value: 20 dB

OK if L_{A,eq} <

threshold limiting value: 20 dB

(OK if A)

(OK if B)

(OK if C)

(OK if D)

(OK if E)
Indoor Wind Turbine noise - lightweight "facade"

- G: 20 dB, 24 dB
- K: 15 dB, 14 dB
- J: 15 dB, 16 dB
- H: 15 dB, 15 dB

Just OK in L_{eq} - threshold limiting value: 20 dB

Perspectives/future work
LF-sound insulation

Technical:
More analysis in normal and enhanced frequency area (25/58/100-3158 Hz)

"New" C_{a,ref.25-3158} adaption term
(evt. C_{a,ref.15-3158})

WT = WindTurbine

Purpose:
Simple calculation of A-weighted indoor windturbine noise

A_{ref.25-3158} - (C_{a,ref.25-3158} + 10\log(S/A))

Perhaps economical subsidies to LF-facade insulation of houses
- & la road- and railway noise
4.3 Annoyance from wind turbine noise? Review of wind turbine noise studies of the last two decades

Speaker: *Sabine von Hünerbein, University of Salford (UK)*

**Abstract:**
In agreement with other environmental noise literature, most work on the annoyance from wind turbines has focussed on noise. Notable work has been carried out in Sweden, the Netherlands, Japan, China, Canada and the US. Their results seem to show that the noise from wind turbines starts to annoy at sound levels that are much lower than that of other sources such as road or rail traffic. At the same time other factors are identified that also correlate highly with annoyance ratings. The presentation will critically review the evidence and raise the question whether it is time to shift the focus from noise annoyance to a much broader view on the factors affecting the acceptance of wind energy installations.

**Slides:**
Introduction

- Growing body of literature (> 200) on wind energy impact
- Majority of rejected planning applications due to noise concerns
- Major 'health outcome' annoyance
- Mostly related to wind turbine noise
- Dose-response relations derived
- Are they the best measures?

Annoyance definition

- Disturbance of activities (noise related)
- Emotional/attitudinal response
- Cognitive response

Guski, Schreckenberg, & Schuemer, 2017
Dose-response for wind turbine noise?

Common exposure measures

- $L_{Aeq, 1h}$: equivalent A-weighted averaged sound level
- $L_{den}$: 24 h time weighted average $L_{Aeq}$
  +0 dB 7am-7pm, +5 dB 7-10pm, +10 dB 10pm-7am
- $L_{dn}$: 24 h time weighted average $L_{Aeq}$
  +0 dB +10 dB 22.00-7.00
Common outcome measures

<table>
<thead>
<tr>
<th>% HA: Highly Annoyed</th>
<th>% A: Annoyed</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Very annoyed</td>
<td>2 Slightly</td>
</tr>
<tr>
<td>4 Very</td>
<td>3 Moderately</td>
</tr>
<tr>
<td>5 Extremely</td>
<td>4 Very</td>
</tr>
<tr>
<td></td>
<td>5 Extremely</td>
</tr>
</tbody>
</table>

Or any combination of sub-ratings

% SA, MA, VA, EA:

Verbal scales
1 Do not notice
2 Notice, but not annoyed
3 Slightly annoyed
4 Rather annoyed
5 Very annoyed
1 Not at all
2 Slightly
3 Moderately
4 Very
5 Extremely
9 Inaudible
1 Not at all
2 Slightly
3 Moderately
4 Very
5 Extremely
98 Refusal
99 Don't know

Dose-response studies

- **Pedersen 2004**
  - Sweden, N = 351
- **Pedersen 2007**
  - Sweden, N = 751
- **Pedersen et al. 2009**
  - NL, N = 725
- **Kuwano 2014**
  - Japan, N = 651 (332)
- **Michaud et al., 2016**
  - Canada, N = 1238
- **Song, 2016**
  - China, N = 227

N & pane size = participant no, colour code dominant terrain type
Sweden 2000/2005, NL

Annoyance question:
“State for each nuisance below if you notice or are annoyed when you spend time outdoors/indoors at your dwelling: odour from industries, odour from manure, flies, noise from hay fans, noise from wind turbines, railway noise, road traffic noise, lawn mowers.

Canada

Annoyance question:
Thinking about the last 12 months, when you are at home, how much does noise from road traffic/aircraft/ railways or trains/wind turbines bother, disturb or annoy you?
Japan

Annoyance question

“Thinking about the last 12 months or so, when you are here at home, how much does each noise listed below bother or annoy you?
road traffic noise/aircraft noise/shinkansen train noise/conventional train noise/noise from factories/construction noise/wind turbine noise/other ( )

China, 2015

Annoyance question:
Adapted from Sweden 2000:
“To what extent are you annoyed by ambient noise when you are outdoors?”
China, 2015

- Residents very close to wind farms,
- Very complex terrain
- All wind turbines on hill-tops
- Predominantly long-term residents
- Not consulted
- Residents do not benefit
- Elderly population

Attitude towards local wind project, US, 2016

1705 respondents
1/3 of large US wind projects included

Central research question:
• What is your attitude toward the local wind project now?
• Independent variables in 5 groups
  1. Planning process/arrival into area
  2. Related attitudes
  3. Sensory perceptions
  4. Project characteristics, compensation
  5. Demographics

Attitude towards local wind project, multivariate regression

Conclusions

- Dose-response relations do not describe impact of wind power installations
- Many factors affect impact of wind energy
- Inclusion bias affects study outcomes
- Research into special sound properties of wind turbines is needed
- Wind turbine noise concern remains one of the most significant obstacles to project development
Equal loudness contours
5  Session #2
   #1 Continued & Industry Perspectives

This session is dedicated to wind turbine manufacturers and their activities concerning noise issues for their products. Note that the first presentation by Lars Søndergaard belongs to the topics of Session #1.
5.1 Measurement at neighbor position

Speaker: **Lars S. Søndergaard, DELTA - a part of FORCE Technology**

**Abstract:**
Project for the Danish EPA to investigate whether the current guidelines for measurement of noise emission and noise propagation calculation from wind turbines described in the Danish Statutory Order give an accurate noise contribution at residents and to make measurements under conditions other than the Danish Statutory Order prescribes.

