Technical University of Denmark

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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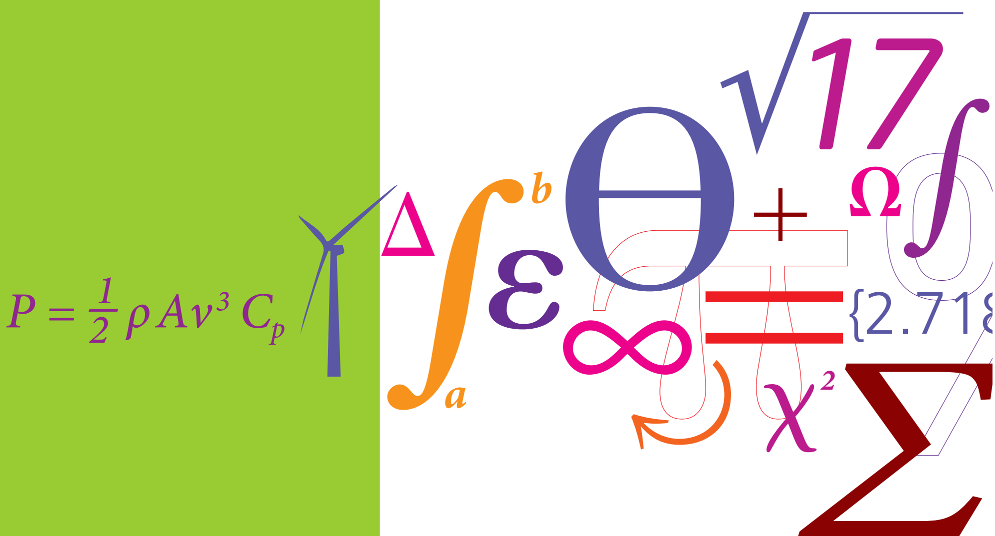
Wind Turbine Acoustic Day 2018

Summary of the 3^{rd} edition

Report E-0168



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 3^{rd} edition

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Title: Wind Turbine Acoustic Day 2018 - Summary of the 3^{rd} 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, 17^{th} 2018 as its third edition. The abstracts and slides for the presentations are reported.

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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.

Content

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, 17^{th} 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 3^{rd} edition of the Wind Turbine Acoustic Day held by DTU Wind Energy on May, 17^{th} 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.

2 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

TIME	Activities	Speakers & *Locations*
8:30-9:00	Registration and coffee	***Niels Bohr Auditorium - DTU Risø Campus (Bldg. 112)***
9:00-9:10	**Welcome**	**Peter Hauge Madsen, Head of Department, DTU Wind Energy**
Session #1: LEGAL, TECHNICAL AND HUMAN ISSUES REGARDING WIND TURBINE NOISE		
9:10-9:35	Adjustments in the regulation of noise from wind turbines	**Jesper Mogensen, Miljø- og Fødevareministeriet (Ministry of Environment and Food), Denmark**
9:35-10:00	Low frequency sound insulation of buildings in relation to wind turbine noise	**Bo Søndergaard, SWECO Danmark A/S**
10:00-10:25	Annoyance from wind turbine noise? Review of wind turbine noise studies of the last two decades	**Sabine Von Hünerbein, University of Salford, UK**
10:25-10:50 - Coffee break		
Session #2: #1-CONT'D - and - 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	**Jérémy 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**
13:25-13:40	Recent developments in noise propagation modelling	**Wen Zhong Shen, DTU Wind Energy**
13:40-13:55	Status of the National Wind Tunnel	**Christian Bak, 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.

DTU Wind Energy

May 17th, DTU-Risø Campus, Roskilde (DK)

List of speakers and abstracts

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.

Jérémy 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.

Christrian 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.

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4 Session #1
Legal, Technical and Human Issues Regarding Wind Turbine Noise

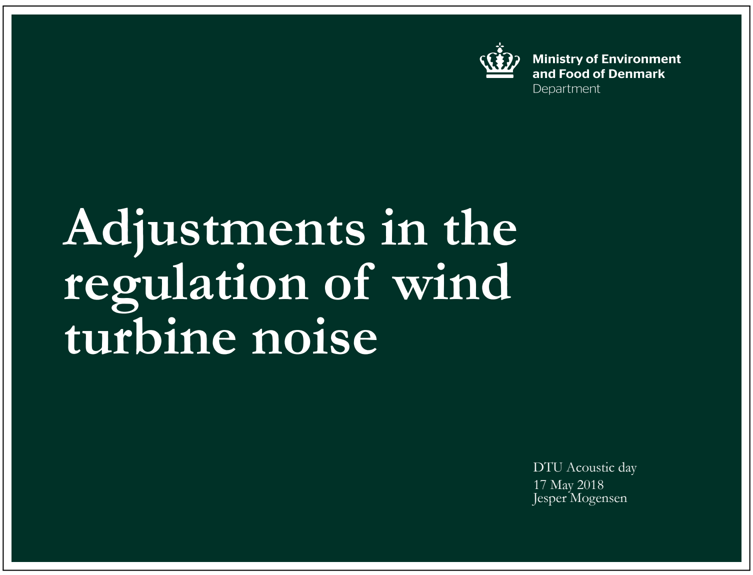
This session is about various aspects of wind turbine noise which directly impact the residents and how they experience noise.

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

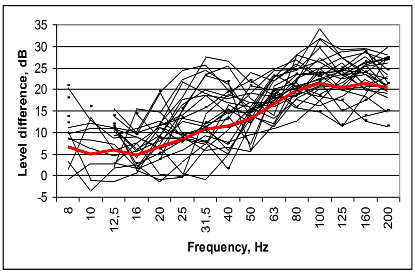
- Mandatory provisions
- Noise limits at 6 and 8 m/s for the total noise from all turbines
  - Calculated noise levels
  - Broadband noise
  - Low frequency noise
- Annex with mandatory methods
  - Emission measurement methods (in general agreement with IEC 61400-11)
  - Calculation methods (broadband 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:
  - DS/ISO 1996-2, 2. edition 2007-06-20: part 2, Annex C
  - British Standard BS 4142:2014:" Methods for rating and assessing industrial and commercial sound" Annex D (normative) Objective method for assessing the audibility of tones in sound: Reference method

- 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.

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- **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.

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- **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: ΔL_m = 10 log (r/1000)
  for r > 1.000 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 15° C
  - Temperature gradient: 0
  - Surface impedance: infinite

- **Suggested correction for multiple reflections**

- Threshold distance l_0

$$l_0 = 2000 \cdot \frac{h}{30} \cdot \sqrt{\frac{6}{v_{ref}}}$$

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

- Rated distance $l' = \frac{l}{l_0}$

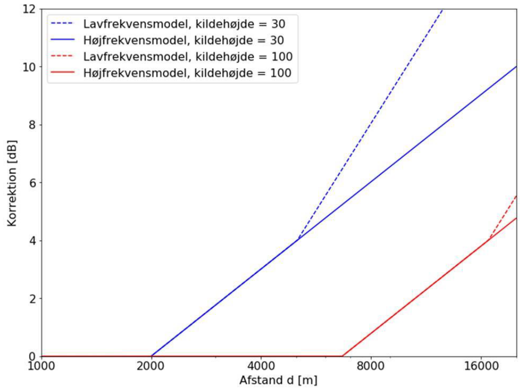
- $$\Delta L_m = \begin{cases} 0 \quad for\, l' \leq 1 \\ 10 \cdot \log l' \; for\, 1 < l' < 2{,}512 \\ N \cdot \log \frac{l'}{2{,}512} + 4\, for\, 2{,}512 \leq l' \leq 5 \\ 10 \cdot \log l' + (N - 10) \cdot \log \frac{5}{2{,}512}\; for\, l' > 5 \end{cases}$$

N: 20 for f ≤ 400 Hz

10 for f ≥ 800 Hz

$$20 - 10 \cdot \frac{\log \frac{f}{400}}{\log 2} \text{ for } 400 < f < 800$$

Correction multiple reflections 6 m/s



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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

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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 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.

Slides:

SWECO

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

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

SWECO

2 projects for the Danish Environmental Protection Agency

Reports:

1. "*Enhanced data-basis for Danish houses insulation against low frequency noise*" by Bo Søndergaard a.o. / Sweco – Acoustica

2. "*New knowledge on low frequency sound insulation of houses in areas near windturbines* " by Claus Møller Petersen a.o. / Sweco – Acoustica

Other participants:
Dan Hoffmeyer/ Delta – Force technology
Birgit Rasmussen/ AAU – SBi

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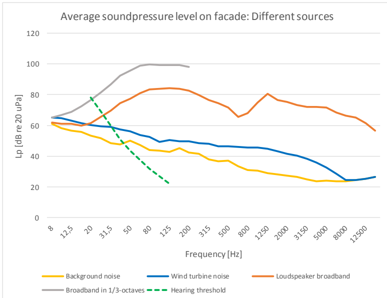
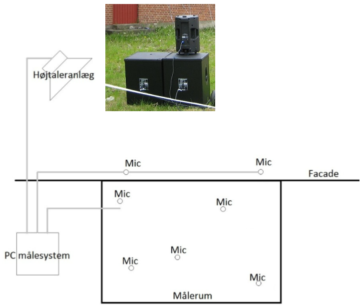
Measurement system





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SWECO

1. Mapping – building materials

New measurements (8-200 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

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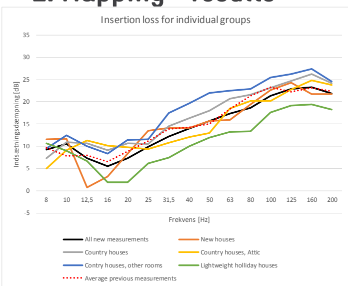
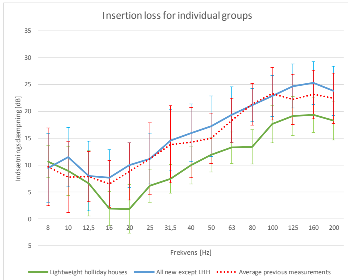
1. Mapping - results





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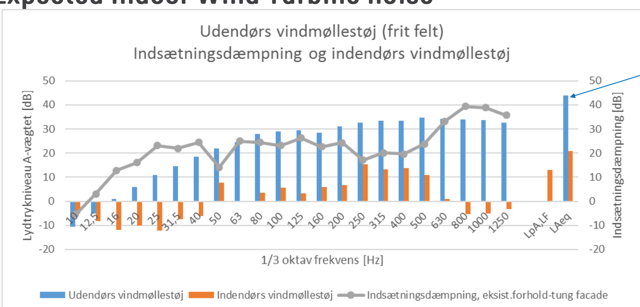
Expected Indoor Wind Turbine noise



L_{Aeq}=44 dB is the limit for outdoor Wind Turbine-noise at 8 m/s for houses at the country side

SWECO

1. Mapping. Changes in indoor LF WT noise

Indoor noise $L_{pA,LF}$ (10-160 Hz) calculated using:

- Existing facade insulation data compared to the new data
- Standard Wind Turbine noise spectrum with SPL = 44 dB* at the facade of a farm house which equals the noise limits at the countryside.

*) This applies to SPL calculated at 500 m distance from the houses, and hub-height 90 m at 8 m/s wind speed 10 m above ground.

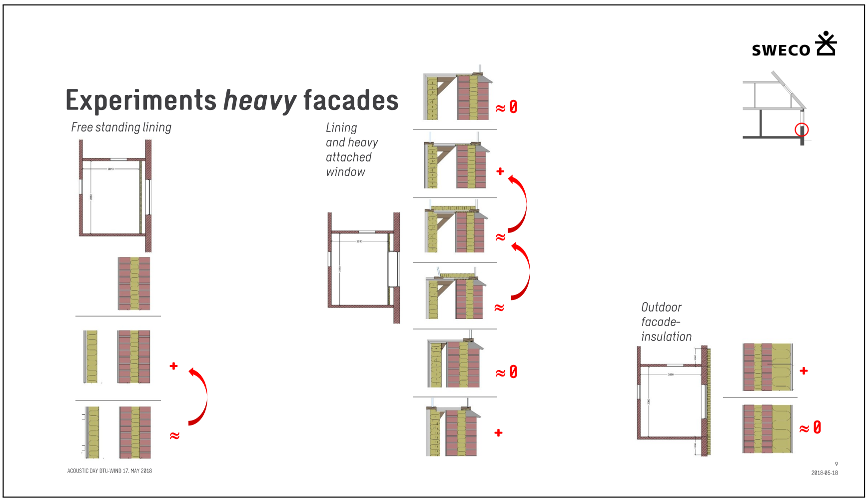
Earlier measurements	0,0 dB
Farm houses (all measurements)	-1,6 dB
Farm houses used attics	0,5 dB
Farm houses – other rooms	-3,7 dB
New houses	0,6 dB
Lightweight summer houses	4,5 dB
All new measurements	1,1 dB
All measurements	0,5 dB
All measurements excl. lightweight summer houses	-0,4 dB

New and old data similar

SWECO

2. New knowledge - project content

- Background
  - Why f << 20 Hz?
  - Can you you hear it – and can you do anything by the buildings?
- Literature
  - Sparsely output of 57 reports, articles, papers (only 14 on sound insulation f=10-160 Hz and 14 on f>50 Hz). A little about windows
- Experiments in typical building type(-s)
  - Heavy (ground floor)
  - Lightweight (1st floor)


SWECO
Experiments heavy facades
Free standing lining
Lining
and heavy
attached
window
Outdoor
facade-
insulation
+
≈
≈ 0
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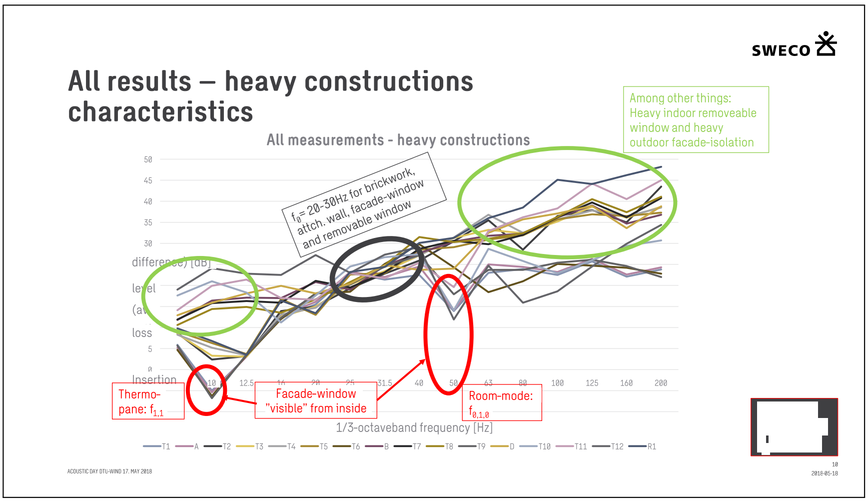
SWECO
All results – heavy constructions characteristics
All measurements - heavy constructions
Among other things:
Heavy indoor removeable
window and heavy
outdoor facade-isolation
f0= 20-30Hz for brickwork,
attch. wall, facade-window
and removable window
Thermo-
pane: f1,1
Facade-window
"visible" from inside
Room-mode:
f0,1,0
Insertion loss (a) level difference) [dB]
1/3-octaveband frequency [Hz]
T1 A T2 T3 T4 T5 T6 B T7 T8 T9 D T10 T11 T12 R1
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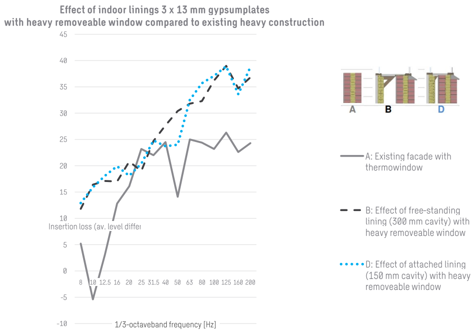
SWECO

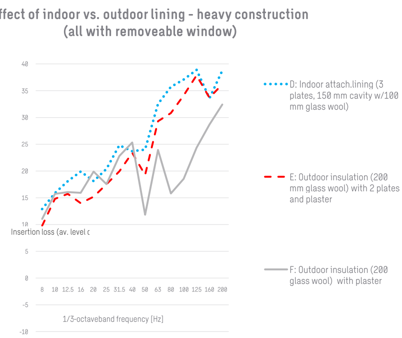
Heavy constructions – cavity and attachment



Free-standing lining nearly similar to attached lining. Remark negative insulation at 10 Hz

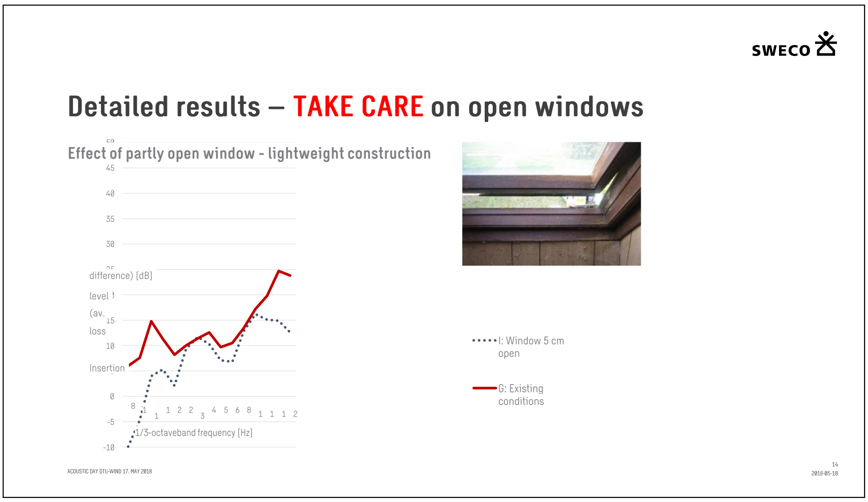
SWECO

Heavy constructions – *in*door vs. *out*door insulation



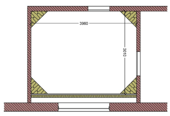
Outdoor insulation with gypsum plates similar to indoor attached lining


