Noise source characterization by high-frequency surface pressure measurements

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Outline

- **Part 1**
  - Overview of aeroacoustic noise sources
    - ➢ The empirical Brooks Pope Marcolini model
- **Part 2**
  - Measurement of high frequency surface pressure fluctuations for blade noise characterization

Overview of aero acoustic noise sources

Two most important noise sources

Table 4.1: Survey of wind turbine aerodynamic noise mechanisms.

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

Wagner et al. (1996)

The Brooks, Pope and Marcolini (BPM) model

- turbulent boundary layer trailing edge noise *(TBLTE noise)*

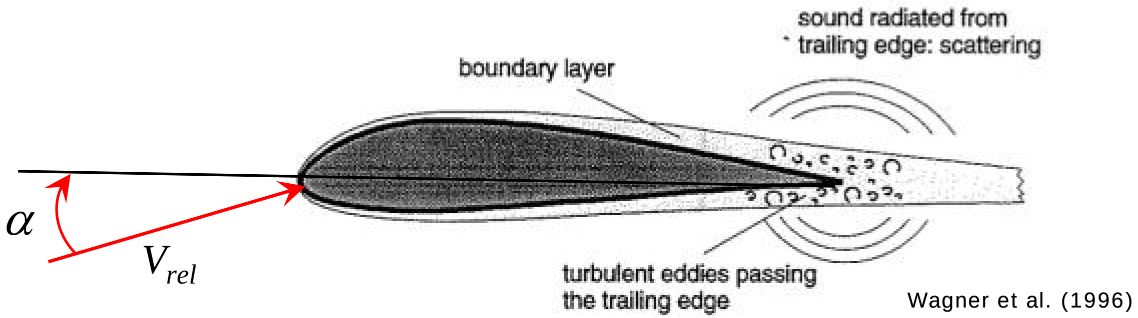


Figure 4.11: Principal mechanism of trailing-edge noise.

Sound pressure level $L_{P,TBLTE} \approx \left(V_{rel}^{5}\,,\,\alpha\right)$

Contributions from both the suction and pressure side

Turbulent inflow noise

- turbulent inflow noise (Amiet, Lowson)

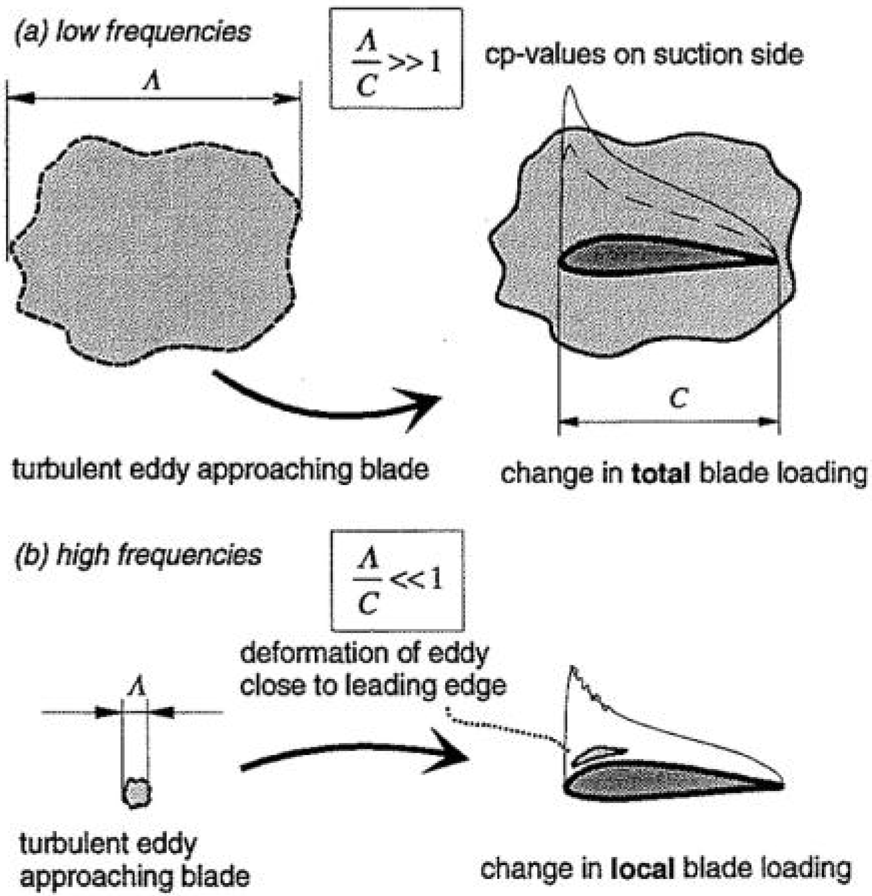


Figure 4.10: Turbulent eddies approaching the rotor blade.

Wagner et al. (1996)

$$L_{P,TI} \approx \left(U_\infty^2, TI^2, l, V_{rel}^4\right)$$

$$L_{P,TI} \approx \left(U_\infty^2, TI^2, l, V_{rel}^3\right)$$

Total noise computation

– BPM model + TI model (Amiet, Lowson)

Input data

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

Aerodynamic model (BEM) computes:

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

Total noise found by summing up the different noise sources from all blade elements of the rotor