**Slides:**

**Measurement at neighbor position**

- Noise measurements at wind turbines and neighbors at Nollund compared with calculations and legislation for noise regulation
- Project for Danish Environmental Protection Agency
Background

- Present regulation for wind turbine noise in Denmark (fx BEK1736)
  - Sound power level measurements
  - 6 and 8 m/s
  - Downwind wind direction
  - Calculation of noise level at neighbors

Frequent questions / statements:
- Why don’t you measure the noise where we live?
- Why do you measure in / assume downwind wind direction?
- Why do you only measure at 6 and 8 m/s
- The level of low frequency noise are higher than you calculate!

Primary purpose/questions

- Are there systematic differences between measurements and calculations? (both at downwind, 6-8 m/s and in other situations, outdoor and indoor)
- Does other wind speeds than 6 and 8 m/s give
  - Other noise?
  - More prominent tones?
  - More low frequency noise?
- Does other wind direction than downwind from turbine to neighbor give
  - More noise?
  - More prominent tones?
  - More low frequency noise?
- (Can wind turbine noise be measured in neighbor distance?)
Strategy

- Site and neighbors chosen and contacted by Danish EPA
- Neighbors offered to be relocated for a time period

- Initial visit to neighbors:
  - Neighbors has pointed out relevant measurement positions indoors
  - Neighbors has provided their perception of the wind turbine noise

- Measurements at large number of measurement positions over “long” time period
- Measurements both close to the turbines, in a medium position and at neighbors to ensure usable signal-to-noise ratio
- Large variation of wind speed and wind direction
- Calculations both according to BEK 1736 and Nord2000

Site – Nollund at Grindsted

3 x V112 3 MW
Neighbor to southeast, WT1 P3

Neighbor to north, WT2 P3
Neighbor to southwest, WT3 P3

Large amount of synchronized equipment

Plus data from turbines (produced power, nacelle wind speed, generator RPM and wind direction)
Challenges

- Arrangements – coordination of
  - equipment
  - weather
  - manpower
  - access (neighbours)
- Large amount of equipment
  - Calibration
  - Insurance
- Desire to measure over multiple continues days
  - No rain
  - Many different wind speeds
  - Many different wind directions
- DK closely populated -> background noise
- Temperature <0 degrees
- Domestic animals

Weather during the measurements

<table>
<thead>
<tr>
<th>Date</th>
<th>Temperature</th>
<th>Humidity</th>
<th>Cloud cover</th>
<th>Air pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>8. december 2016</td>
<td>8 to 11 °C</td>
<td>85 - 99 %</td>
<td>2/8 - 8/8</td>
<td>1016 - 1017 hPa</td>
</tr>
<tr>
<td>3. januar 2017</td>
<td>3 - 7 °C</td>
<td>70 - 80 %</td>
<td>4/8 - 8/8</td>
<td>990 - 1000 hPa</td>
</tr>
<tr>
<td>4. januar 2017</td>
<td>-3 - 5 °C</td>
<td>50 - 65 %</td>
<td>0/8 - 7/8</td>
<td>990 - 1020 hPa</td>
</tr>
<tr>
<td>5. januar 2017</td>
<td>-10 - -3 °C</td>
<td>57 - 92 %</td>
<td>0/8 - 6/8</td>
<td>1020 - 1040 hPa</td>
</tr>
<tr>
<td>6. januar 2017</td>
<td>-12 - -5 °C</td>
<td>80 - 95 %</td>
<td>0/8 - 6/8</td>
<td>1030 - 1040 hPa</td>
</tr>
</tbody>
</table>
Control of turbine load

Can wind turbine noise be measured at neighbors?
Can wind turbine noise be measured at neighbors?

Measurements compared to calculations, BEK 1736

### Nord2000 scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud cover [1/8]</td>
<td>6</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>7</td>
<td>6</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Wind speed 10m [m/s]</td>
<td>9.6</td>
<td>10.8</td>
<td>8.4</td>
<td>8.4</td>
<td>8.4</td>
<td>8.7</td>
<td>7.2</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>Wind dir. [deg.]</td>
<td>294</td>
<td>311</td>
<td>329</td>
<td>222</td>
<td>355</td>
<td>349</td>
<td>345</td>
<td>348</td>
<td>348</td>
</tr>
<tr>
<td>Temperature [°C]</td>
<td>5</td>
<td>11</td>
<td>12</td>
<td>10</td>
<td>7</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>16</td>
</tr>
<tr>
<td>Humidity [%]</td>
<td>70</td>
<td>74</td>
<td>70</td>
<td>68</td>
<td>69</td>
<td>69</td>
<td>69</td>
<td>73</td>
<td>55</td>
</tr>
</tbody>
</table>

### Measurements compared to calculations, BEK 1736

[Graph showing measurements compared to calculations]
Measurements compared to calculations, BEK 1736
Does other wind speeds than 6 and 8 m/s and/or other wind directions than downwind give more prominent tones?

900-1800 Hz

Summary

- Good consistency between measured and calculated noise levels (both 10 – 10,000 Hz and 10 – 160 Hz), and no systematic differences are observed
- Difficult to measure wind turbine noise at neighbor position (due to background noise)
- Other wind speeds than 6 and 8 m/s
  - The A-weighted noise level corresponds to what can be calculated on the basis of measured sound power levels for the wind turbines for other wind speeds than 6 and 8 m/s.
  - Eventual tones in the noise from the turbines are not necessarily most audible at the wind speeds 6 and 8 m/s. More audible tones are observed at lower wind speeds
- Other wind directions than downwind
  - For the examined wind directions higher noise level are not observed when comparing downwind with other wind directions.
  - Eventual tones in the noise from the turbines can be more audible in other wind directions than downwind.
Ideas for future work

- Large dataset -> Can always be analyzed more / correlations investigated
- Amplitude Modulation
  - 1 of 9 outdoor mic positions analyzed for AM
  - Analyzed remaining 8 positions
  - Correlation between nearfield and farfield AM?
  - Indoor AM?
- Tonality
  - Significance of day/night time?
  - Correlation with local wind speed (10 m met mast)

Thank you for your attention

Questions?

Danish EPA report: Internoise 2017:

http://assets.madebydelta.com/docs/share/Akustik/Wind_turbine_noise_at_neighbor_dwellings_comp_calculations_and_measurements.pdf
5.2 Developments in acoustics at Vestas Wind Systems A/S

Speaker: Jérémy Hurault, Vestas Wind Systems A/S

Co-authors: Jérémy Hurault, Kaj Dam Madsen, Mohammad Kamruzzaman and Francesco Grasso

Abstract:
The presentation will hold a short introduction on the perspectives and then a more detailed presentation on aero-acoustic developments.