SWECO
Detailed results – lightweight constructions
Effect of number of gypsumplates (independant ceiling) compared to existing - lightweight construction
Insertion loss (av. level differer
1/3-octaveband frequency [Hz]
G
L2
L3
L2: As G plus indep.ceililng w/ 3 gypsumplates
L3: As G plus indep.ceiling w/1 gypsumplate
G: Existing roof and window
Number of plates is important (3 better than 1 layer)
ACOUSTIC DAY DTU-WIND 17. MAY 2018
13
2018-05-18

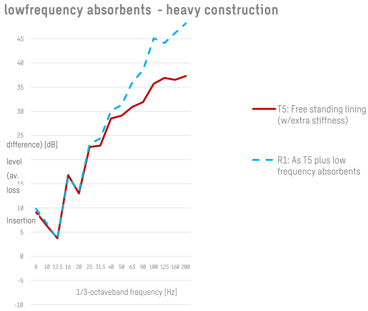

SWECO
Detailed results – TAKE CARE on open windows
Effect of partly open window - lightweight construction
Insertion loss (av. level difference) [dB]
1/3-octaveband frequency [Hz]
I: Window 5 cm open
G: Existing conditions
ACOUSTIC DAY DTU-WIND 17. MAY 2018
14
2018-05-18

SWECO

Experiments - room acoustics

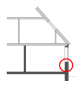


Effect lowfrequency absorbents - heavy construction

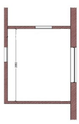


SWECO

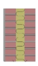
Indoors windturbine-noise – *heavy* facade



Exisiting building



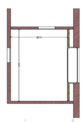
A



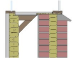
	$L_{pA,LF}$	$L_{pA,total}$
A	*13 dB*	*21 dB*

OK re. $L_{pA,LF}$ - threshold limiting value: 20 dB

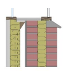
Lining and – heavy window



B

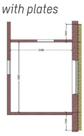


D

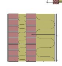


	$L_{pA,LF}$	$L_{pA,total}$
B	*2 dB*	*5 dB*
D	*3 dB*	*5 dB*

Outdoor facade insulation with plates



E

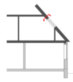


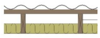
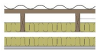
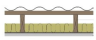
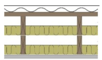
	$L_{pA,LF}$	$L_{pA,total}$
E	*7 dB*	*8 dB*

(calculated with indoor heavy, removeable window)

SWECO

Indoor Wind Turbine noise - *lightweight* ”facade”



		$L_{pA,LF}$	$L_{pA,total}$	
G		20 dB	24 dB	Just OK re. $L_{pA,LF}$ - threshold limiting value: 20 dB
K		13 dB	14 dB	
J		15 dB	16 dB	
H		15 dB	15 dB	

(calculated with indoor heavy, removeable window)

SWECO

Perspectives/future work
LF-soound insulation

Technical:
More analysis in normal and enhanced frequency area (25/50/100-3150 Hz)

”New” $C_{WT,50-3150}$ – adaption term
(evt. $C_{WT,25-3150}$)
WT = WindTurbine

Purpose:
Simpel calculation of A-weighted indoor windturbine noise
$L_{A,indoor}=L_{A,outdoor}-(R'_{w}+C_{WT,50-3150})+10*\log(S/A)$

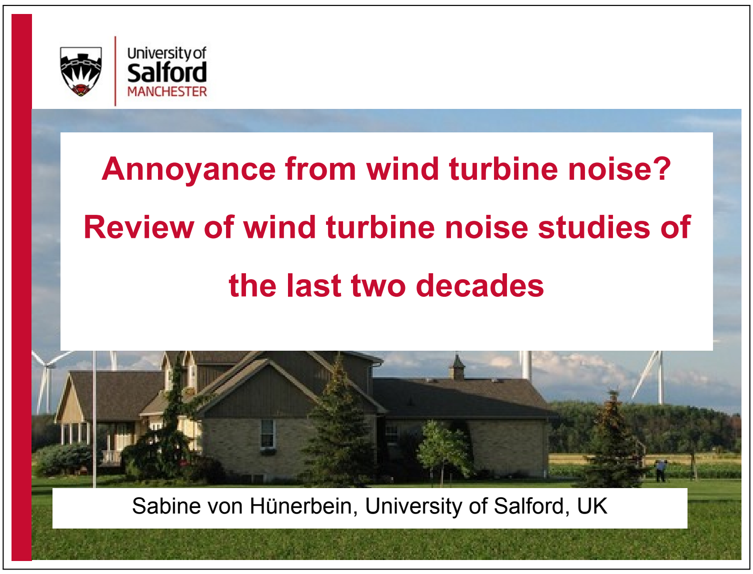
Perhaps economical subsidies to LF-facadeinsulation of houses
– á la road- and railway noise

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:



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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?

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Annoyance definition

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

Guski, Schreckenberg, & Schuemer, 2017
https://www.sciencesquared.eu/news/traffic-noise-more-merely-annoying-it-cause-serious-ill-health

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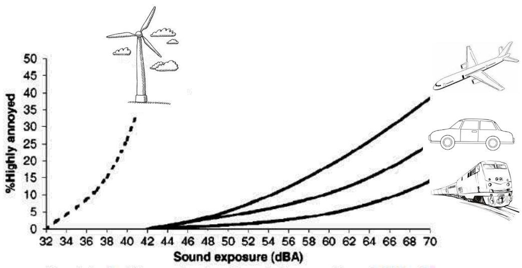
Dose-response for wind turbine noise?



Reprinted with permission from Pedersen, E. and K.P. Waye (2004). Perception and annoyance due to wind turbine noise—a dose-response relationship. The Journal of the Acoustical Society of America 116: 3460. Copyright 2004, Acoustical Society of America.

http://randacoustics.com/wind-turbine-sound/annoyance/

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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

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Common outcome measures

% HA: Highly Annoyed

5 Very annoyed

4 Very
5 Extremely

% A: Annoyed

3 Slightly annoyed
4 Rather annoyed
5 Very annoyed

2 Slightly
3 Moderately
4 Very
5 Extremely

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

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Dose-response studies

Pedersen 2004
Sweden,
N = 351

Pedersen 2007
Sweden,
N = 751

Pedersen *et al.* 2009
NL, N = 725

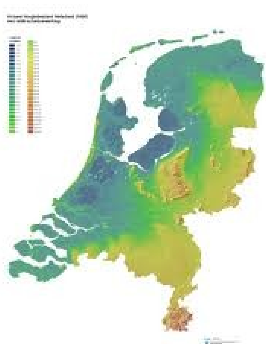
Kuwano 2014
Japan, N =
651 (332)

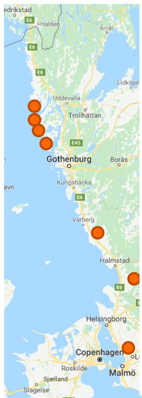
Michaud *et al.*, 2016
Canada, N = 1238

China,
N = 227
Song, 2016

N & pane size = participant no, colour code dominant terrain type

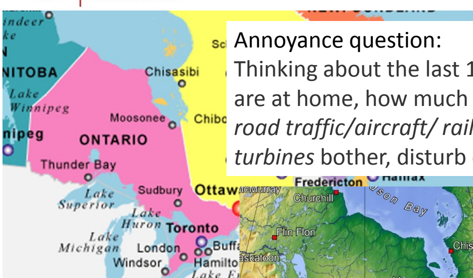
Sweden 2000/2005, NL





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



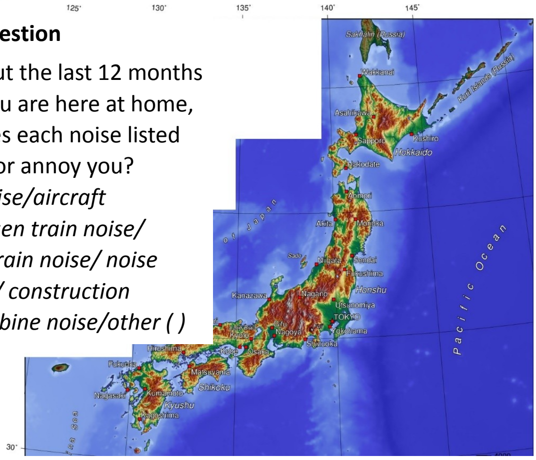
Annoyance question:
Thinking about the last 12 months, when you are at home, how much does noise from *road traffic/aircraft/ railways or trains/wind turbines* bother, disturb or annoy you?

Japan

Annoyance question

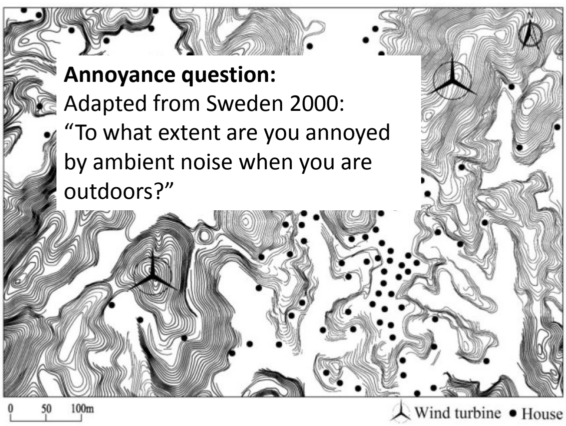
"Thinking about the last 12 months or so, when you are here at home, how much does each noise listed below bother or annoy you?

road traffic noise/aircraft noise/shinkansen train noise/ conventional train noise/ noise from factories/ construction noise/wind turbine noise/other ( )

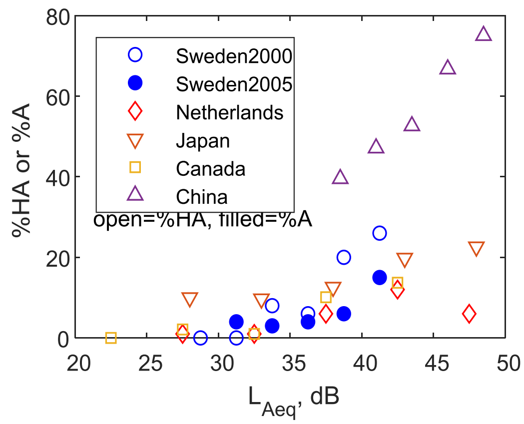


China, 2015

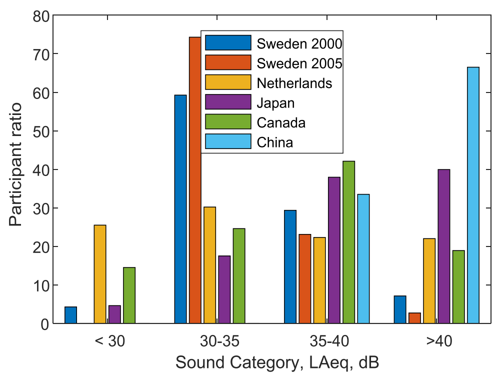
Annoyance question:
Adapted from Sweden 2000:
"To what extent are you annoyed by ambient noise when you are outdoors?"



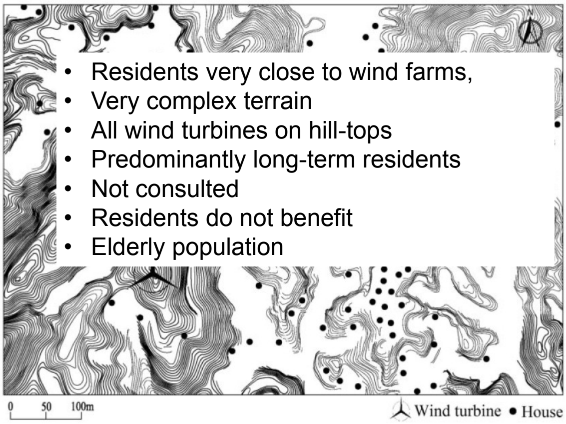
Study comparison



Percentage of participants in exposure categories

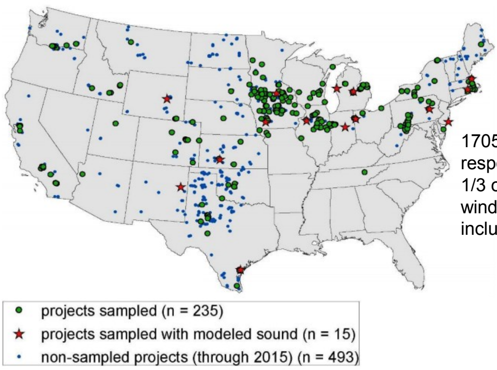


China, 2015



- 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

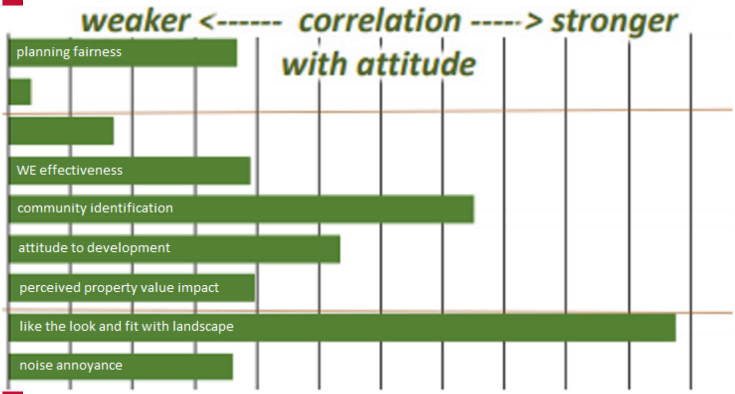
Hoen, B., J. Firestone, J. Rand, D. Elliott, G. Hübner, J. Pohl, R. Wiser, E. Lantz (2018) Overall Analysis of Attitudes of 1,705 Wind Power Project Neighbors. Lawrence Berkeley National Laboratory. Preliminary Results Webinar. January 30, 2018.

US study focus

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



Hoen, B., J. Firestone, J. Rand, D. Elliott, G. Hübner, J. Pohl, R. Wiser, E. Lantz (2018) Overall Analysis of Attitudes of 1,705 Wind Power Project Neighbors. Lawrence Berkeley National Laboratory. Preliminary Results Webinar. January 30, 2018.

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

Danish Wind Turbines in Copenhagen Harbour. Image credit: CGP Grey.
http://reversehomesickness.com/europe/wind-turbines-in-denmark/ | Europe | Pinterest

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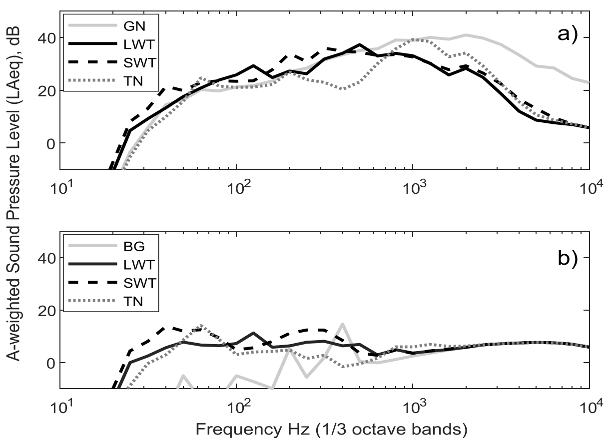
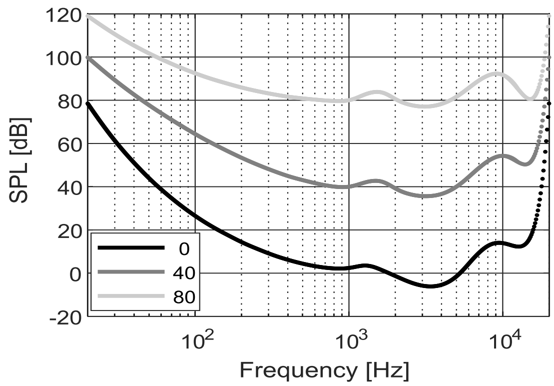
Comparative Spectra



Equal loudness contours



5 Session #2
#1 Continued & Industry Perspectives

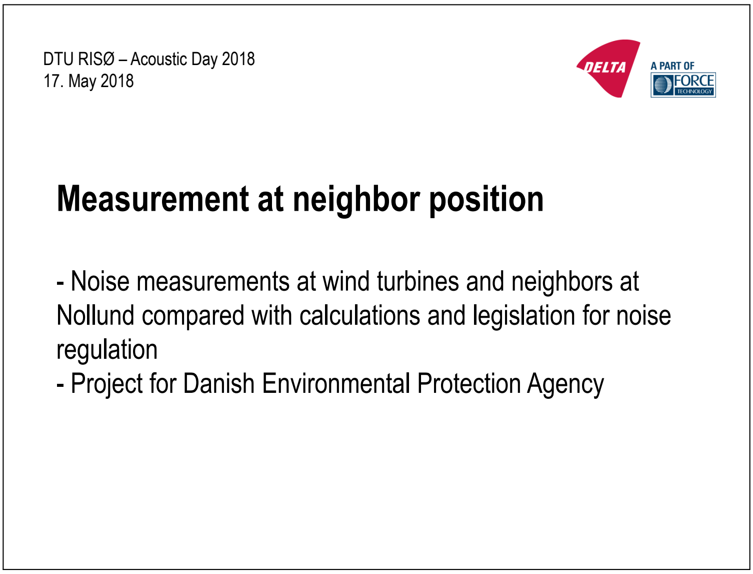
This session is dedicated to wind turbine manufacturers and their activities concerning noise issues for their products. Note that the first presentation by Lars Søndergaard belongs to the topics of Session #1.