Slides:
Outline

1. Vestas, the global leader in wind technology
2. Low CoE, Low Noise Turbines
3. Designing for Low Noise Aeroacoustics:
   1. Optimal trade-off between tip speed and PowerTrain lay-out
   2. Airfoils optimised for both Aerodynamics an Acoustics
   3. Sound reducing blade add-ons (Serrated Trailing Edges)
   4. Prediction and Validation
4. Conclusion
Vestas in brief
The only global wind energy company

- + 23,300
  We employ more than 23,300 people worldwide and have more than 35 years of experience with wind energy

- + 38,892
  We have a total of 38,892 combined turbines under service, or around 76 GW

- + 63,500
  We have more than 63,500 turbines or 90 GW of installed wind power capacity in 77 countries worldwide spanning six continents

- € 10,0bn
  Vestas’ revenue for 2017 was EUR 10.0bn

Versatile solutions for any wind energy project
Ongoing innovation from the undisputed global wind leader

- 2 MW PLATFORM
  - V90 2.0 MW®
  - V100 2.0 MW®
  - V110 2.0 MW®

- 4 MW PLATFORM
  - V105 3.45 MW™
  - V112 3.45 MW™
  - V117 3.45 MW™
  - V126 3.45 MW™
  - V136 3.45 MW™
  - V150 4.2 MW™

** As of 9 November 2017, including V80-1.8/2.0 MW™ and V90-1.8 MW™
** As of 9 November 2017, including V112-3.0 MW™
Not shown: V90-3.0 MW®, constituting 9 GW
Not shown: ‘Other’ turbine models constituting 23 GW
Technology strategy and solutions

Technology evolution

- V117 - 4.2 MW
- V110 - 2.0 MW
- V112 - 3.0 MW
- V116 - 2.0 MW
- V117 - 3.3 MW
- V120 - 2.0 MW
- V126 - 3.3 MW
- V136 - 3.45 MW
- V136 - 4.2 MW
- V150 - 4.2 MW


Delivering value every step of the way

Innovating to lower the cost of energy

Delivering value every step of the way

Profitably bringing market-driven, innovative solutions to our customers.

Custom configurations based on modularised building blocks.

Broad and flexible product portfolio to precisely meet the unique needs of every site.

Collaboration with external partners to develop innovative solutions and integrate external technologies in new ways.
Controlled unfolding of 4 MW platform potential
More annual energy production from same trusted platform

- **3.0 MW**
  - Product Vestas 3 MW WTs
  - Up to 3.3 MW nominal rating

- **3.3 MW**
  - Product Vestas 3.3 MW WTs
  - V112-3.3 MW™
  - V117-3.3 MW™
  - V126-3.3 MW™

- **3.45 MW**
  - Product Vestas 3.45 MW WTs
  - V105-3.45 MW™
  - V112-3.45 MW™
  - V117-3.45 MW™
  - V126-3.45 MW™
  - V136-3.45 MW™

- **3.45-4.2 MW**
  - Upgrade to 3.45 MW nominal rating
  - V105-3.45 MW™
  - V112-3.45 MW™
  - V117-3.45 MW™
  - V126-3.45 MW™
  - V136-4.2 MW™

Up to
56% 
AEP increase
since 2010*

- **3.45 MW**
  - Add to 4.2 MW nominal rating variants
  - V117-4.2 MW™
  - V112-4.2 MW™
  - V117-4.2 MW™
  - V126-4.2 MW™
  - V136-4.2 MW™

- **4.2 MW**
  - Addition of 4.2 MW nominal rating variants
  - V136-4.2 MW™
  - New rotor: 150 m
  - New segment: tropical class
  - Up to 4.2 MW Power Optimised Mode
  - Platform name updated to 4 MW

Announced Q2/2017

* Corporate Slide Deck Q4/2017 (Public)
V136-4.2 MW™ Turbine Variant

High production at industry leading sound power levels

- **More Torque**: Upgraded gearbox powering lower rotor rotational speed, enabling enhanced project specific siteability.
- **More Power**: Upgraded generator to 4.0 MW nominal rating with 4.2 MW Power Optimised Mode.
- **Low Sound Power**: Segment leading sound power level at 103.3 dB(A).

**Tower Portfolio**
- Accommodating 150-230 m tip height. Option for site specific towers.

*Compared to V136-3.45 MW. Depending on wind condition.

Classification: Restricted

- 103.9 dB(A) maximum sound power level.
- 1.6 dB(A) compared to V136-3.45 MW.

**Up to 11% AEP Increase**

V150-4.2 MW™ Turbine Variant

Highest yielding onshore low wind turbine in the industry

- **Larger Swept Area**: Blade length increased to 73.7 m using Vestas most advanced aerodynamic design and materials.
- **Higher Energy Production**: Combined with increase in capacity factor.

**Tower Portfolio**
- Site specific tower portfolio to meet tip heights ranging from 180-241 m leveraging industry leading 166 m hub height.

*Compared to V150-3.45 MW. Depending on wind condition.

Classification: Restricted

- 17,671 m² swept area.
- +22% swept area.

- 104.9 dB(A) maximum sound power level.

**Up to 21% AEP Increase**
1. Optimal trade-off between tip speed and PowerTrain lay-out

- Tip speed, correlated with noise emission $\sim U^5$
- But, low tip speed means higher drive train cost (higher torque to transmit)
- System approach to carefully select tip speed for Low cost of Energy and Maintain noise emission below target
2. Rotor Design for Aerodynamic Noise Performance

- Blade shape design by gradient based optimizer:

- Blade design based on Vestas optimised airfoils:
  - Airfoil design and selection
  - Multi Disciplinary Optimization
  - Simulation and extensive wind tunnel testing
  - Building on extensive experience and database

- Variable order B-spline control points

- High aerodynamic efficiency
- Low TBL-TE noise emission

- 33 different constraints covering:
  - Geometry
  - Manufacturing
  - Aerodynamics
  - Acoustics
3. Serrations for Reduction of Trailing Edge Noise

- For a typical MW class wind turbine, Trailing Edge noise is the dominant noise source.
- TE noise can be addressed by application of serrations.

Key Parameters for Efficient Serration Design

1. Serration dimensions $H$ to local turbulence scale ratio (Howe: $H \approx$ BL thickness, $St = w h / U_c >> 1$)
2. Serration length $H$ to width $\lambda$ ratio and (Howe: $H/\lambda > 1$)
3. The angle between local flow direction and serration edge (Howe: $\phi < 45\text{deg}$)

Virginia Tech (VT) Stability wind tunnel

Test set-up description
- Specific wall treatment and foam to minimize background noise
- Good signal to noise ratio up to Re=4m/Ma=0.21
- Very low inflow turbulence TI<0.03%

Full scale wind turbine validation

Wind tunnel design guidelines transferred to full scale blades
- Best compromise in terms of noise reduction and loads management derived from wind tunnel experiments
- Design adapted for 3D full scale blade

- One microphone IEC sound power measurement with and without serrations at several noise modes

Serration prototypes have been installed on various Vestas turbines

Vestas FB page, V136
STE Noise Reduction Performance Gen 1: V126 3.3 MW

- More than 2dB(A) reduction were found with first design iteration.
- Efficient reduction at peak frequency by 4 dB(A).

STE Noise Reduction Performance Gen 2: V112-3.3MW

- 1dB further reduction with improved STE design method leads to -3dB reduction with Vestas turbines.
- New Gen 2 serrations provides >5dBA in some frequency band around peak noise.
4. Aeroacoustic Prediction and Validation

- Semi-Empirical Models
- Simplified Analytical Models
- CFD Based Methods

Coupling of Aerodynamic tools to noise prediction tools
- Airfoil level
- Rotor level

Rotor Noise Simulation: Validation & Assessment

<table>
<thead>
<tr>
<th>Case #</th>
<th>Turbine</th>
<th>Rotor Diameter [m]</th>
<th>Hub height, [m]</th>
<th>Wind Class &amp; Other Info</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>V126-3.3MW</td>
<td>126m</td>
<td>116m</td>
<td>IEC 3A</td>
</tr>
<tr>
<td>B</td>
<td>V112-3.3MW</td>
<td>112m</td>
<td>116m</td>
<td>IEC 2B</td>
</tr>
<tr>
<td>C</td>
<td>V136-3.45MW</td>
<td>136m</td>
<td>116m</td>
<td>IEC 2A</td>
</tr>
</tbody>
</table>
Good agreement between simulation and measurement for max. noise level at rated power.

Agreement is not as good as rated power at low & high wind speeds.
V112 3.3MW: Exp. vs Sim., Noise Spectra

- Good agreement at all frequencies
- Atmospheric attenuation model is required for a good fit at high frequency although little impact the OASPL

V136 3.45MW: Exp. vs Sim. OASPL

- Simulation is within +/- 0.5dB of the measurement for available wind speed
Conclusion

Serration History and Background at Vestas

First Serration Wind Tunnel Test 2012
Full Scale Concept Test V117 Feb. 2014
Application for all Vestas Turbines 2015
Local flow optimization for better noise reduction (V136 & future turbines) 2016
Future new technology providing greater noise reduction
-2dBA reduction
-3dBA reduction

-2dBA reduction

-3dBA reduction
Conclusion

➢ Vestas has been extensively taking into account aeroacoustics noise source in WTG design since 2012

➢ The 3 key axis of this strategy are:
  1. Optimal trade-off between tip speed and PowerTrain lay-out
  2. Airfoils optimized for both Aerodynamics and Acoustics
  3. Sound reducing blade add-ons (Serrated Trailing Edges)

➢ An aeroacoustic noise prediction tool has been developed to support development and research into next generation quiet wind turbines
  • Good agreement between simulation vs measurement are found
  • Predicted overall sound power level (OASPL) at the rated power region is within ±0.5dB uncertainty range.

➢ This serration add-ons has been developed and validated for all Vestas turbines, up to 3dBA noise reduction at the rated power

➢ Vestas will keep developing low noise rotor further, utilizing low noise airfoils and add-ons technology
5.3 Developments in wind turbine noise: limitations and opportunities

Speaker: Tomas R. Hansen, Siemens Gamesa Renewable Energy A/S

Abstract:
Noise from wind turbines is one of the constraining factors for how many wind turbines will be built in the future and thereby how much clean energy we can produce by use of onshore wind turbines. What will be the important factors to ensure turbines also in the future? Which are the limitations Siemens-Gamesa sees in the market related to noise and how do we react to this?

Slides:
Limitations and opportunities

Limitations

• Noise regulations are becoming more and more detailed and setting up more strict regulations for wind turbine noise in order to protect neighbors.

• At Siemens Gamesa see this as a necessary and positive development to secure a stable market in the future and ensure further development of clean and sustainable energy.

• In some onshore markets 20 to 40% of all turbines are noise reduced.

• This result in substantial loss of power output from the turbines.

Therefore development of low noise technology have a high priority for Siemens Gamesa.

Developments in low noise technology

Low noise technology is a wide range of developments in the turbine.

We are working in 3 main areas:

Noise reduction at the source:
• Blade design
• Blade add-on

But also a wider perspective on the wind turbine noise:
• Control features
  • Turbine level
  • Park level
Air absorption and frequency spectrum – example

Dino tails and vortex generators

Sound Power spectrum of a 101 m rotor with and without DinoTails and extra VG’s

A-weighted Sound Power Level reduced

\[ L_{WA} = -1.1 \text{ dB} \]

Due to air absorption the positive influence of the changed shape of the spectrum increases with increasing distance to the turbine it influence \( L_{WA} \)

A-weighted Sound Power Level, \( L_{WA} \): -1.1 dB

The Add-on kit influence in neighbor locations (ISO 9613-1:1993, 10 °C, 80 % RH, 1 ATM)

- 500 m, \( L_{pA} \): -2.4 dB
- 1000 m, \( L_{pA} \): -3.0 dB
- 2000 m, \( L_{pA} \): -3.8 dB

We do have two examples in DK where the customer don’t need to use low noise settings anymore

In one case 6 turbines were changed from -3 dB setting to standard setting using this effect

This is real noise reduction at the receiver position!
SiemensGamesa DinoTails

Flap with serrated trailing edge
• Applied to outer part of the blade
• DinoTails introduced by Siemens around 2002
• Reduce noise and increase power output
• Serrations are now industry state-of-the-art

Can we do even better than DinoTails?
• Yes we can 😊

DinoTail Next Generation

Inspiration from the silent flight of the owl
• Owls fly much quieter than other birds
• Low-noise wing technology
• Can we apply this to wind turbine blades?