5.1 Measurement at neighbor position

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

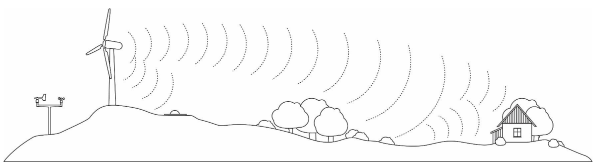
Abstract:
Project for the Danish EPA to investigate whether the current guidelines for measurement of noise emission and noise propagation calculation from wind turbines described in the Danish Statutory Order give an accurate noise contribution at residents and to make measurements under conditions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

Slides:



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?)*

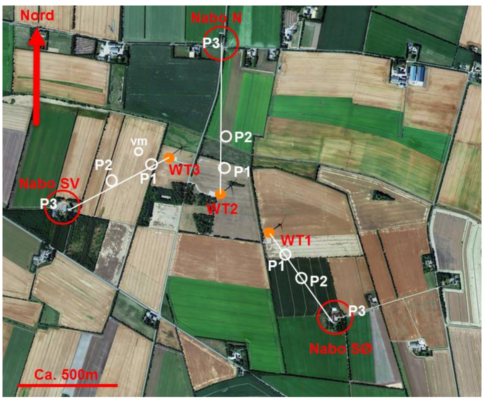
Strategy

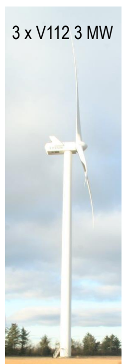
- *Site and neighbors chosen and contacted by Danish EPA*
- *Neighbors offered to be relocated for a time period*

- *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



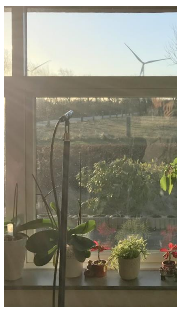


Neighbor to southeast, WT1 P3

Neighbor to north, WT2 P3

Neighbor to southwest, WT3 P3

Large amount of synchronized equipment



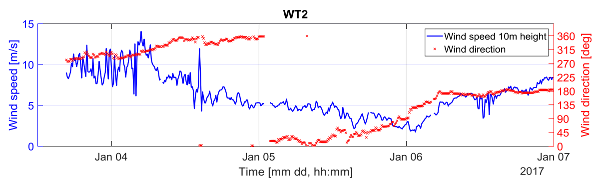
x 6 + x 3 + x 6 + x 3

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

Challenges

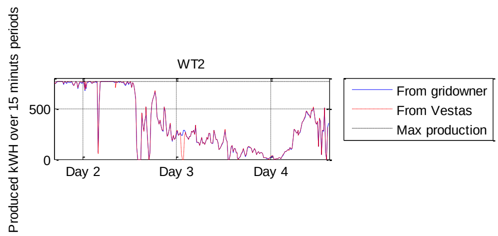
- *Arrangements – coordination of*
  - *equipment*
  - *weather*
  - *manpower*
  - *access (neighbours)*
- *Large amount of equipment*
  - *Calibration*
  - *Insurance*
- *Desire to measure over multiple continues days*
  - *No rain*
  - *Many different wind speeds*
  - *Many different wind directions*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

Weather during the measurements

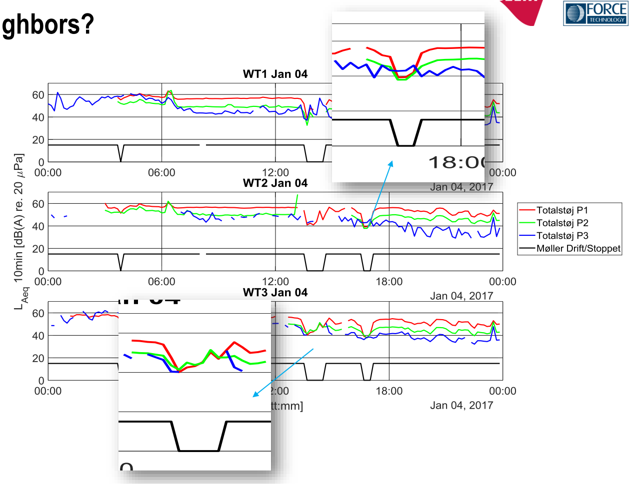


Date	Temperature	Humidity	Cloud cover	Air pressure
8. december 2016	8 to 11 °C	85 - 99 %	2/8 - 8/8	1016 - 1017 hPa
3. januar 2017	3 - 7 °C	70 - 80 %	4/8 - 8/8	990 - 1000 hPa
4. januar 2017	-3 - 5 °C	50 - 85 %	0/8 - 7/8	990 - 1020 hPa
5. januar 2017	-10 - -3 °C	57 - 92 %	0/8 - 6/8	1020 - 1040hPa
6. januar 2017	-12 - -5 °C	80 - 90 %	0/8 - 8/8	1030 - 1040 hPa

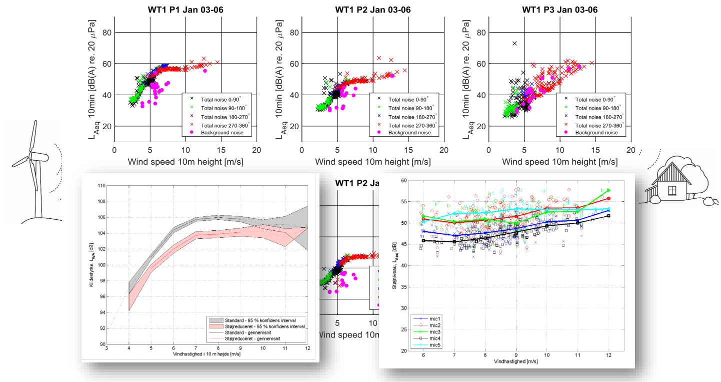
Control of turbine load



Can wind turbine noise be measured at neighbors?



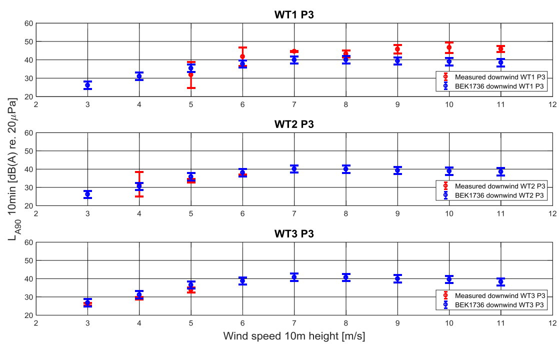
Can wind turbine noise be measured at neighbors?



https://www2.mst.dk/Udgiv/publikationer/2016/04/978-87-93435-66-7.pdf

http://referencelaboratoriet.dk/filer/metodeliste/2015_Rapport_nr28_Toneindhold_i_vindmoellestoej_hos_naboer_RL17-15.pdf

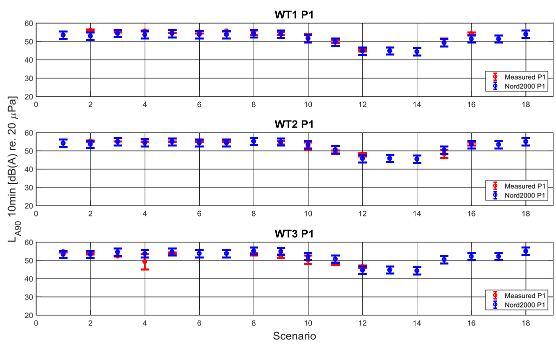
Measurements compared to calculations, BEK 1736



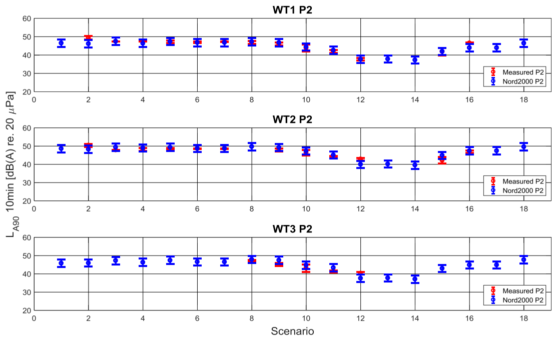
Nord2000 scenarios

Scenario	1	2	3	4	5	6	7	8	9
Cloud cover [1/8]	6	1	1	3	4	7	6	6	0
Wind speed 10m [m/s]	9.6	10.8	8.4	8.6	8.4	8.8	8.7	7.2	7.0
Wind dir. [deg.]	294	311	329	222	355	349	345	348	346
Temperature [deg.]	5	5	4	4	4	4	4	4	-1
Humidity [%]	70	74	70	68	69	69	69	73	55
Scenario	10	11	12	13	14	15	16	17	18
Cloud cover [1/8]	0	1	5	5	0	0	0	0	8
Wind speed 10m [m/s]	6.4	5.3	4.3	3.9	4.0	5.4	6.1	6.3	6.6
Wind dir. [deg.]	355	358	20	14	48	179	171	170	175
Temperature [deg.]	-2	-3	-5	-5	-6	-8	-7	-4	-3
Humidity [%]	63	93	73	85	56	87	80	68	70

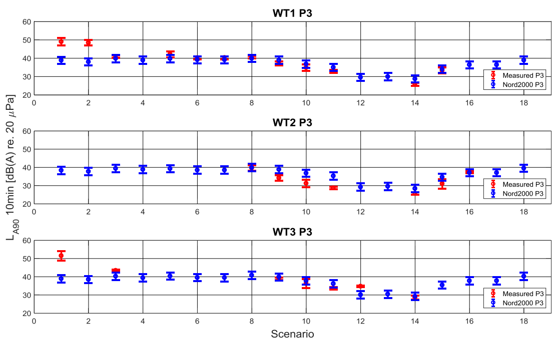
Measurements compared to calculations, BEK 1736



Measurements compared to calculations, BEK 1736

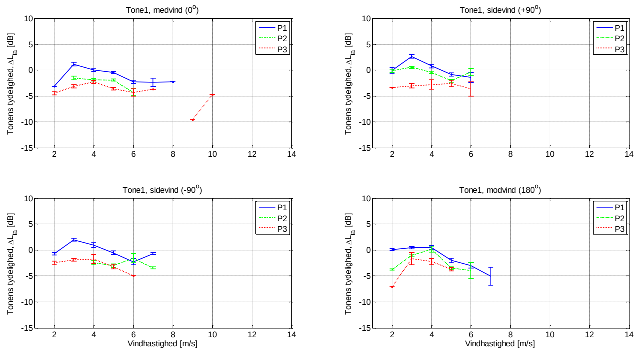


Measurements compared to calculations, BEK 1736



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:


Wind turbine noise at neighbor dwellings, comparing calculations and measurements

https://www2.mst.dk/Udgiv/publikationer/2017/11/978-87-93614-35-2.pdf

http://assets.madebydelta.com/docs/share/Akustik/Wind_turbine_noise_at_neighbor_dwellings%2C_comparing_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

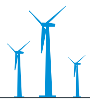
4. Conclusion

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

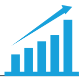


+38,892

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

Vestas.

Versatile solutions for any wind energy project

Ongoing innovation from the undisputed global wind leader

	2 MW PLATFORM					4 MW PLATFORM							
PRODUCT-CAPACITY	V90-2.0 MW®	V100-2.0 MW®	V110-2.0 MW®	V116 2.0 MW™	V120 2.0 MW™	V105-3.45 MW™	V112-3.45 MW™**	V117-3.45 MW™	V117-4.2 MW™	V126-3.45 MW™	V136-3.45 MW™	V136-4.2 MW™	V150-4.2 MW™
YEAR OF PROTOTYPE	2004	2009	2014	2017	2018	2014	2013	2013	2018	2013	2016	2018	2018
	Installed* 40 GW					Installed** 17 GW							

* 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.

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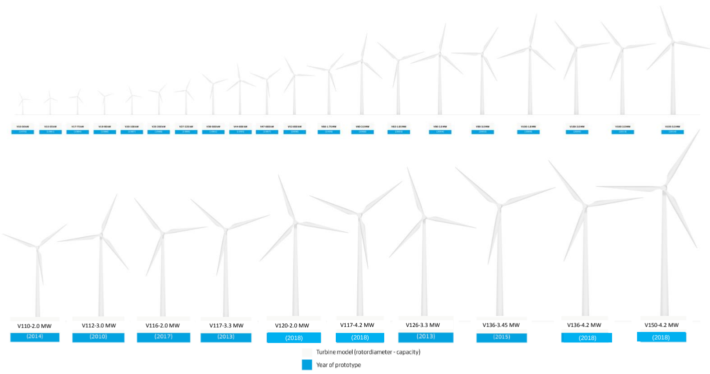
Technology strategy and solutions

Technology evolution



6 Corporate Slide Deck Q4/2017 (Public) 16/05/2018 **Wind.** It means the world to us.™

Innovating to lower the cost of energy

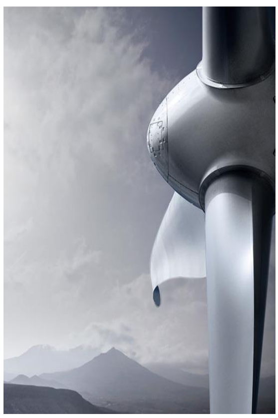
Delivering value every step of the way

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

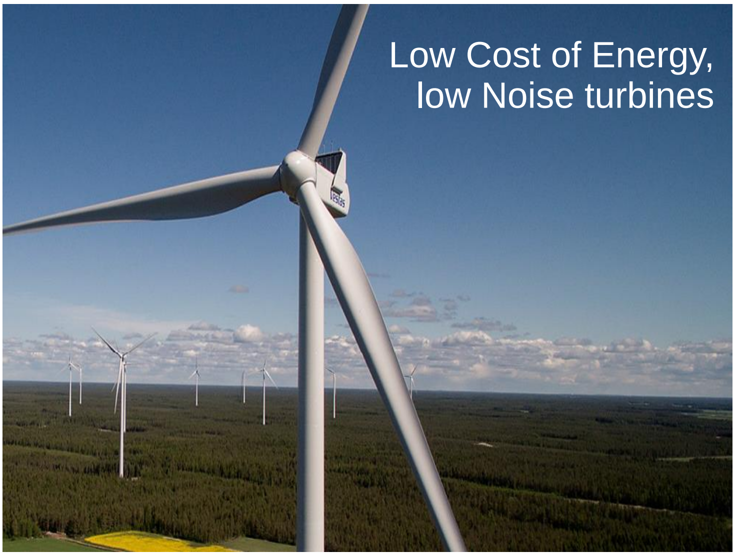
Custom configurations based on modularised building blocks.

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.

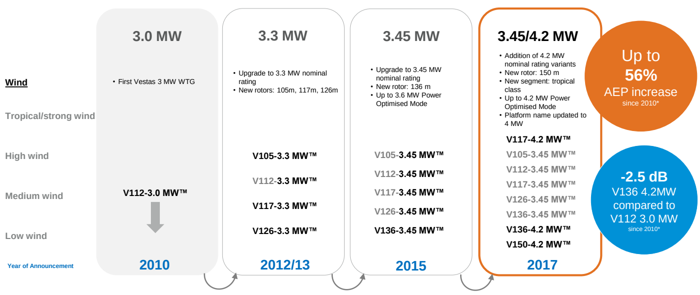


7 16/05/2018 **Wind.** It means the world to us.™



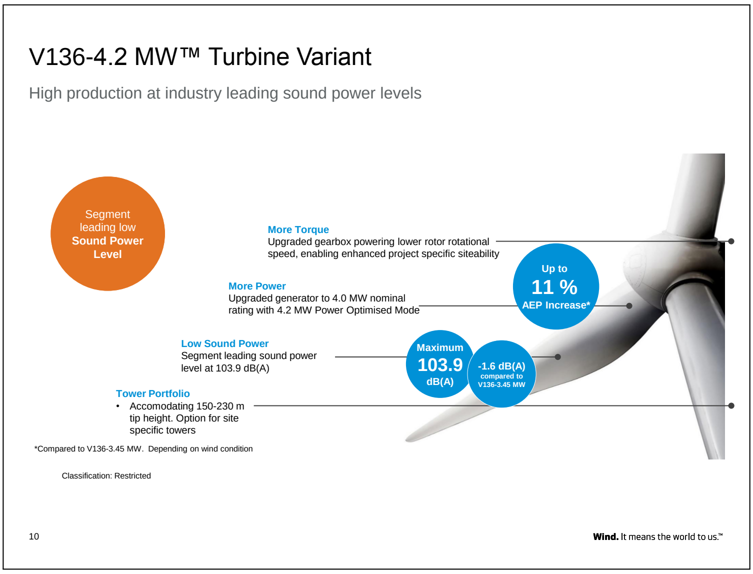
Controlled unfolding of 4 MW platform potential

More annual energy production from same trusted platform



Announced Q2/2017

9 Corporate Slide Deck Q4/2017 (Public)


V136-4.2 MW™ Turbine Variant
High production at industry leading sound power levels
Segment leading low Sound Power Level
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
Up to 11 % AEP Increase*
Low Sound Power
Segment leading sound power level at 103.9 dB(A)
Maximum 103.9 dB(A)
-1.6 dB(A) compared to V136-3.45 MW
Tower Portfolio
• Accomodating 150-230 m tip height. Option for site specific towers
*Compared to V136-3.45 MW. Depending on wind condition
Classification: Restricted
10
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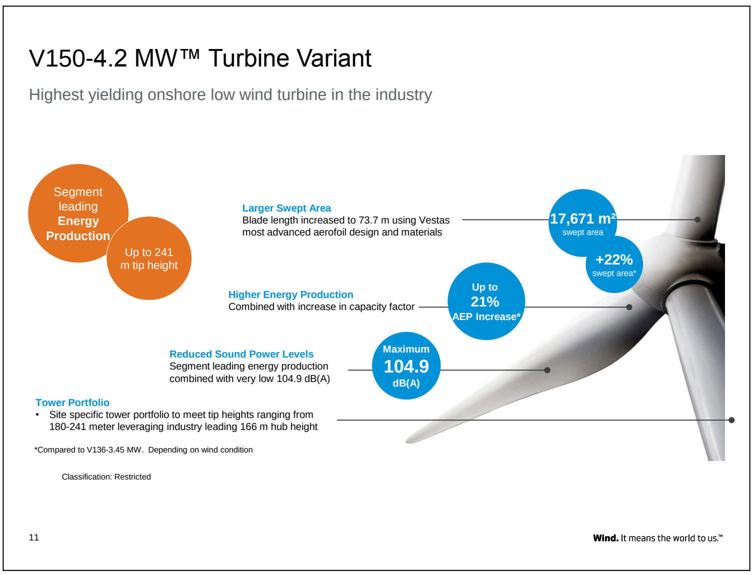
V150-4.2 MW™ Turbine Variant
Highest yielding onshore low wind turbine in the industry
Segment leading Energy Production
Up to 241 m tip height
Larger Swept Area
Blade length increased to 73.7 m using Vestas most advanced aerofoil design and materials
17,671 m² swept area
+22% swept area*
Higher Energy Production
Combined with increase in capacity factor
Up to 21% AEP Increase*
Reduced Sound Power Levels
Segment leading energy production combined with very low 104.9 dB(A)
Maximum 104.9 dB(A)
Tower Portfolio
• Site specific tower portfolio to meet tip heights ranging from 180-241 meter leveraging industry leading 166 m hub height
*Compared to V136-3.45 MW. Depending on wind condition
Classification: Restricted
11
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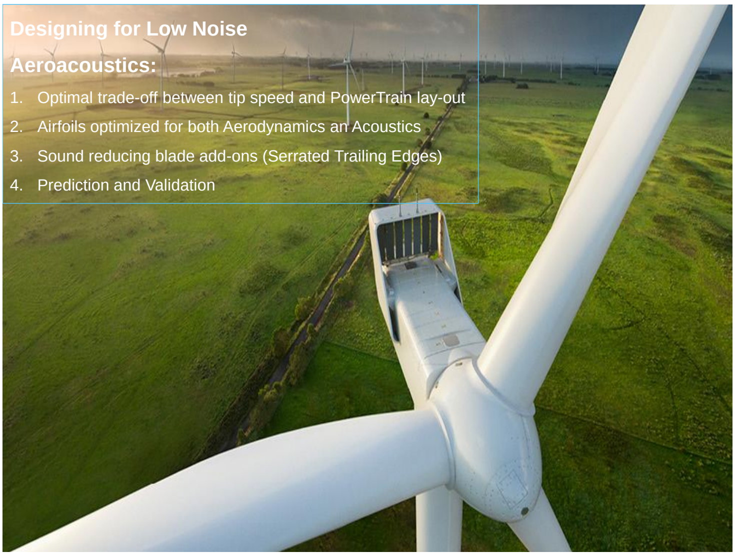
Designing for Low Noise



Aeroacoustics:

1. Optimal trade-off between tip speed and PowerTrain lay-out
2. Airfoils optimized for both Aerodynamics an Acoustics
3. Sound reducing blade add-ons (Serrated Trailing Edges)
4. Prediction and Validation

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

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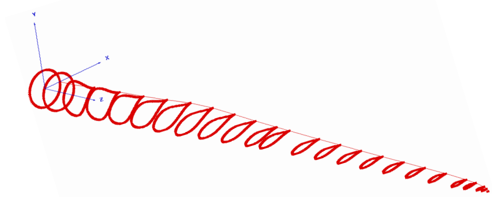
2. Rotor Design for Aerodynamic Noise Performance

- Blade shape design by gradient based optimizer:



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

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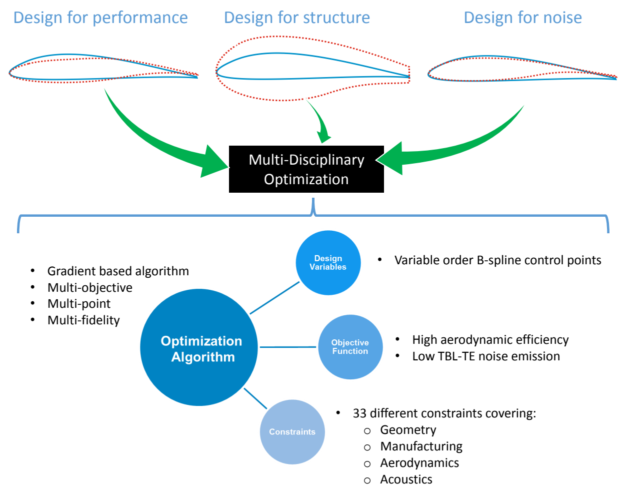
2. Rotor Design for Aerodynamic Noise Performance



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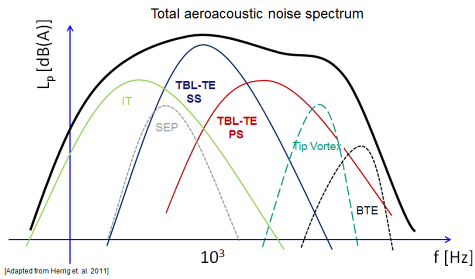
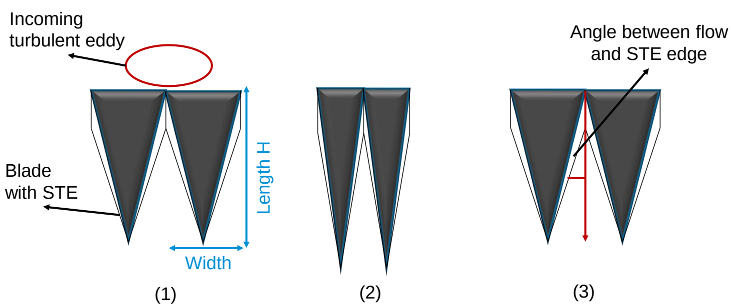
3. Serrations for Reduction of Trailing Edge Noise

Typical wind turbine noise spectrum, without mechanical 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

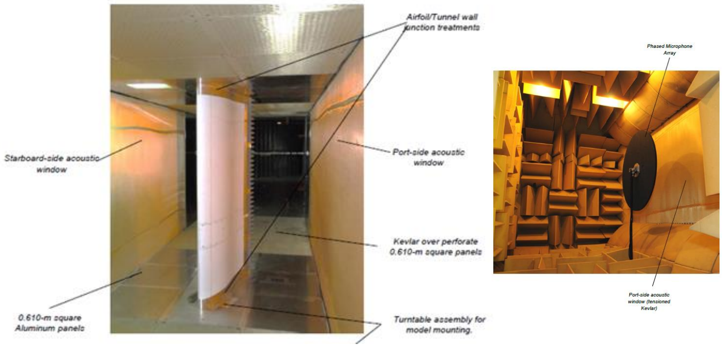


1. Serration dimensions **H** to local turbulence scale ratio (Howe: H~BL thickness, St=w h/Uc>>1)
2. Serration length **H** to width **\lambda** ratio and (Howe: H/\lambda > 1)
3. The angle between local flow direction and serration edge (Howe: **\phi** < 45deg)

[1] M. S. Howe, "Sawtooth trailing edge noise", J. Acoust. Soc. Am., Vol. 90, No.1 ,July 1991
[2] M. S. Howe, "Aerodynamic noise of a serrated trailing edge," J. Fluids Struct. 5, 33-45 (1991).

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%

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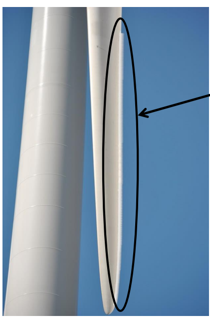
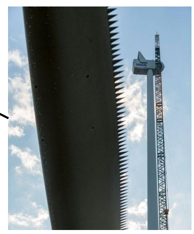
Full scale wind turbine validation

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



Serration prototypes have been installed on various Vestas turbines



Vestas FB page, V136

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

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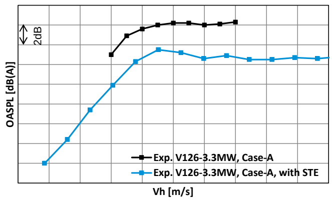
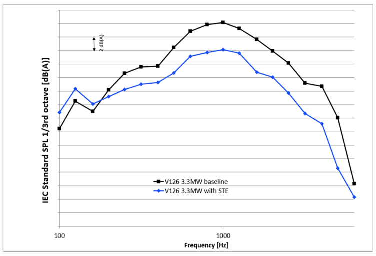
STE Noise Reduction Performance Gen 1: V126 3.3 MW



- More than 2dB(A) reduction were found with first design iteration

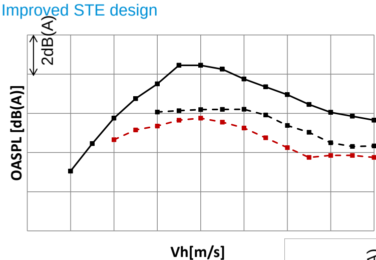
- Efficient reduction at peak frequency by 4 dB(A)



20

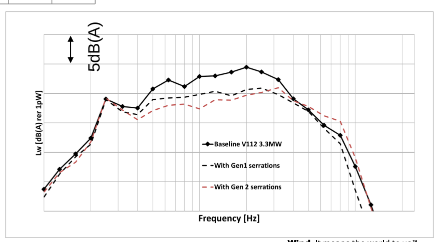
STE Noise Reduction Performance Gen 2: V112-3.3MW

Improved STE design



- -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



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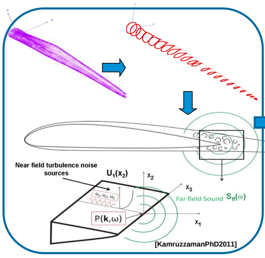
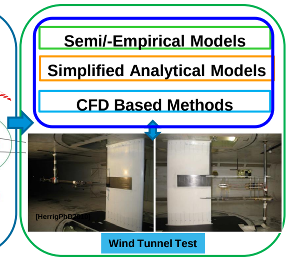
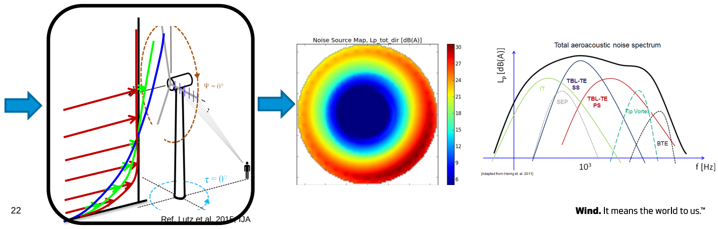
4. Aeroacoustic Prediction and Validation





Coupling of Aerodynamic tools to noise prediction tools

- **Airfoil level**
- **Rotor level**



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Rotor Noise Simulation: Validation & Assessment

Case #	Turbine	Rotor Diameter [m]	Hub height, [m]	Wind Class & Other Info
A	V126-3.3MW	126m	116m	IEC 3A
B	V112-3.3MW	112m	116m	IEC 2B
C	V136-3.45MW	136m	116m	IEC 2A

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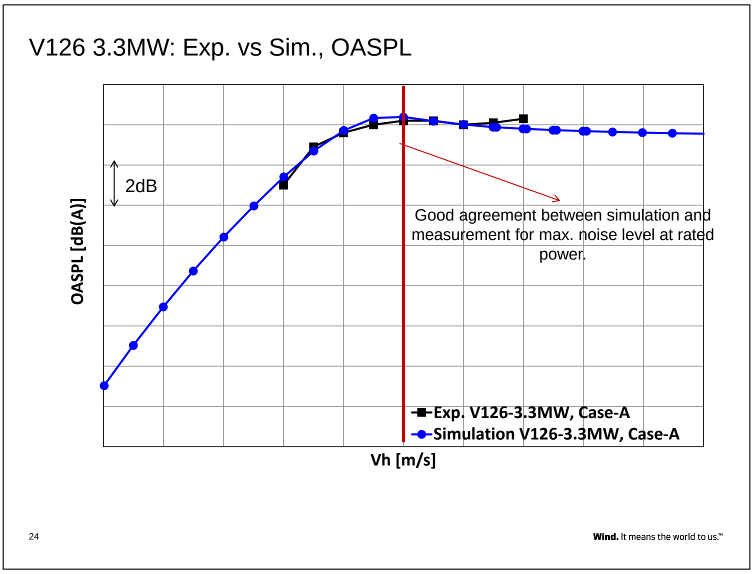
V126 3.3MW: Exp. vs Sim., OASPL
2dB
OASPL [dB(A)]
Good agreement between simulation and measurement for max. noise level at rated power.
Exp. V126-3.3MW, Case-A
Simulation V126-3.3MW, Case-A
Vh [m/s]
24
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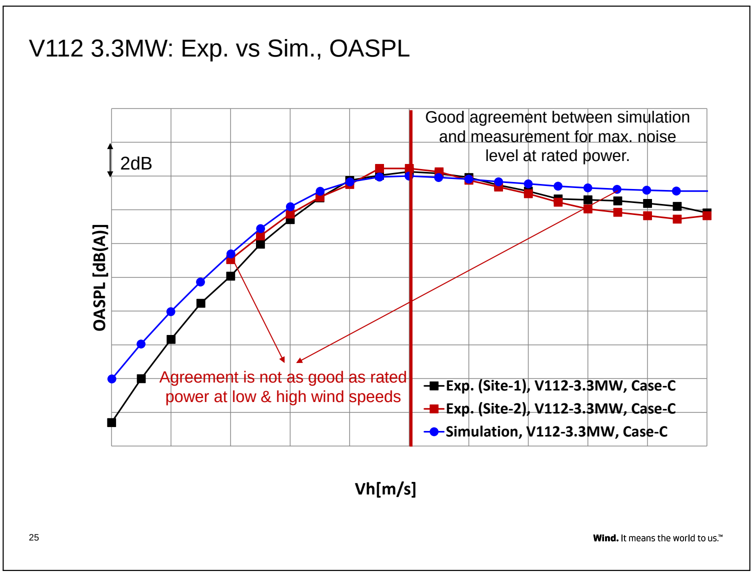
V112 3.3MW: Exp. vs Sim., OASPL
Good agreement between simulation and measurement for max. noise level at rated power.
2dB
OASPL [dB(A)]
Agreement is not as good as rated power at low & high wind speeds
Exp. (Site-1), V112-3.3MW, Case-C
Exp. (Site-2), V112-3.3MW, Case-C
Simulation, V112-3.3MW, Case-C
Vh[m/s]
25
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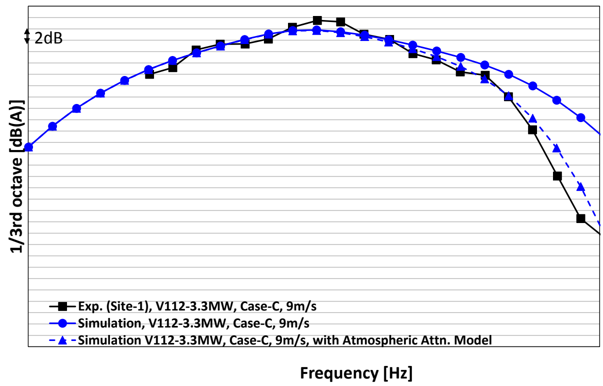
V112 3.3MW: Exp. vs Sim., Noise Spectra



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

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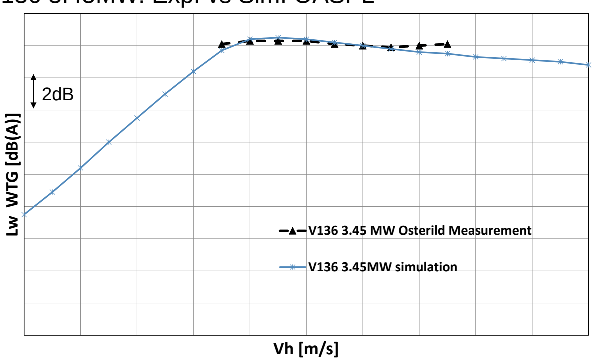
V136 3.45MW: Exp. vs Sim. OASPL



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

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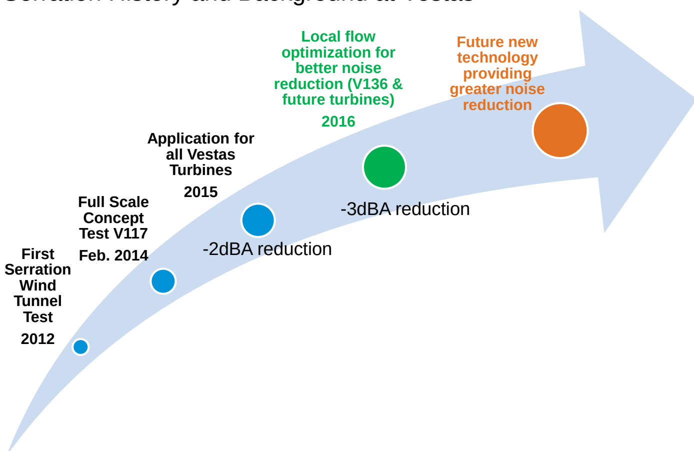
Serration History and Background at Vestas



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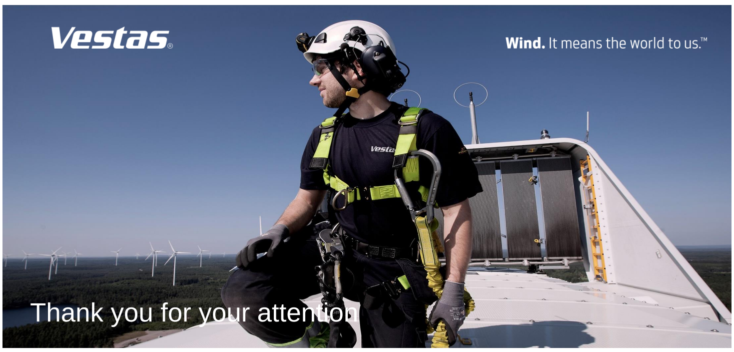
Conclusion

- 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 an 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 SiemensGamesa 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 SiemensGamesa

Tomas R. Hansen, 17.05.2018

SIEMENS Gamesa RENEWABLE ENERGY

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

Tomas R. Hansen, 17.05.2018

SIEMENS Gamesa RENEWABLE ENERGY

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 dB

Tomas R. Hansen, 17.05.2018

SIEMENS Gamesa RENEWABLE ENERGY

Air absorption and frequency spectrum – example

Due to air absorption the positive influence of the changed shape of the spectrum increases with increasing distanced 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, $L_{p,A}$: -2.4 dB
- 1000 m, $L_{p,A}$: -3.0 dB
- 2000 m, $L_{p,A}$: -3.8 dB

We do have two examples in DK where the costumer 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!