New concept: combed teeth
Design and performance

Advanced design and validation methods
- Optimized for acoustics, performance and structural integrity
- Numerical computations, wind tunnel and field testing
- DinoTail-NG shows substantial noise reduction at all wind speeds
- No adverse effects on aerodynamic performance

Comparison of noise spectra of 3 modern turbines
3 turbines from our product portfolio
Rotor size between 110 and 135 m.
Different blade design philosophy and different add-on
- 106.0 dB is the smallest and oldest rotor
- 106.1 dB is the largest rotor but different blade design and add-on
- 107 is the most modern rotor and conservative in number and spectral shape
Comparison of noise spectra of 3 modern turbines

Results

• 5 turbines in a row
• noise limit 40 dB (Sweden)
• Spectra not normalized to equal level

The noise looks almost similar but some important differences occur while looking closely at the lines:

• The 107.0 dB turbine do have the lowest noise impact at the receiver position
• Noise limit is 48 m further away for the 106.1 dB turbine
Conclusions and outlook

DinoTail Next Generation has pushed the state-of-the-art

- Design inspired by low noise flight of the owl
- Substantial noise reduction
- No adverse effects on performance
- Applied to most onshore SiemensGamesa turbines

Noise levels at receiver position is more important than ever

- Several markets use more advanced propagation models
- We are pushing the limits for power produced within noise limits
- Advanced control features will squeeze even more energy out of the turbines

Our mission:
We make real what matters – Clean energy for generations to come
Thanks

17 May 2018
6 Session #3

Recent Research Advancements

This session is dedicated to research efforts currently undertaken at DTU Wind Energy related to wind turbine noise. This efforts span from wind tunnel and field measurements to modelling of aerodynamic noise sources and sound propagation.
6.1 Cross-Cutting Activities and Wind Turbine Noise

Speaker: *Franck Bertagnolio, DTU Wind Energy*

Abstract:
In this presentation, self-financed research activities (so-called CCA) currently conducted at DTU Wind Energy on a Vestas V52 test turbine are described with focus on measurements related to noise. Furthermore, some measurements are compared with the HAWC2-noise model which combines the well-known aeroelastic and load prediction code with a recently implemented noise module. Some features of the software are also presented.

Slides:
Outline

➢ Cross-Cutting Activities 2015-18
  ➔ Rapid look back
  ➔ Current and near-future activities

➢ HAWC2-Noise – Wind turbine noise model
  ➔ Basics of the model
  ➔ Examples

CCA 2015/2016 – Wind Turbine Noise

6 surface pressure mics.

+Inflow sensors
Pitot tubes

Instrumented NTK-500 WT

Wireless microphone array

Modelling & Validation

8 ground acoustic mics.
Surface Pressure Mics. on Blade
GRAS 40LS 1/4” CCP Precision Surface Microphones

Correlation T.E. SP mic. vs. Noise
Each point = Averaged spectra based on 3 rotor rotations

NTK turbine

T.E.

Nacelle anemometer
TURBULENT INFLOW NOISE

From atmospheric turbulence

From other turbines' wake
Turb. Inflow NOISE

**NTK meas. vs. model:**

All noise sources

TI noise only

Using sensors and measurements from various other activities within CCA 2018

*High-Frequency Pitot tube*

Use LIDAR data from parallel experiments
Development of wireless microphones for sound propagation measurements

From Airfoil Noise to Rotor Noise

Wind turbine rotor noise modeling
Wind Turbine Noise Sources

Main wind turbine aeroacoustic noise mechanisms

- Leading edge separation possible
- Tip vortex
- Trailing edge flow
- Turbulence in oncoming flow
- Stalled flow

Rotor Aerodynamic & Noise Model

- Inflow
- Rotor plane

Aerodynamics using BEM method

The model includes:
- Wind shear
- Yaw
- Tilt/Coning
- Blade geometry (+ twist & pitch)
- Turbulent inflow
- Tower flow deficit/perturbation (inviscid)

Noise modeling in spectral domain:
- Trailing Edge Noise
- Turbulent Inflow noise
- Stall noise

Noise modeling in time domain....
HAWC2-Noise

BEM rotor aerodynamics in HAWC2

\( \alpha, V_{rel} \)

Noise models use discretized HAWC2 blade sections

Far-field noise

Noise calculation models

Unsteady Effects AND Directivity

1 blade only!

Maps of emission noise
Unsteady Effects AND Directivity

Maps of emission noise

Sudden Gust at Low Wind Speed

Sound from 2MW turbine
For 3 blades!

SPL

Total noise
Stall noise
Trailing edge
Leading edge
Noise in Wake

SPL(A)

Full-wake

Half-wake

SPL

Low-Frequency Noise

HAWC2 model + Mann turbulence

SWT 3.6MW

NREL 5MW
Conclusions

➢ Experimental activities
  ➢ Field experiments
  ➢ Need for more exhaustive model validation
  ➢ Wind tunnel...

➢ HAWC2-Noise modelling tool
  ➢ Relatively new module
  ➢ Validation in progress...
  ➢ WTNoise simulation codes benchmark
    IEA Wind Task 39
    + Task 29
    & DANAERO database
6.2 Statistical prediction of far-field wind turbine noise, with probabilistic characterization of atmospheric stability

Speaker: *Mark Kelly, DTU Wind Energy*

Co-authors: *Mark Kelly, Emre Barlas and Andrey Sogachev*

Abstract:
Here we provide statistical low-order characterization of noise propagation from a single wind turbine, as affected by mutually interacting turbine wake and environmental conditions. This is accomplished via a probabilistic model, applied to an ensemble of atmospheric conditions based upon atmospheric stability; the latter follows from the basic form for stability distributions established by Kelly and Gryning (2010). For each condition, a parabolic-equation acoustic propagation model is driven by an atmospheric boundary-layer ("ABL") flow model; the latter solves Reynolds-Averaged Navier-Stokes equations of momentum and temperature, including the effects of stability and ABL depth, along with the drag due to the wind turbine. Sound levels are found to be highest downwind for modestly stable conditions not atypical of mid-latitude climates, and noise levels are less elevated for very stable conditions, depending on ABL depth.

The probabilistic modelling gives both the long-term mean and rms noise level as a function of distance, per site-specific atmospheric stability statistics. The variability increases with the distance; for distances beyond 3 km downwind, this variability is the highest for stability distributions that are modestly dominated by stable conditions. However, mean noise levels depend on the widths of the stable and unstable parts of the stability distribution, with more stably-dominated climates leading to higher mean levels.