Tomas R. Hansen, 17.05.2018

SIEMENS Gamesa RENEWABLE ENERGY

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

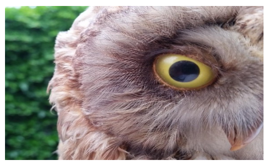
Can we do even better than DinoTails?

- Yes we can ☺

Tomas R. Hansen, 17.05.2018

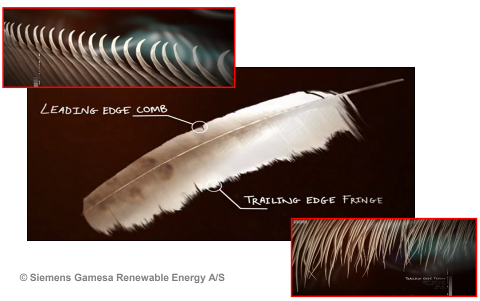
SIEMENS Gamesa RENEWABLE ENERGY

DinoTail Next Generation

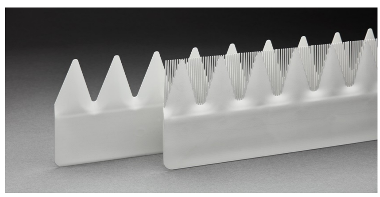


Inspiration from the silent flight of the owl

- Owls fly much quieter than other birds
- Low-noise wing technology
- Can we apply this to wind turbine blades?



New concept: combed teeth



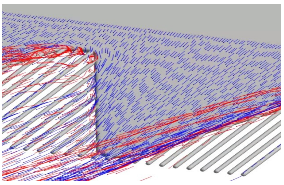
Tomas R. Hansen, 17.05.2018

SIEMENS Gamesa RENEWABLE ENERGY

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



Tomas R. Hansen, 17.05.2018

SIEMENS Gamesa RENEWABLE ENERGY

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

Tomas R. Hansen, 17.05.2018

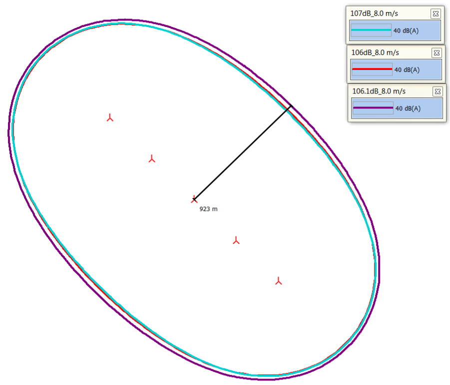
SIEMENS Gamesa RENEWABLE ENERGY

Comparison of noise spectra of 3 modern turbines

Results

- 5 turbines in a row
- noise limit 40 dB (Sweden)
- Spectra <u>not</u> normalized to equal level

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



Tomas R. Hansen, 17.05.2018

SIEMENS Gamesa RENEWABLE ENERGY

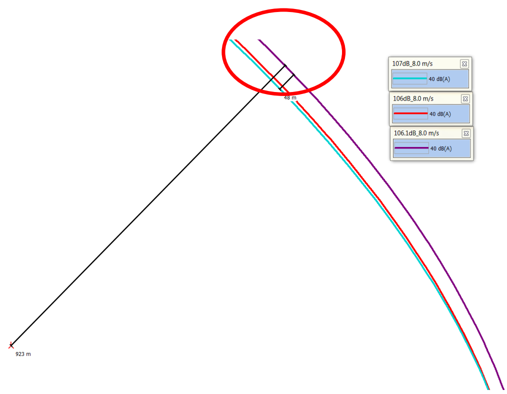
Comparison of noise spectra of 3 modern turbines

Results

- 5 turbines in a row
- noise limit 40 dB (Sweden)
- Spectra <u>not</u> 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



Tomas R. Hansen, 17.05.2018

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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

Tomas R. Hansen, 17.05.2018

SIEMENS Gamesa RENEWABLE ENERGY

Our mission:

We make real what matters – Clean energy for generations to come

Tomas R. Hansen, 17.05.2018

SIEMENS Gamesa RENEWABLE ENERGY

Contact

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System Owner Noise /
Section Head Load&Control

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tomas.hansen@siemensgamesa.com

Thanks

17 May 2018

Tomas R. Hansen, 17.05.2018

SIEMENS Gamesa
RENEWABLE ENERGY

6 Session #3
Recent Research Advancements

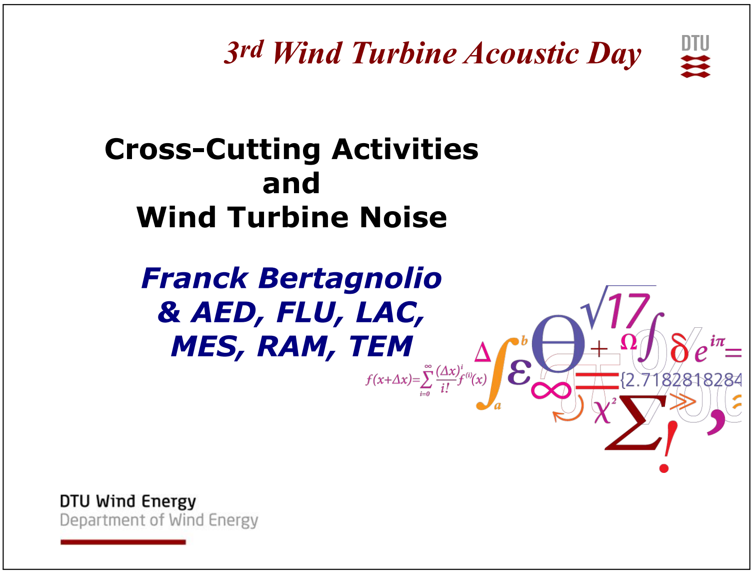
This session is dedicated to research efforts currently undertaken at DTU Wind Energy related to wind turbine noise. This efforts span from wind tunnel and field measurements to modelling of aerodynamic noise sources and sound propagation.

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:

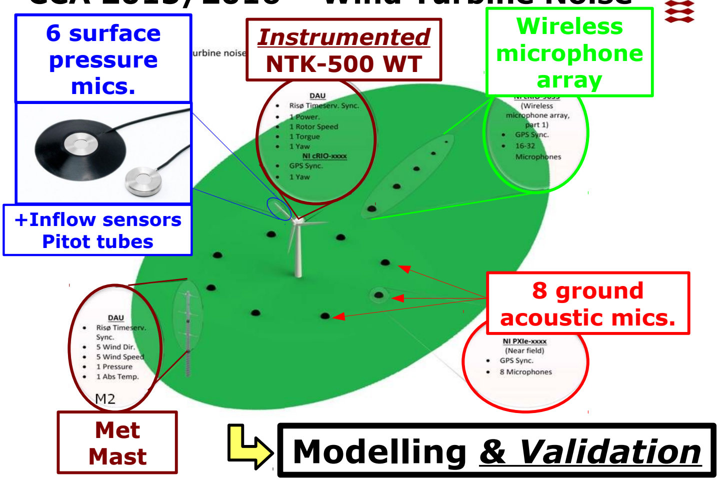


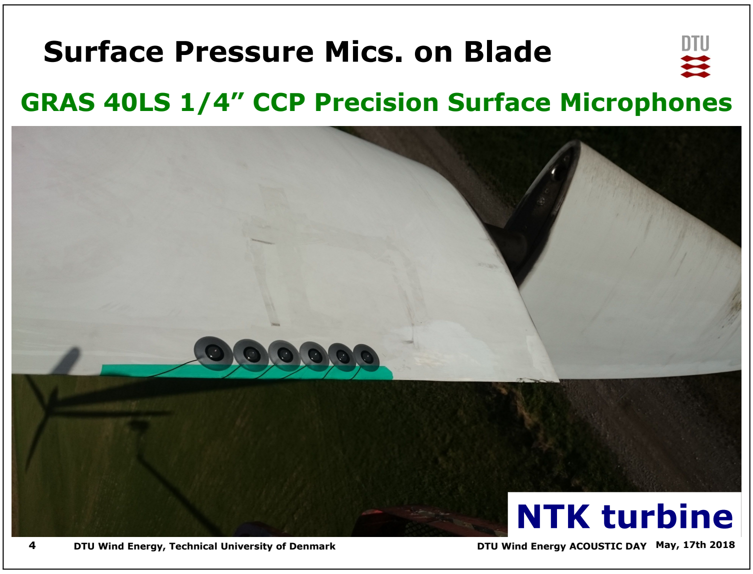
Outline

- **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




Surface Pressure Mics. on Blade
DTU
GRAS 40LS 1/4” CCP Precision Surface Microphones
NTK turbine
4
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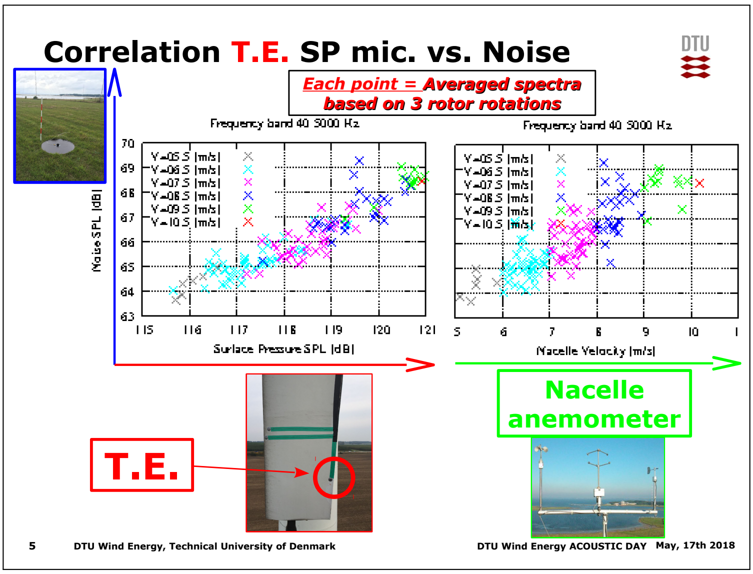
DTU Wind Energy ACOUSTIC DAY
May, 17th 2018


Correlation T.E. SP mic. vs. Noise
DTU
Each point = Averaged spectra
based on 3 rotor rotations
Frequency band 40 5000 Hz
Noise SPL [dB]
Surface Pressure SPL [dB]
Nacelle Velocity [m/s]
Nacelle anemometer
T.E.
5
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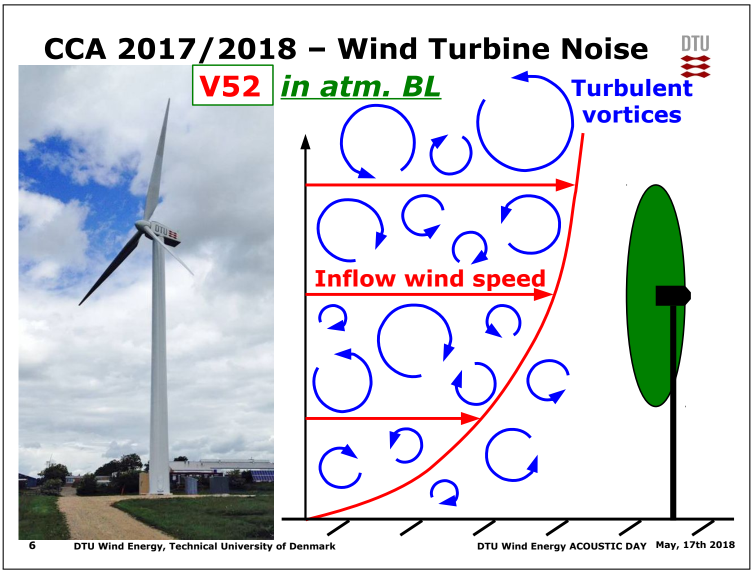
CCA 2017/2018 – Wind Turbine Noise
V52
in atm. BL
Turbulent vortices
Inflow wind speed
6
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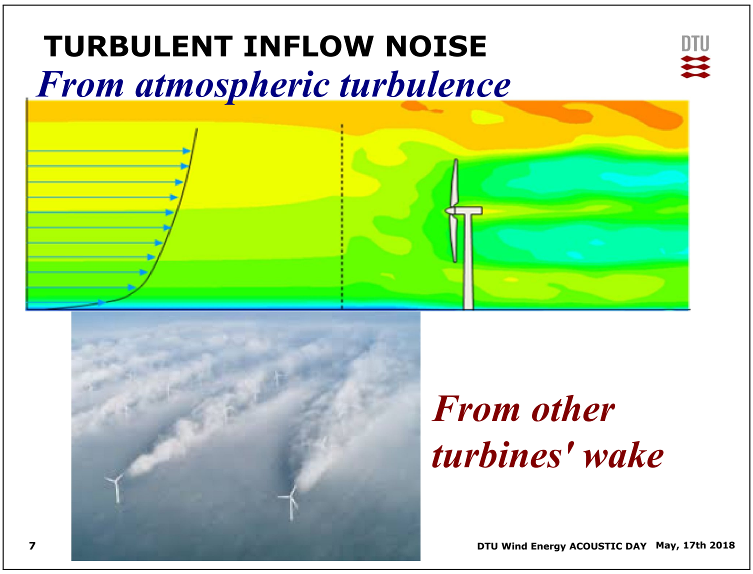
TURBULENT INFLOW NOISE
From atmospheric turbulence
From other turbines' wake
7
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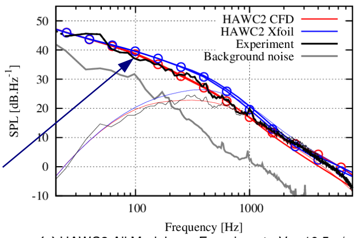
Turb. Inflow NOISE

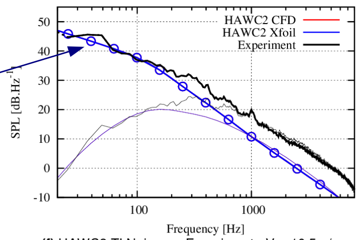
NTK meas. vs. model:

All noise sources

TI noise only



(e) HAWC2 All Models vs. Experiment - V_N=10.5m/s



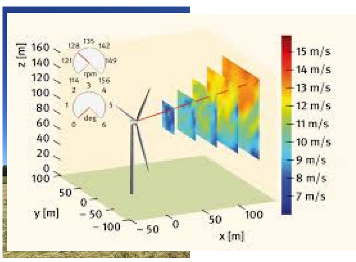
(f) HAWC2 TI Noise vs. Experiment - V_N=10.5m/s

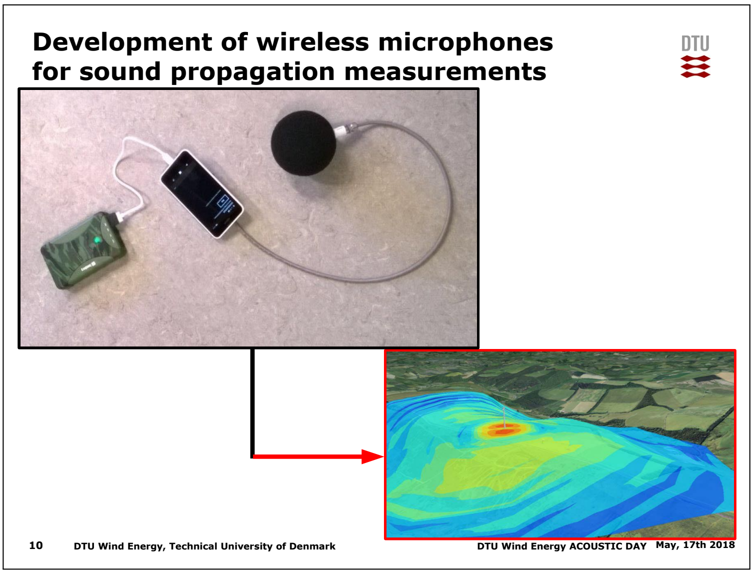
Using sensors and measurements from various other activities within CCA 2018

DTU

High-Frequency Pitot tube

Use LIDAR data from parallel experiments




Development of wireless microphones
for sound propagation measurements
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10
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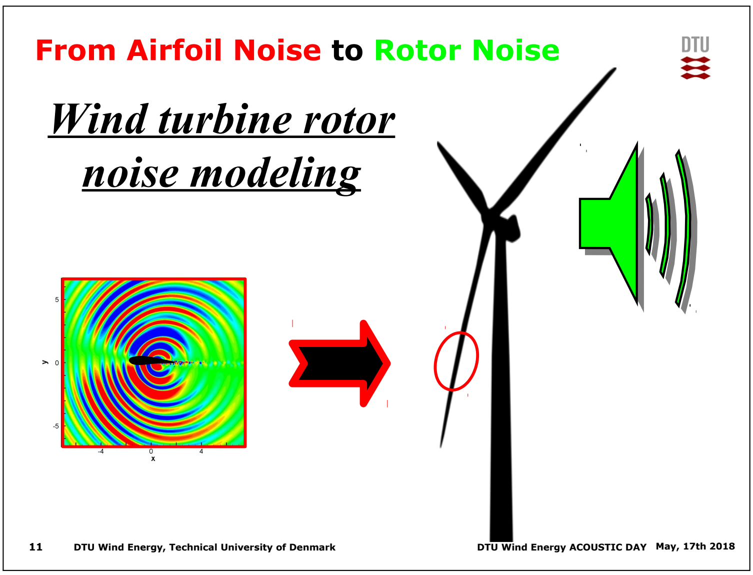
From Airfoil Noise to Rotor Noise
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Wind turbine rotor
noise modeling
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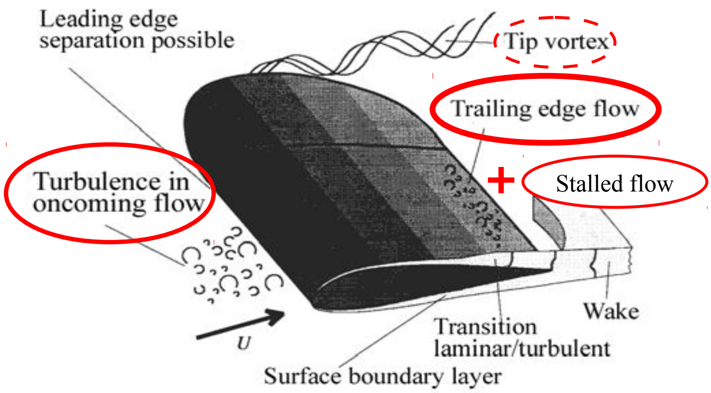
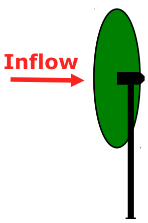
Wind Turbine Noise Sources

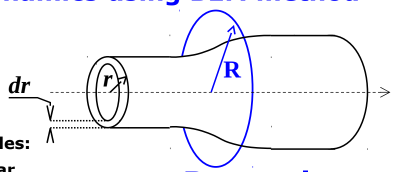
Main wind turbine aeroacoustic noise mechanisms



Rotor Aerodynamic & Noise Model



Aerodynamics using BEM method



The model includes:

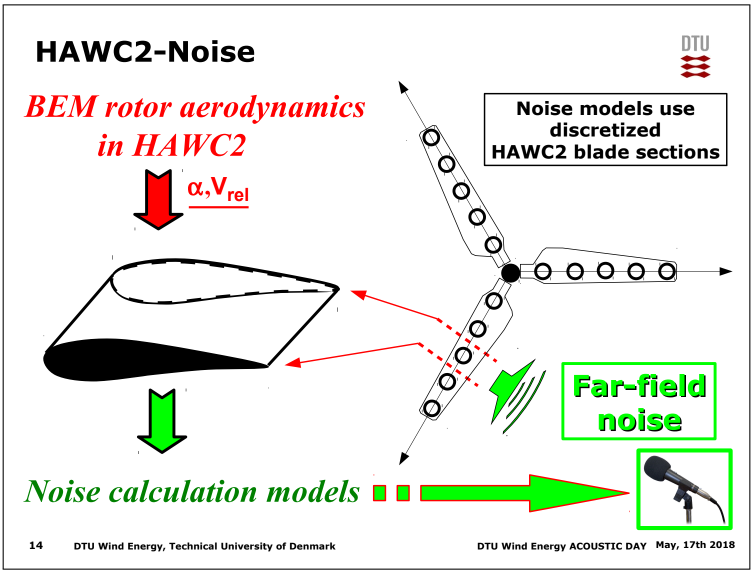
- Wind shear
- Yaw
- Tilt/Coning
- Blade geometry (+ twist & pitch)
- Turbulent inflow
- Tower flow deficit/perturbation (inviscid)

Noise modeling in spectral domain:

- Trailing Edge Noise
- Turbulent Inflow noise
- Stall noise

Integrated along the blade span

Noise modeling in time domain....


HAWC2-Noise
DTU
BEM rotor aerodynamics in HAWC2
α,Vrel
Noise models use discretized HAWC2 blade sections
Far-field noise
Noise calculation models
14
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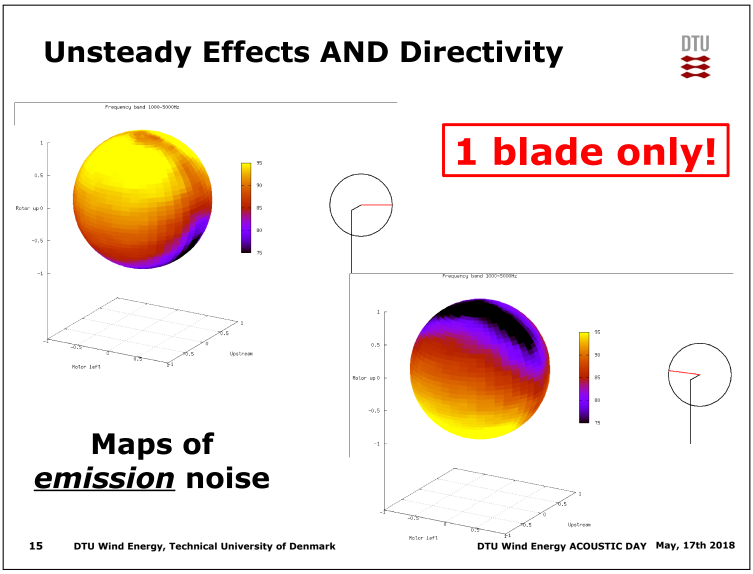
Unsteady Effects AND Directivity
DTU
1 blade only!
Maps of emission noise
15
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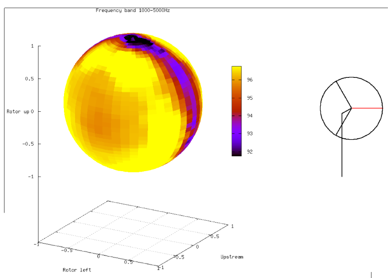
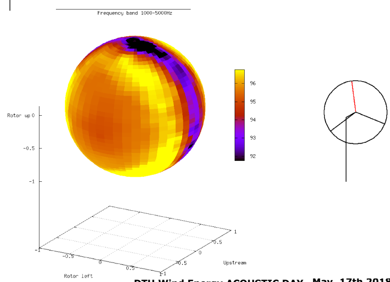
Unsteady Effects AND Directivity



3 blades!



Maps of
***emission* noise**

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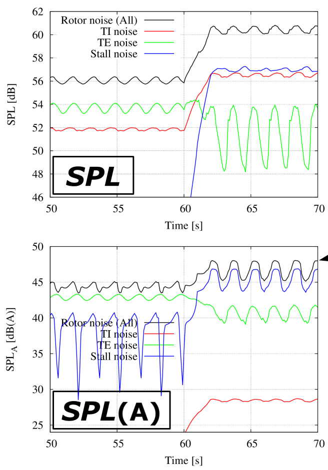
Sudden Gust at Low Wind Speed

Sound from 2MW turbine
For 3 blades!



Total noise
Stall noise
Trailing edge
Leading edge

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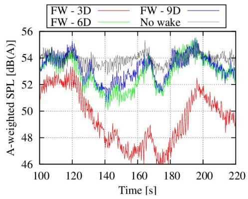
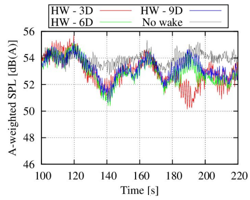
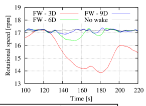
Noise in Wake

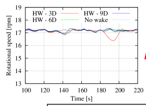
SPL(A)





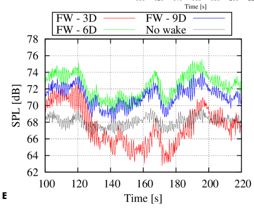
Full-wake

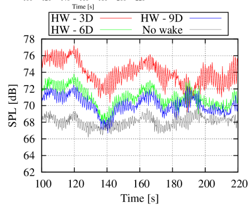




Half-wake

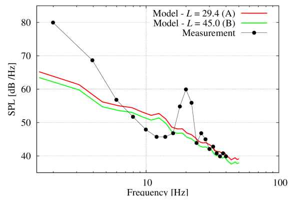
SPL



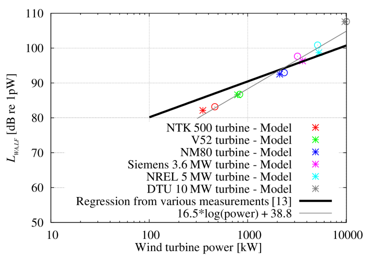


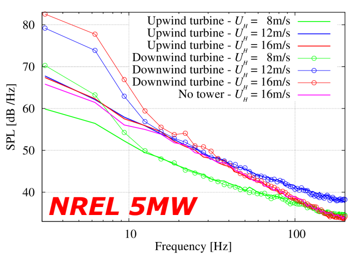
Low-Frequency Noise

SWT 3.6MW



HAWC2 model + Mann turbulence





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*

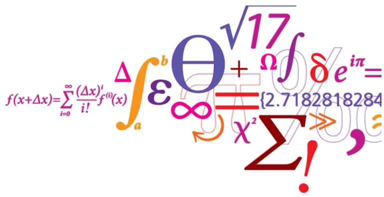
Abstract:
Here we provide statistical low-order characterization of noise propagation from a single wind turbine, as affected by mutually interacting turbine wake and environmental conditions. This is accomplished via a probabilistic model, applied to an ensemble of atmospheric conditions based upon 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



RAM section

DTU Wind Energy
Department of Wind Energy

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)

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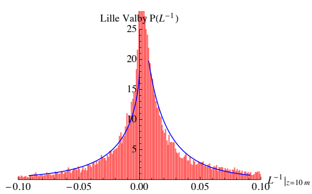
Probabilistic ABL-state model…

- 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 $U(z)$ [Kelly+Troen 2015,16]



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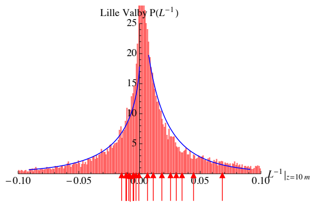
Probabilistic ABL-state model…

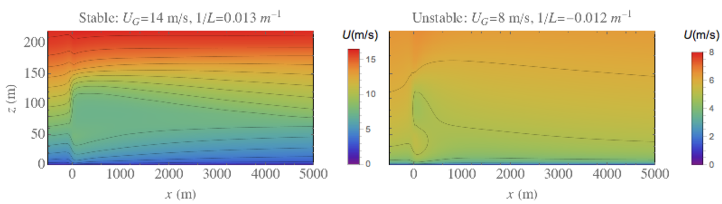
- First try: ensemble of atmospheric-stability states
  - stability most influences flow field
    - shear/profile
    - wake
  - We know how to model stability (L^{-1}) and its PDF;
    - $P(L^{-1})$ has universal shape [Kelly+Gryning 2010]
    - We know e.g. limits of effect on shear [Kelly *et al*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

$$\Delta\mathrm{SPL}(r,f) = \sum_i a_i P\left(L_i^{-1}\right) \Delta\mathrm{SPL}(r,f|L_i^{-1})$$



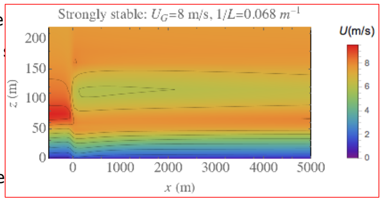
ABL modelling : flow fields

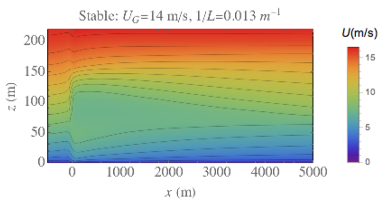
- ScaDis: RANS w/2-eqn. turbulence model [Sogachev *et al* 2002…]
  - Advanced stability treatment ; satisfies M-O theory [Sogachev+Kelly 2012]
  - Captures ABL 'top' (T-inversion)
  - Radiation/clouds also
  - Mean fields or diurnal cycles
  - Actuator disc → turbulent wake

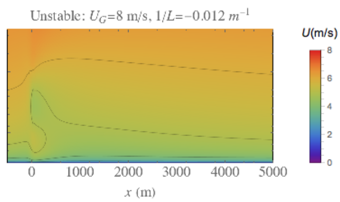


ABL modelling : flow fields

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

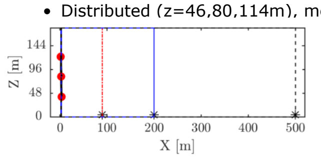


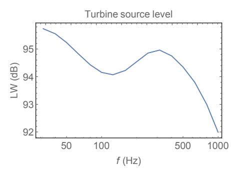




Propagation model

- 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:

$$\mathrm{SPL}(f,r) = \mathrm{LW}(f) - 10\ln(4\pi r^2) - \alpha(f)r + \Delta L(f,r)$$

Propagation model

- Parabolic Equation (PE): 2-D spectral solver (also 3-D)
  - Frequency-dependent propagation (refractive)
  - Sound-speed profile (from $U(z)$ and $T(z)$)
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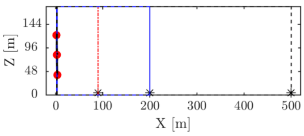
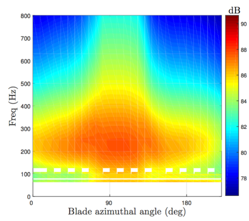


Source

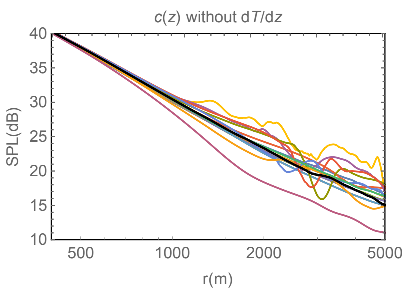


  - Plus geometrical spreading, molec.absorption:

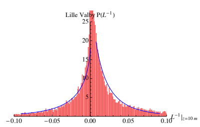
$$\mathrm{SPL}(f,r) = \mathrm{LW}(f) - 10\ln(4\pi r^2) - \alpha(f)r + \Delta L(f,r)$$

'Simple' results…

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



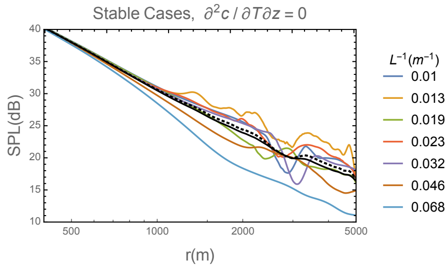
- Black: probabilistic model → weighted mean
  - using local/typical 1/L distribution (at right)



'simple' results…stable cases

- stable cases

- No T(z) in PE



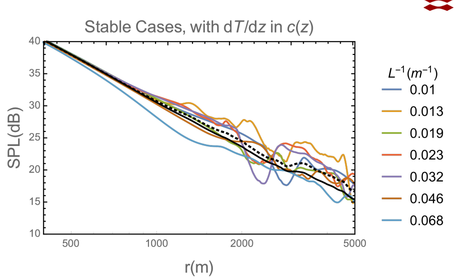
- Dotted line: stable-side average

– 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

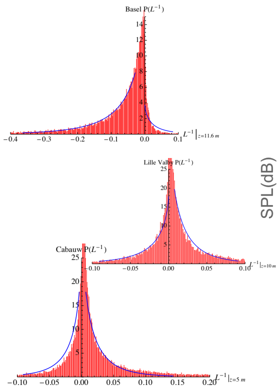


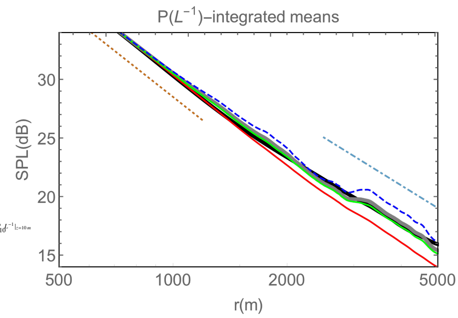
– Very stable case (blue lines):
  - *less sound, more loss…* → loss reduced by including $T(z)$

– Weakly stable case (red/orange):
  - Not much change by including $T(z)$ in PE calcs

Overall results: mean SPL

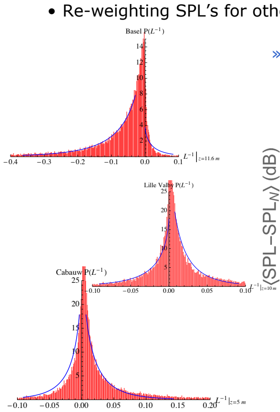
- Re-calculate SPL's for different sites/climatologies



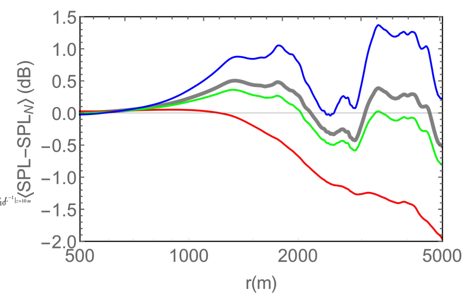


Overall results: mean SPL differences

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

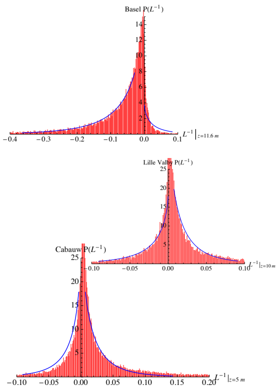


» **Difference from neutral result**:

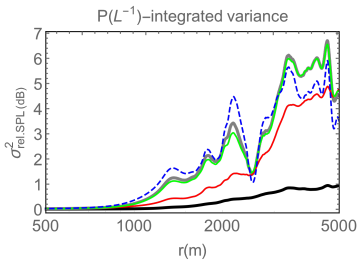


Overall results: SPL <u>variance</u>

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



» **Variability**:



Conclusions

- Verified:
  - Stable climatology important (not direct, counter-intuitive)
  - Modest/weak stabilities more important <u>and</u> 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 <u>does</u> depend on* $P(L^{-1})$ *(especially night/cold)*

- Noise still perceptible at 3km downwind

- To do…
  - Deal with $P(L^{-1}, U, \boldsymbol{h}_{\mathbf{ABL}})$
  - Use turbulence in PE (incl.wake),
  - Different sfc.-impedance / terrain
  - Extend range, check @angles to mean wind
  - Compare to Nord2k, others…