Slides:
Statistical prediction of far-field wind turbine noise, with probabilistic characterization of atmospheric stability

Mark Kelly, Emre Barlas, Andrey Sogachev

ABL turbine noise-propagation modelling

- Single turbine, single wake...
  - What is the SPL downwind?

- Combined modelling (chain)
  - Probabilistic ABL-state model
ABL turbine noise-propagation modelling

- Single turbine, single wake... ⇒ What are the SPL statistics downwind?

- Combined modelling (chain)
  - Probabilistic ABL-state model
driven by:
  - Parabolic Equation (PE) model
  + using output from
  - ABL flow model (RANS)

Probabilistic ABL-state model...

- First try: ensemble of atmospheric-stability states
  - stability most influences flow field
    - shear/profile
    - wake
  - We know how to model stability ($L^{-1}$) and its PDF;
    - $P(L^{-1})$ has universal shape [Kelly+Gryning 2010]
    - We know e.g. limits of effect on shear [Kelly et al 2014]
    - summing $L^{-1}$ regimes: works for modeling $U(x)$ [Kelly+Troen 2015, 16]
Probabilistic ABL-state model...

• First try: ensemble of atmospheric-stability states
  • stability most influences flow field
  • shear/profile
  • wake
  - We know how to model stability ($L^{-1}$) and its PDF;
    • $P(L^{-1})$ has universal shape [Kelly+Gryning 2010]
    • We know e.g. limits of effect on shear [Kelly et al 2014]
    • summing $L^{-1}$ regimes: works for modeling $u(x)$ [Kelly+Troen 2015,16]

$$\Delta SPL(r,f) = \sum \alpha \cdot \mathcal{P}(L_2^{-1}) \Delta SPL(r,f|L_2^{-1})$$

ABL modelling : flow fields

• ScaDis: RANS w/2-eqn. turbulence model [Sogachev et al 2002, ]
  - Advanced stability treatment ; satisfies M-O theory [Sogachev+Kelly 2012]
  - Captures ABL ’top’ (T-inversion)
  - Radiation/clouds also
  - Mean fields or diurnal cycles
  - Actuator disc $\rightarrow$ turbulent wake
ABL modelling : flow fields

- ScaDis: RANS w/2-eqn. turbulence model
  - Advanced stability treatment
  - Captures ABL 'top' (dT/dz)
  - Radiation/clouds also
  - Mean fields or diurnal cycles
  - Actuator disc to turbulent wake

Propagation model

- Parabolic Equation (PE): 2-D spectral solver (also 3-D)
  - Frequency-dependent propagation (refractive)
  - Sound-speed profile (from \( U(x) \) and \( T(x) \))
  - Acoustic ground impedance [grass]
  - Input: ScaDis mean flow fields
  - Source:
    - Distributed \( z=46.80.114 \) m, mean
    - Plus geometrical spreading, molec.absorption:
      \[
      SPL(f, r) = 10W(f) - 10 \ln(4\pi r^2) - \alpha(f)r + \Delta L(f, r)
      \]
### Propagation model

- Parabolic Equation (PE): 2-D spectral solver (also 3-D)
  - Frequency-dependent propagation (refractive)
  - Sound-speed profile (from $U(z)$ and $T(z)$)
  - Acoustic ground impedance [grass]
  - Input: ScaDis mean flow fields
- Source:
  - Distributed ($z=46.80.114m$), mean
  - Plus geometrical spreading, molec.absorption:
    \[
    \text{SPL}(f,r) = 10W(f') - 10\ln(4\pi r^2) - a(f')r + \Delta L(f,r)
    \]

### 'Simple' results...

- All cases
  - unstable
  - stable
  - Neutral
- No $T(z)$ in PE

- Black: probabilistic model $\rightarrow$ weighted mean
  - using local/typical $1/L$ distribution (at right)
'simple' results...stable cases

• stable cases

• No T(z) in PE

• Dotted line: stable-side average
  - Very stable cases (lighter blue line, brown):
    • (Apparently) less sound, more loss...
    • Shear due to ABL top/inversion!
      - ...but the PE is missing the T-jump at ABL "top"...

results...stable cases

• stable cases

• Now use T(z) in PE model

- Very stable case (blue lines):
  • *less sound, more loss*... → loss reduced by including T(z)

- Weakly stable case (red/orange):
  • Not much change by including T(z) in PE calcs
Overall results: mean SPL

- Re-calculate SPL’s for different sites/climatologies

Overall results: mean SPL differences

- Re-weighting SPL’s for other sites/climatologies

Difference from neutral result:
Overall results: SPL variance

- Re-weighting SPL’s for other sites/climatologies

Variability:

Conclusions

- Verified:
  - Stable climatology important (not direct, counter-intuitive)
  - Modest/weak stabilities more important and more common!
  - Stronger stabilities: more dependent on ABL depth (T-profile)
    • wake decay vs. stable stratification;
      (→ consider wake turbulence...)

- Mean SPL not so sensitive to "surface-climatology" P(1/L)
- SPL Variability does depend on P(L⁻¹) (especially night/cold)

- Noise still perceptible at 3km downwind

- To do...
  - Deal with P(L⁻¹,U,H
  - Use turbulence in PE (incl. wake),
  - Different sfc.-impedance / terrain
  - Extend range, check @angles to mean wind
  - Compare to Nord2k, others...
6.3 Recent developments in noise propagation modelling

Speaker: Wen Zhong Shen, DTU Wind Energy

Co-authors: Wen Zhong Shen, Emre Barlas and Wei Jun Zhu

Abstract:
Wind turbine noise from source to receiver is a complicated process, which is influenced by atmospheric conditions and turbine operation conditions. This talk summarizes the recent developments at DTU in modelling the noise propagation process which include the coupling modelling of atmospheric flow, wind turbine wake flow, noise source and noise propagation, as well as the moving source strategy.

Slides:
1. Introduction to noise propagation

2. Noise propagation modelling using a PE method
   • Propagation model
   • Flow input models
   • Source coupling for propagation

3. Results
   • Noise propagation under wind shear and turbulence
   • Variability of wind turbine noise in a diurnal cycle

4. Conclusions
2. Propagation modelling using a PE method

Propagation model (WindSTAR)

- Solve the wave equation in frequency domain
  (Assumptions: axisymmetric - 2D, harmonic wave, far field and one way propagation – no backscattering)

- There are two different approaches:
  Scalar PE: Effective speed of sound approach
  Vector PE: Maintaining the vector properties of velocity.