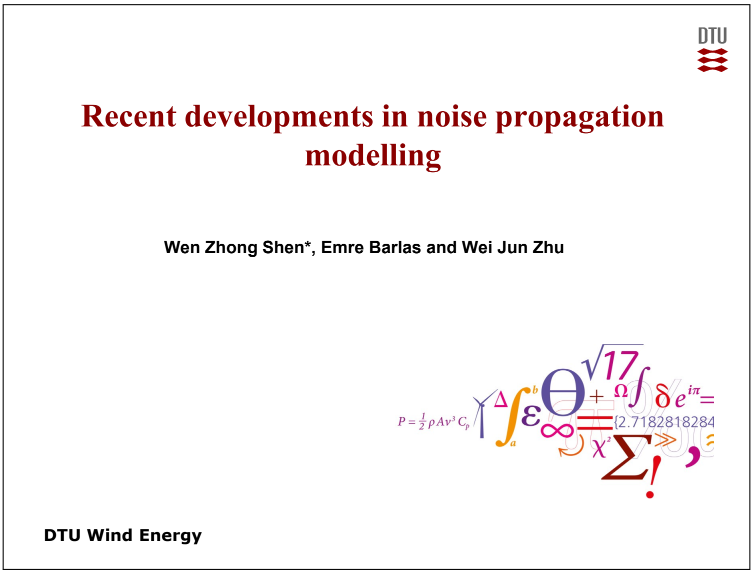
6.3 Recent developments in noise propagation modelling

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:



Outline

1. Introduction to noise propagation

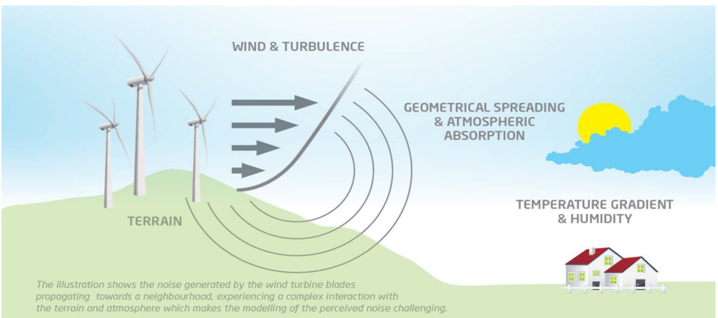
2. Noise propagation modelling using a PE method
   - Propagation model
   - Flow input models
   - Source coupling for propagation

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

4. Conclusions

1. Introduction

- Noise propagation from source to receiver



2. Propagation modelling using a PE method

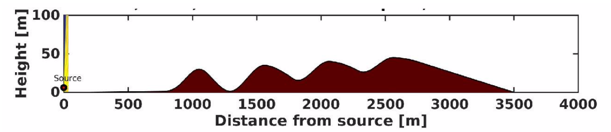
Propagation model (WindSTAR)

- **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**

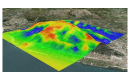
$$\left[\Delta + k^2(1+\epsilon) + \frac{2ik}{c_0}\mathbf{v}\cdot\nabla - \frac{2i}{\omega}\frac{\partial v_i}{\partial x_j}\frac{\partial^2}{\partial x_i \partial x_j}\right]P'(\mathbf{r}) = 0$$

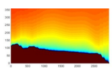


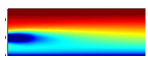
2. Propagation modelling using a PE method

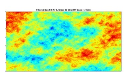
Flow input models

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


WEng Top View Single Height


WEng Side View


Analytical Wake Model


Synthetic Turbulence

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

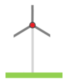
Unsteady Navier-Stokes approach:
- **3D Navier-Stokes solver with LES-AL/AD**
- **Realistic wake and turbulent medium**

2. Propagation modelling using a PE method

Source-propagation coupling:

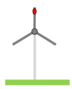
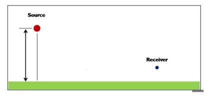
Single point source

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



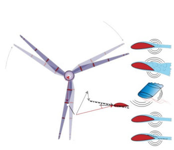
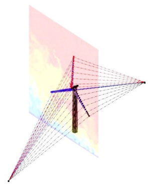

Lumped sources along the vertical line

- Point source at blade tips
- Quasi-unsteady
- Time dependent SPL

IBPM Coupling

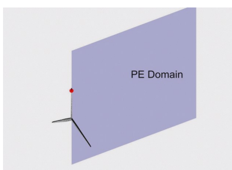
- More accurate source modelling
- Engineering source models (IBPM)
- Fully unsteady

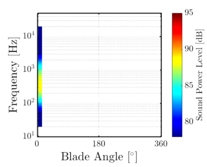
2. Propagation modelling using a PE method

Coupling effects

Moving source to mimic the blade passage

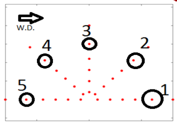


Source power level is obtained from semi empirical noise model for a wind turbine (BEM+BPM+AMIET)



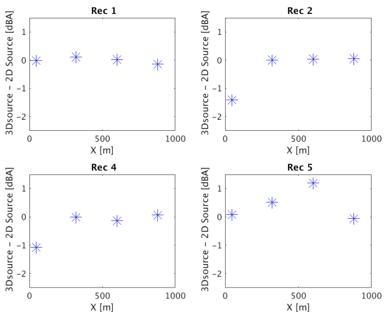
DTU

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.



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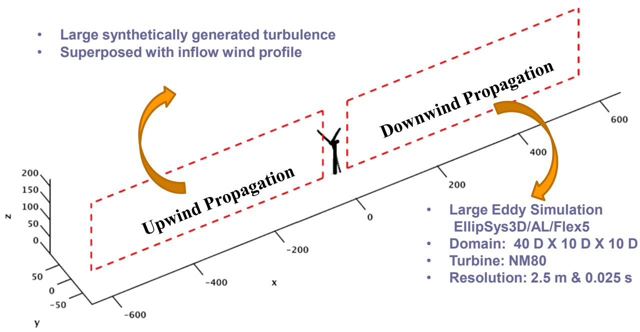
DTU

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

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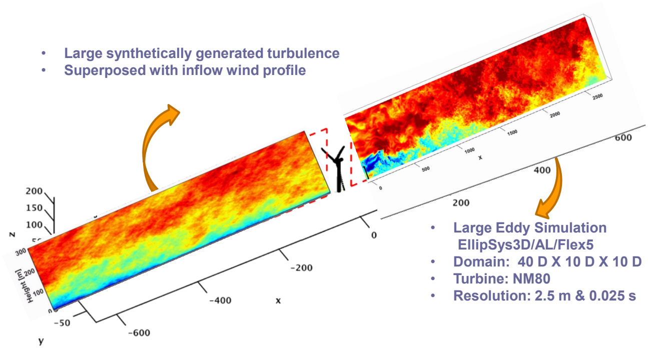
3. Results

3.1 Noise propagation under wind shear and turbulence

- 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

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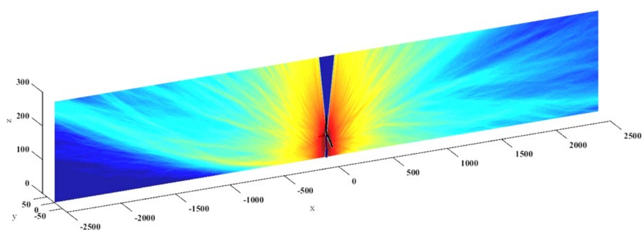
3. Results

3.1 Noise propagation under wind shear and turbulence

With unsteady flow and varying source strength

Sound pressure levels summed up to 800 Hz

TI 10% and shear exponent: 0.14



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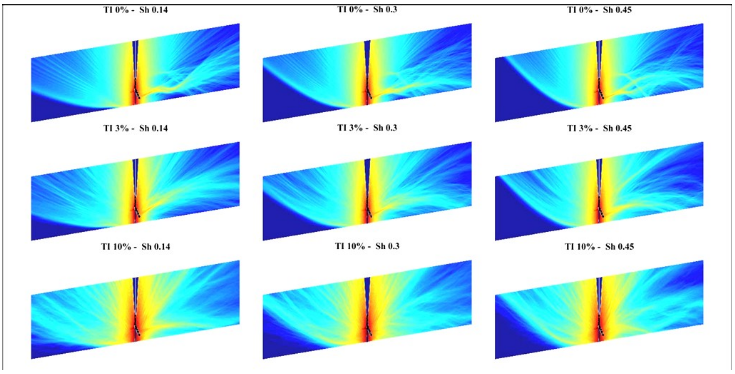
3. Results

- **From left to right : Increasing Shear (0.14, 0.3 , 0.45)**
- **From Top to bottom : Increasing turbulence intensity (0 %, 3 %, 10 %)**



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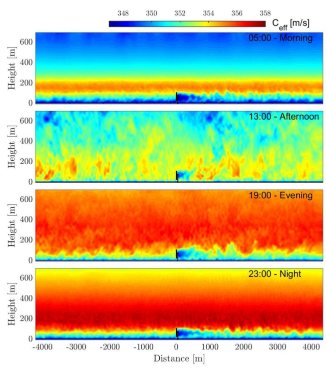
3. Results

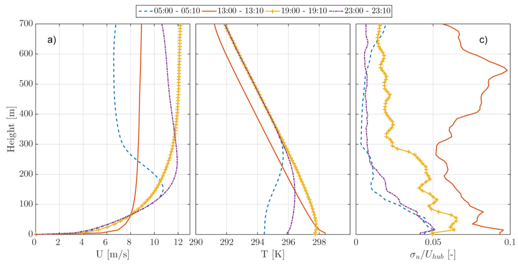
3.2 Variability of wind turbine noise in a diurnal cycle



Acoustic Day, May 17, 2018 13

3. Results

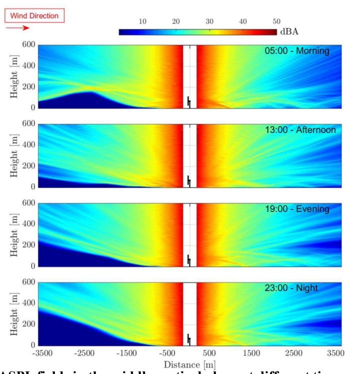
3.2 Variability of wind turbine noise in a diurnal cycle



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

3. Results

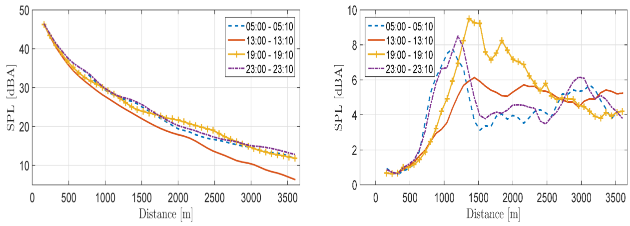
3.2 Variability of wind turbine noise in a diurnal cycle



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

DTU Wind Energy

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?

17 May 2018

Why a wind tunnel?

Test at:

105m/s=378km/t

Correspond to more than a category 5 hurricane

From wyrk.com

Tornado in Oklahoma

From www.lolking.net

TGV train

3

17 May 2018

THE HISTORY OF THE ESTABLISHMENT

The history behind the Danish National Wind Tunnel

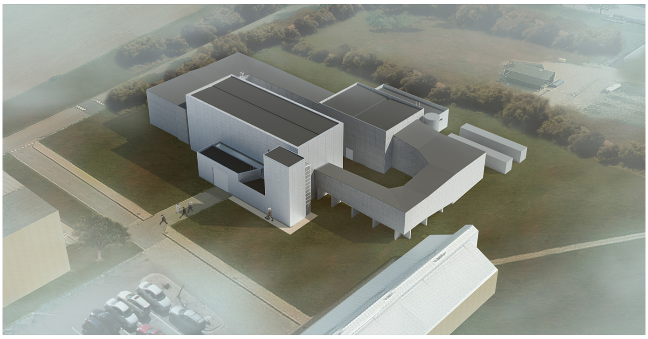
- 2011 April
  - DTU got the green light from Ministry of Higher Education and Science for establishing a wind energy dedicated wind tunnel as a national research infra structure
- 2011 December
  - After discussions with the Danish wind turbine manufacturers, universities and other relevant institutions, 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

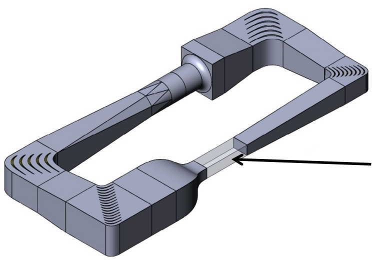
THE WIND TUNNEL DESIGN

The final design



8 17 May 2018

Design of the tunnel
Test section

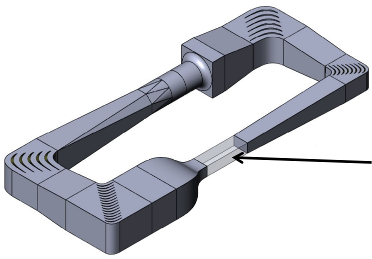


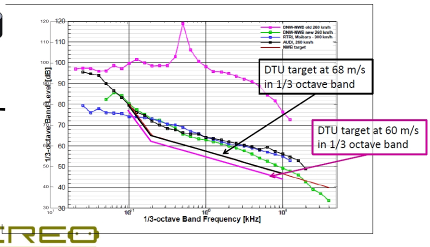
Description	Value
Maximum Reynolds number [-]	**$7.0x10^6$**
Maximum flow speed [m/s]/[km/h]	**~105/378**
Test section: Width [m]	**3.00**
Test section: Height[m]	**2.00**
Test section: Length [m]	**~9**
Maximum turbulence intensity [%]	**Max 0.1**
Anechoic chamber with background noise at 60m/s with kevlar walls 2m from airfoil [dB]	**<70**

9 17 May 2018

Design of the tunnel
Noise reduction

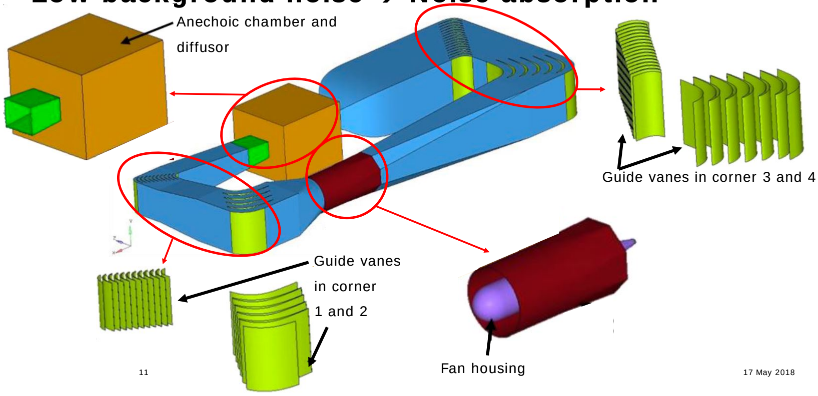
Background plot from: A. Bergmann, The Aeroacoustic Wind Tunnel DNW-NWB, German-Dutch Wind Tunnels DNW, 38108 Braunschweig, Germany, 18th AIAA/CEAS Aeroacoustics Conference (33rd AIAA Aeroacoustics Conference) overlayed by DTU specifications.





10 17 May 2018

Design of the tunnel
Low background noise → Noise absorption



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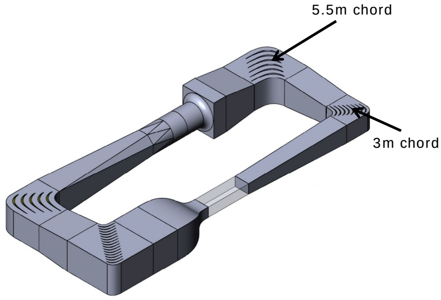
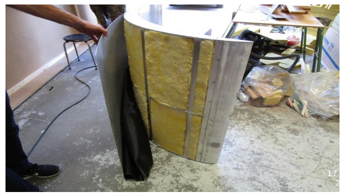
Design of the tunnel
Corners/guidevanes





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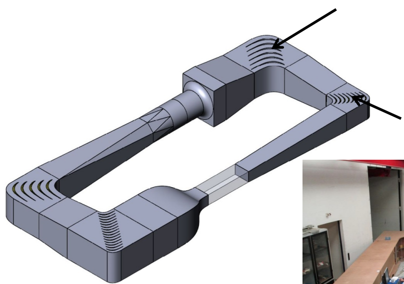
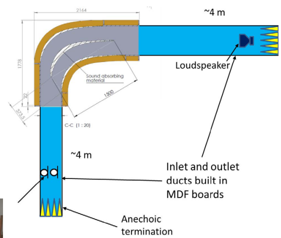
Design of the tunnel
Corners/guidevanes





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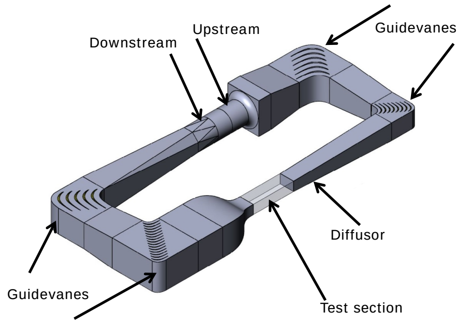
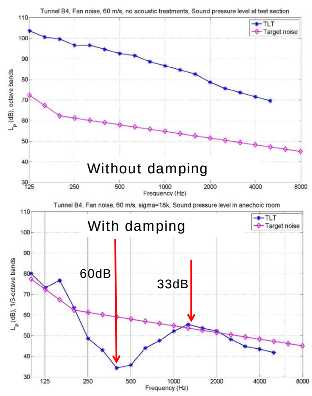
Design of the tunnel
Predicted background noise





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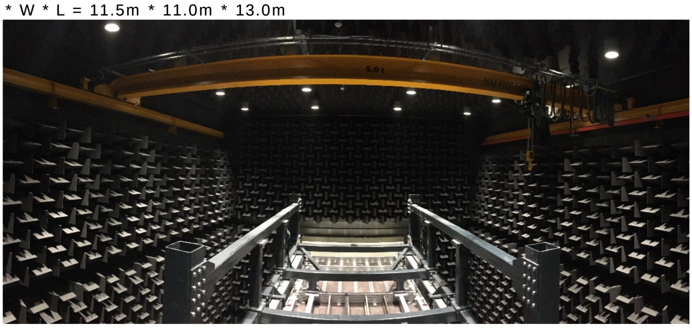
Design of the tunnel
The anechoic chamber

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



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STATUS

17 May 2018

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

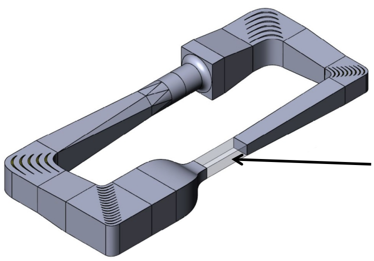
17

17 May 2018

SOME OF THE THINGS TO DO IN THE COMING MONTHS

17 May 2018

Construction and mounting of Kevlar walls



Photos from Virginia Tech tunnel

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17 May 2018

Test of a symmetric airfoil

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

20

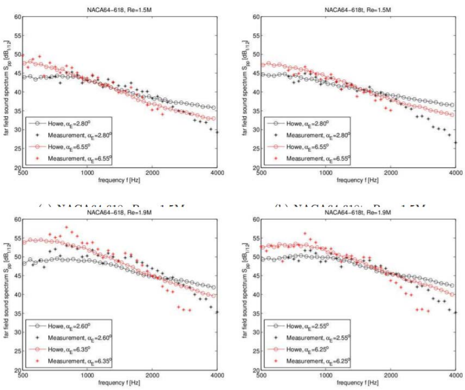
17 May 2018

SOME OF THE THINGS TO DO IN THE COMING YEARS

17 May 2018

Airfoil design
Noise

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



(c) NACA64-618, $Re = 1.9$M (d) NACA64-618t, $Re = 1.9$M

19 May 2018

Airfoil design
Noise reducing devices

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

Photo by Siemens

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

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SHARING THE KNOWLEDGE

17 May 2018

Workshop in 2019

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

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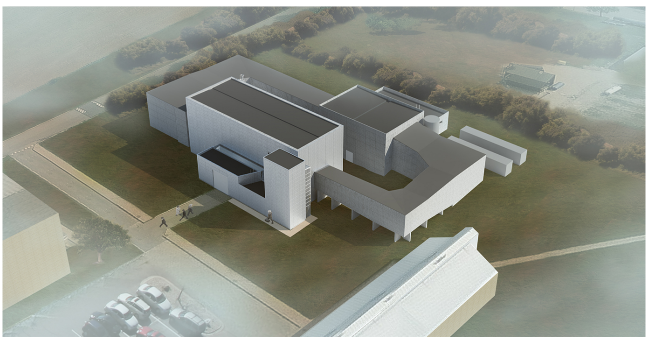
17 May 2018

Thank you!
… and check www.plct.dk



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17 May 2018

6.5 The Acoustic Measurement Setup in the Poul la Cour Wind Tunnel

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

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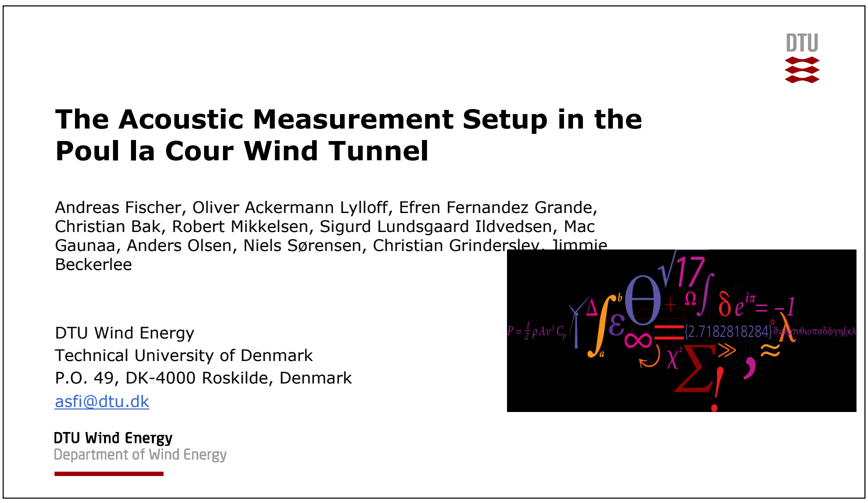
Abstract:
The Poul La Cour Wind Tunnel provides the possibility to test aerofoils at high Reynolds numbers. It can be configured in two different set-ups: the aerodynamic and the acoustic setup. This talk focuses on the acoustic set-up which is similar to the one developed at Virginia Tech. It consists 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.

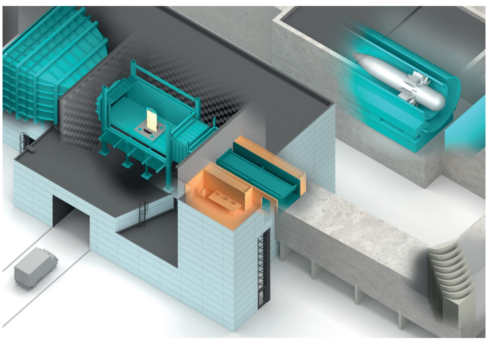
Slides:



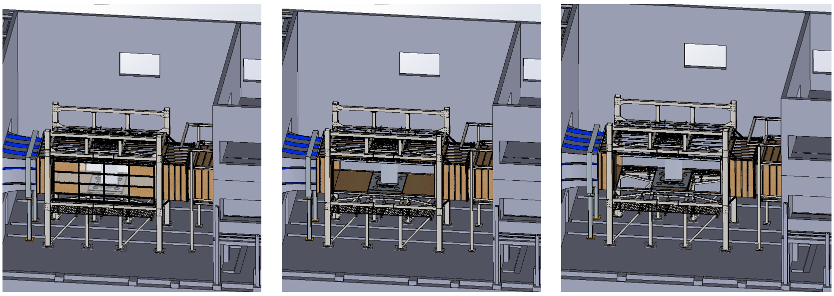
Outline

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

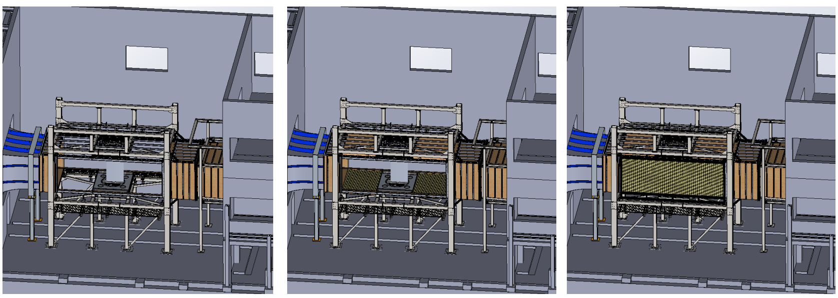
The test section and surrounding anechoic chamber



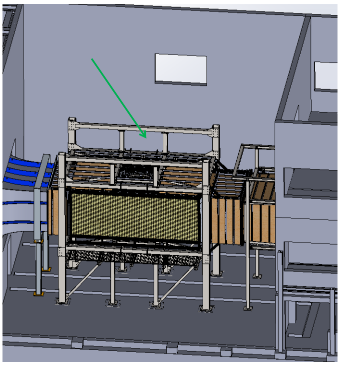
Transformation from aerodynamic configuration…

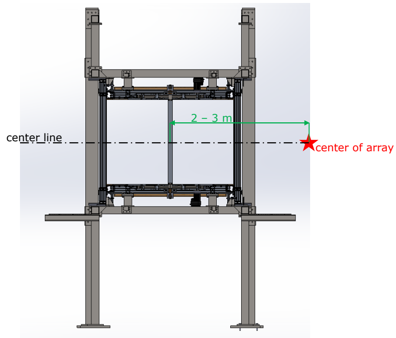


… to aero-acoustic configuration

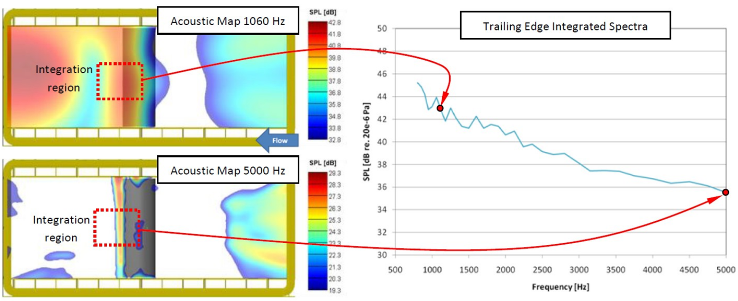


Microphone array position

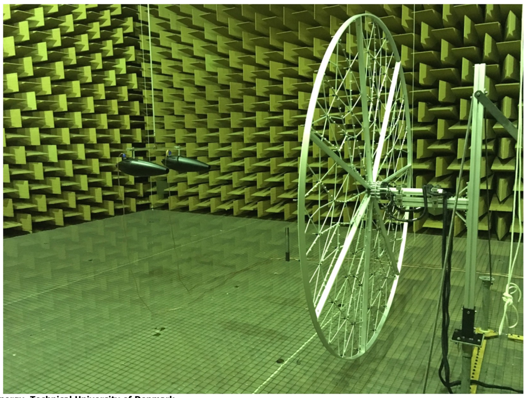




Microphone array measurements in the Virginia Tech wind tunnel (AVEC)



Brüel&Kjær microphone array



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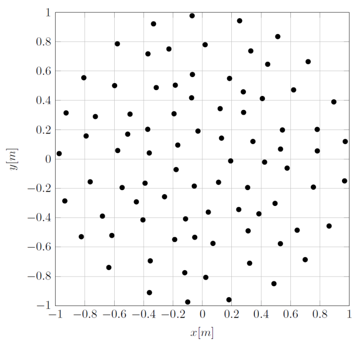
Microphone array geometry

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



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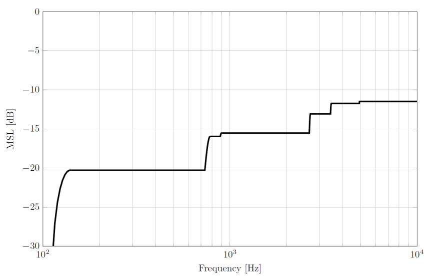
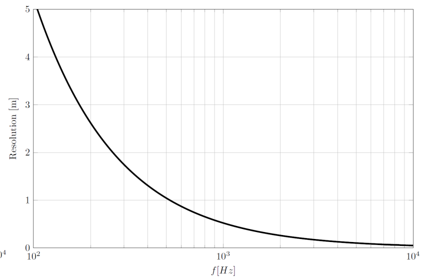
Microphone array characteristics

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



Rayleigh resolution at 2.5 m distance to source



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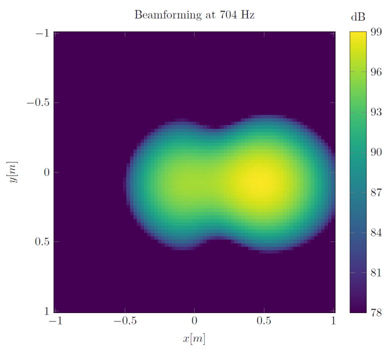
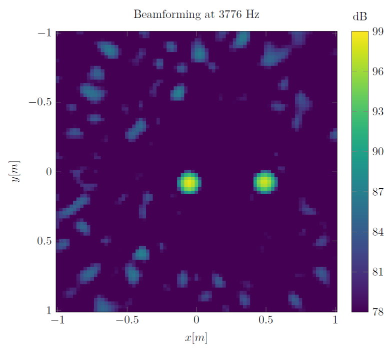
Source resolution





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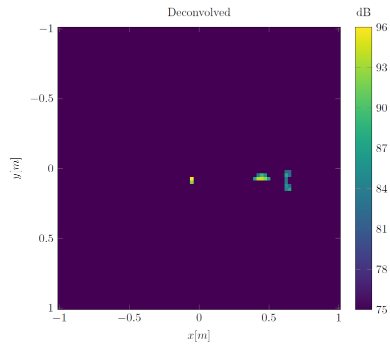
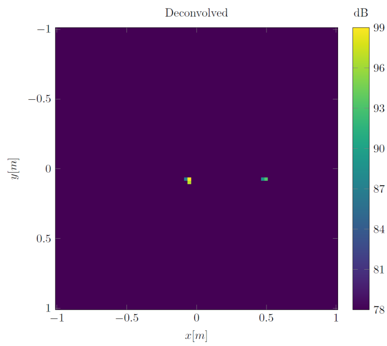
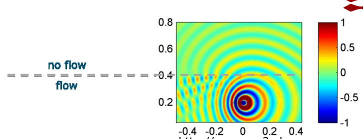
Source resolution



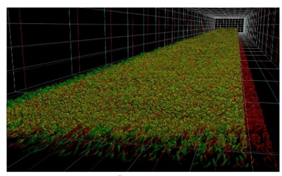


Acoustic boundary corrections

- 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



http://www.psa3.nl



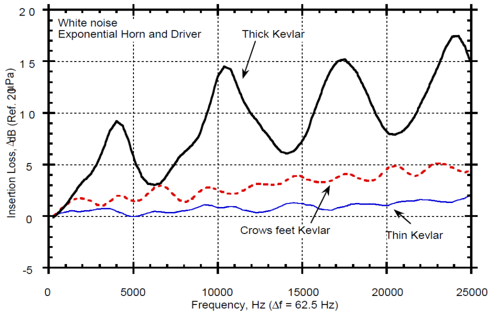
P. Schlatter and R. Örlü¸ (2010) "Assessment of direct numerical simulation data of turbulent boundary layers." J. Fluid Mech. 659. 116-126

Acoustic properties of Kevlar (Jaeger et al. 2000)

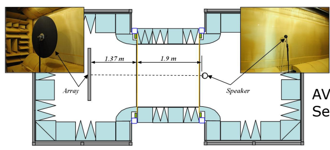
Kevlar 120®, thin weave

Kevlar 124®, crow's foot weave

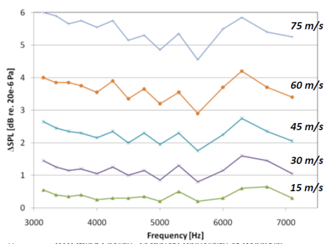
Kevlar 500®, thick weave

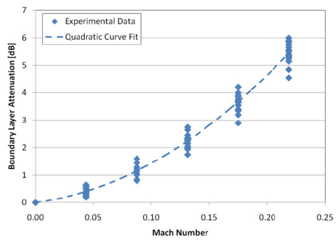


Virginia Tech turbulence and shear layer corrections

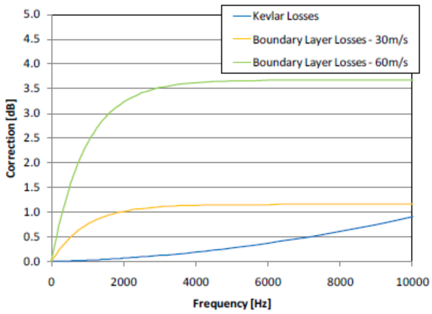


AVEC/Virginia Tech Setup





Kevlar vs boundary layer losses (VT)



Aerodynamic boundary corrections

Two principal sources

a) Correction to angle of attack due to transpiration through acoustic window

b) Blockage

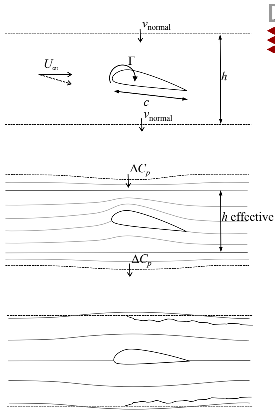
- Increased by wall deflection
- Reduced due to transpiration through acoustic window

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.

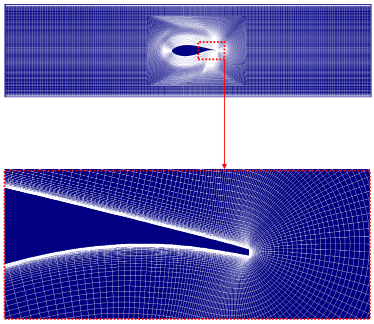
c) Using standard formulae (Allen and Vicente, 1947) to correct force, moment and pressure coefficients



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

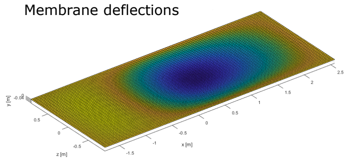
Computational approach

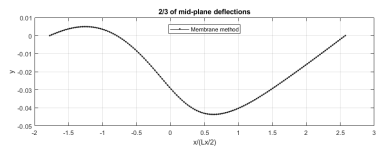
- Computational Fluid Dynamics (CFD)
  - EllipSys2D – a code developed for wind turbine use
- 2D, Incompressible, steady state
- Convective terms by the QUICK scheme
- Turbulence modeling by k-omega SST model
- Grid configuration 62 blocks of 32^2 cells (total: 63,488) , y+ < 2
- No-slip conditions on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

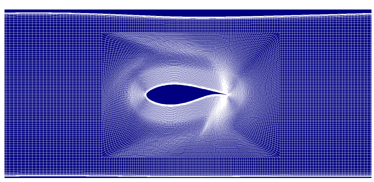


Computational approach

Membrane deflections

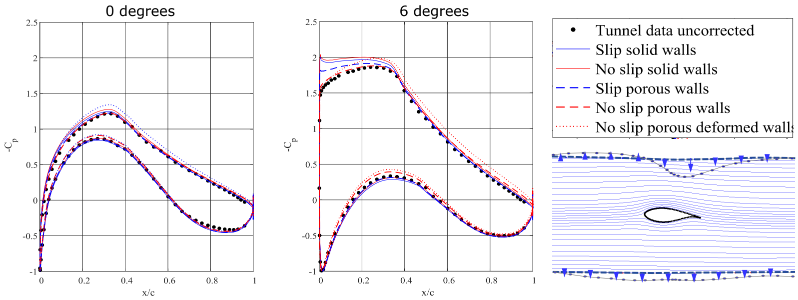






Wall Boundary Conditions Investigated:
- Solid (no deformation), slip and no-slip
- Kevlar walls, no deformation, slip and no-slip
- Kevlar walls, deformed, no-slip

Aerofoil pressures



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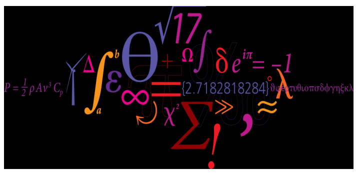
Thank you!



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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.

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