- Turbulent Wind Wide Angle Parabolic Equation

\[
\Delta + k^2(1+\epsilon) + \frac{2ik}{e} \nabla \cdot \nabla - \frac{2i}{e} \frac{\partial}{\partial x_j} \frac{\partial^2}{\partial x_j \partial x_k} \right] P(x) = 0
\]

2. Propagation modelling using a PE method

Flow input models

Engineering approach:
- Engineering flow solution
- Embedded wake using a wake model
- Synthetic turbulence

Steady Navier-Stokes approach:
- 3D Navier-Stokes solver with RAND-AD
- Synthetic turbulence

Unsteady Navier-Stokes approach:
- 3D Navier-Stokes solver with LES-AL/AD
- Realistic wake and turbulent medium
2. Propagation modelling using a PE method

Source-propagation coupling:

Single point source
- Classical approach for PE
- Monopole source at hub
- Steady mean SPL

Lumped sources along the vertical line
- Point source at blade tips
- Quasi-unsteady
- Time dependent SPL

IBPM Coupling
- More accurate source modelling
- Engineering source models (IBPM)
- Fully unsteady

Coupling effects

Moving source to mimic the blade passage
Source power level is obtained from semi empirical noise model for a wind turbine (BEM+BPM+AMIEET)
2. Propagation modelling using a PE method

Coupling effects between 2 unsteady coupling methods
- Error decreases with increasing distance.
- At upwind (Rec 5) error increases but is small.

3. Results

3.1 Noise propagation under wind shear and turbulence

Flow Input Model
- Large synthetically generated turbulence
- Superposed with inflow wind profile

- Large Eddy Simulation
  EllipSys3D/AL/Flex5
- Domain: 40 D X 10 D X 10 D
- Turbine: NM80
- Resolution: 2.5 m & 0.025 s
3. Results

3.1 Noise propagation under wind shear and turbulence

- Large synthetically generated turbulence
- Superposed with inflow wind profile

With unsteady flow and varying source strength

Sound pressure levels summed up to 800 Hz

TI 10% and shear exponent: 0.14
3. Results

3.2 Variability of wind turbine noise in a diurnal cycle
3. Results

3.2 Variability of wind turbine noise in a diurnal cycle

Time-averaged streamwise velocity, temperature and streamwise turbulence intensity at 3 diameters upstream of the turbine.

Instantaneous OASPL fields in the middle vertical plane at different times of the day.

Instantaneous OASPL fields in the middle vertical plane at different times of the day.
3. Results

3.2 Variability of wind turbine noise in a diurnal cycle

Time averaged OASPL (left) and Amplitude Modulation (right) for receivers at 2 m height in four periods of the day.

4. Conclusions

- PE models have been coupled with flows from different flow solvers.
- Effects of turbulence, wake, and atmospheric stability have been considered.
- Different source-propagation coupling strategies have been developed.
- The code has been parallelized using MPI.
Thank you for your attention
6.4 Status of the National Wind Tunnel: The Poul la Cour Tunnel

Speaker: Christian Bak, DTU Wind Energy

Abstract: N/A.

Slides:
WHY A WIND TUNNEL?

Why a wind tunnel?
Test at:
105 m/s = 378 km/h
Correspond to more than a category 5 hurricane

Tornado in Oklahoma

The tip in the future

TGV train

From wyrk.com
From www.lolking.net
THE HISTORY OF THE ESTABLISHMENT

The history behind the Danish National Wind Tunnel

- 2011 April
  - DTU got the green light from Ministry of Higher Education and Science for establishing a wind energy dedicated wind tunnel as a national research infra structure
- 2011 December
  - After discussions with the Danish wind turbine manufacturers, universities and other relevant institutions, a project application was handed in to the Ministry of Higher Education and Science
  - Budget: 74MDKK/10 M€
- 2012 May
  - Grant for establishment of the wind tunnel
- 2014 April
  - Basic design fixed
- 2016 April
  - Construction started
- 2018 April
  - Wind tunnel inaugurated
Main specifications

**1. priority:**
- Aerodynamics on airfoils at Reynolds numbers between 6 and 8 million
- Thick airfoils and airfoils with high lift
- Thin airfoils with light compressible flow
- Aeroacoustics on airfoils

THE WIND TUNNEL DESIGN
### The final design

![Image of the final design](image)

### Design of the tunnel

**Test section**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Reynolds number [-]</td>
<td>$7.0 \times 10^6$</td>
</tr>
<tr>
<td>Maximum flow speed [m/s]/[km/h]</td>
<td>~105/378</td>
</tr>
<tr>
<td>Test section: Width [m]</td>
<td>3.00</td>
</tr>
<tr>
<td>Test section: Height [m]</td>
<td>2.00</td>
</tr>
<tr>
<td>Test section: Length [m]</td>
<td>~9</td>
</tr>
<tr>
<td>Maximum turbulence intensity [%]</td>
<td>Max 0.1</td>
</tr>
<tr>
<td>Anechoic chamber with background noise at 60m/s with kevlar walls 2m from airfoil [dB]</td>
<td>&lt;70</td>
</tr>
</tbody>
</table>

![Diagram of test section](image)
Design of the tunnel
Noise reduction

Background plot from: A. Bergmann, The Aeroacoustic Wind Tunnel DNW-NWB, German-Dutch Wind Tunnels DNW, 38108 Braunschweig, Germany, 18th AIAA/CEAS Aeroacoustics Conference (33rd AIAA Aeroacoustics Conference) overlayed by DTU specifications.

Design of the tunnel
Low background noise → Noise absorption

Anechoic chamber and diffusor
Guide vanes in corner 1 and 2
Guide vanes in corner 3 and 4
Fan housing
Design of the tunnel

Predicted background noise

- Upstream
- Downstream
- Diffusor
- Guidevanes

The anechoic chamber

- Anechoic 100Hz to 10kHz
- H * W * L = 11.5m * 11.0m * 13.0m

Without damping

- 60dB

With damping

- 33dB
Status

• The fan has been running and we have observed that the aerodynamic losses are smaller than our optimistic estimates, i.e. we can easily obtain 105m/s!
• The tunnel was inaugurated 10 April 2018
• Pending:
  – Equipment to be installed in the test section (e.g. turn table, wake rake and Kevlar walls)
  – Characterization of flow and noise
  – First measurements on airfoil
SOME OF THE THINGS TO DO IN THE COMING MONTHS

Construction and mounting of Kevlar walls
Test of a symmetric airfoil

NACA 63018 to measure symmetry and noise – and benchmarked in the VirginiaTech Tunnel

SOME OF THE THINGS TO DO IN THE COMING YEARS
Airfoil design
Noise

- Correct modeling?
- Noise spectrum and low frequencies (>100Hz)
- Influence from angle-of-attack?

Airfoil design
Noise reducing devices

- Noise can be reduced by some devices such as serrations.
- Can we do more?
The operation

• The wind tunnel is for
  – Danish wind turbine manufacturers
  – Danish universities and GTS institutes
  – Foreign wind turbine manufacturers
  – Foreign universities
  – Other manufacturers and industries
• Two persons will operate the tunnel permanently
• A team of at least 10 researchers at DTU will use, develop and support the tunnel

SHARING THE KNOWLEDGE
Workshop in 2019

• We are planning a workshop in the start of 2019:
  – Experimental airfoil aerodynamics and aeroacoustics

Thank you!
... and check www.plct.dk
6.5 The Acoustic Measurement Setup in the Poul la Cour Wind Tunnel

Speaker: **Andreas Fischer, DTU Wind Energy**

Co-authors: Andreas Fischer, Oliver Ackermann Lylloff, Efren Fernandez Grande, Christian Bak, Robert Mikkelsen, Sigurd Lundsgaard Ildvedsen, Mac Gaunaa, Anders Olsen, Niels Sorensen, Christian Grinderslev and Jimmie Beckerlee

**Abstract:**
The Poul La Cour Wind Tunnel provides the possibility to test aerofoils at high Reynolds numbers. It can be configured in two different set-ups: the aerodynamic and the acoustic setup. This talk focuses on the acoustic set-up which is similar to the one developed at Virginia Tech. It consists of large Kevlar walls that allow the sound to propagate, but contain the flow. The test section is surrounded by a large anechoic chamber where an 84 channel Brüel&Kjær microphone array is located. Array data processing techniques to extract the aerofoil noise will be presented.

**Slides:**

The Acoustic Measurement Setup in the Poul la Cour Wind Tunnel

Andreas Fischer, Oliver Ackermann Lylloff, Efren Fernandez Grande, Christian Bak, Robert Mikkelsen, Sigurd Lundsgaard Ildvedsen, Mac Gaunaa, Anders Olsen, Niels Sorensen, Christian Grinderslev, Jimmie Beckerlee

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Outline

- Acoustic wind tunnel setup
- Measurement technique
- Acoustic boundary corrections
- Aerodynamic boundary corrections

The test section and surrounding anechoic chamber
Transformation from aerodynamic configuration...

... to aero-acoustic configuration
Microphone array position

Microphone array measurements in the Virginia Tech wind tunnel (AVEC)
Brüel&Kjær microphone array

Microphone array geometry

- Planar array of 2 m diameter
- 84 microphones
- Divided into 7 pizza slices to yield pseudo random distribution
Microphone array characteristics

Maximum sidelobe level at a maximum array opening angle = 90 degrees

Rayleigh resolution at 2.5 m distance to source

Source resolution

Beamsforming at 79 Hz

Beamsforming at 377 Hz
Source resolution

Acoustic boundary corrections

• Shear layer diffraction
  – Negligible at 90 deg elevation of the observer

• Absorption in turbulent boundary layer
  – Expect to be the dominant mechanism
  – Complex problem, will be treated experimentally/statistically
  – Supported by PE method simulations

• Insertion loss of transmission through Kevlar sheet
  – Well defined problem with empirical correction method

Acoustic properties of Kevlar (Jaeger et al. 2000)

Kevlar 120®, thin weave
Kevlar 124®, crow’s foot weave
Kevlar 500®, thick weave

Virginia Tech turbulence and shear layer corrections

AVEC/Virginia Tech Setup
Aerodynamic boundary corrections

Two principal sources
a) Correction to angle of attack due to transpiration through acoustic window
b) Blockage
   - Increased by wall deflection
   - Reduced due to transpiration through acoustic window
Modelled by:
  a) Simulating the presence of the model with point singularities
  b) Using a panel method to determine the effects of the porous flexible wall boundary conditions on the velocity and gradients at the airfoil.
  c) Using standard formulae (Allen and Vicente, 1947) to correct force, moment and pressure coefficients

Devenport et al., The Kevlar-walled anechoic wind tunnel, Journal of Sound and Vibration, 332 (2013) 3971-3991
Computational approach

- Computational Fluid Dynamics (CFD)
  - EllipSys2D – a code developed for wind turbine use
- 2D, Incompressible, steady state
- Convective terms by the QUICK scheme
- Turbulence modeling by k-omega SST model
- Grid configuration 62 blocks of 32^2 cells (total: 63,488), y+ < 2
- No-slip conditions on the airfoil
- Dirichlet conditions at the inlet
- Zero gradient assumption at the outlet

Wall Boundary Conditions Investigated:
- Solid (no deformation), slip and no-slip
- Kevlar walls, no deformation, slip and no-slip
- Kevlar walls, deformed, no-slip
Aerofoil pressures

0 degrees

6 degrees

Thank you!

14 May 2018
7 Conclusions

Approximately 60 persons attended the Wind Turbine Acoustic Day 2018. Although the event is only advertised in Denmark and aimed at the Danish wind turbine noise community primarily, there were a few participants from abroad (e.g. UK, Japan and USA).

Between the sessions at coffee breaks, attendees had the opportunity to meet and discuss with each other. The organizers hope that this event helps create a better synergy within the wind turbine noise community.

After the presentations, the participants had the opportunity to visit the newly built ‘Poul la Cour’ National Wind Tunnel facility located at DTU-Risø Campus.

The next edition of the Acoustic Day should take place in 2020. The organizer will contact attendees of this year’s edition in the very near future, and try to collect their impressions and suggestions on how to improve this event.
DTU Wind Energy is a department of the Technical University of Denmark with a unique integration of research, education, innovation and public/private sector consulting in the field of wind energy. Our activities develop new opportunities and technology for the global and Danish exploitation of wind energy. Research focuses on key technical-scientific fields, which are central for the development, innovation and use of wind energy and provides the basis for advanced education at the education.

We have more than 230 staff members of which approximately 60 are PhD students. Research is conducted within 9 research programmes organized into three main topics: Wind energy systems, Wind turbine technology and Basics for wind energy.