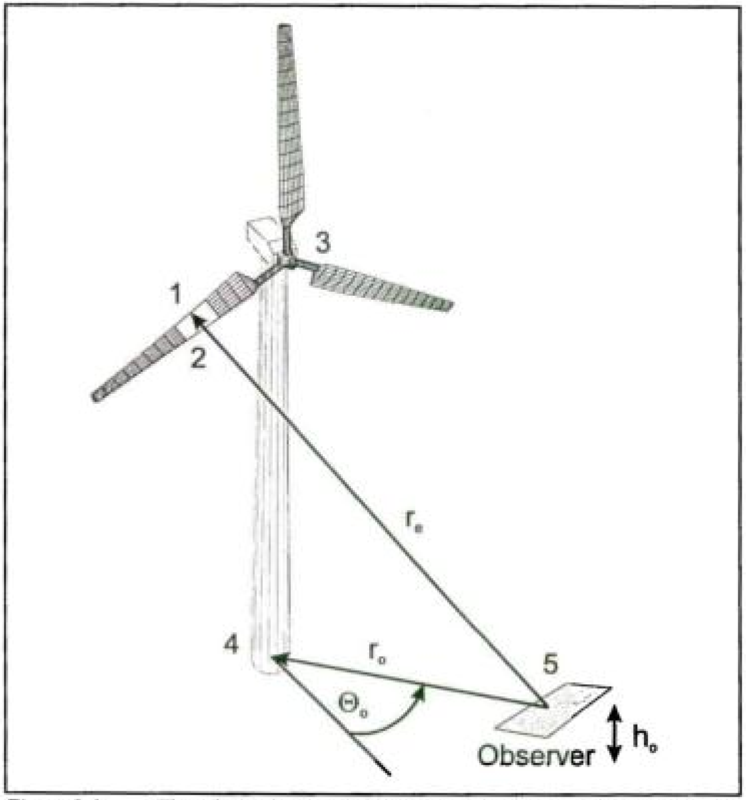
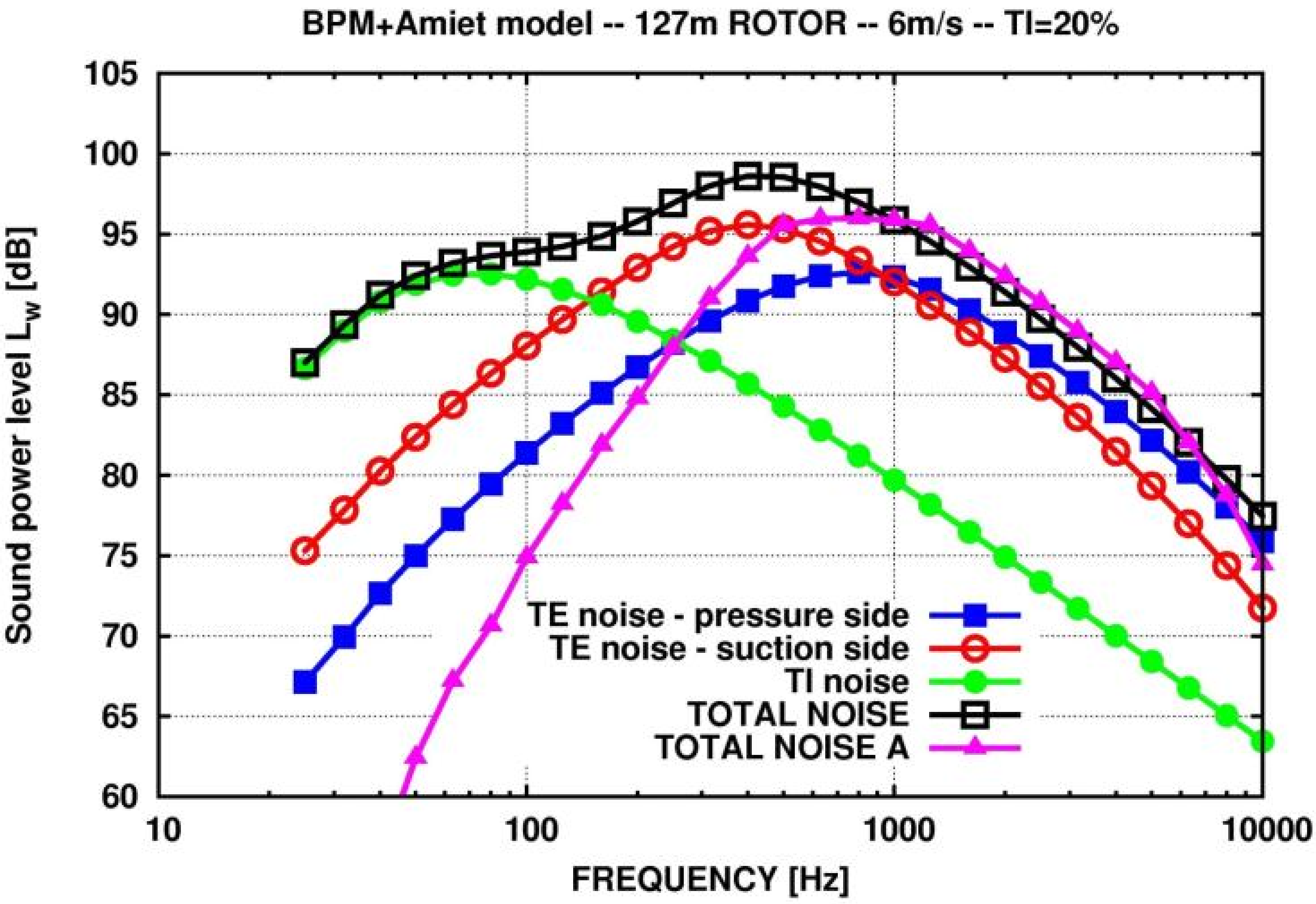


Figure 3-1 *The relation between a blade segment and the observer, with the different coordinate systems indicated with numbers.*

HAa Madsen et al. -- Presentation at EWEA 2012 acoustic workshop

An example of contribution of the different aero acoustic noise sources



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BPM model – a validation example

Total sound power level

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

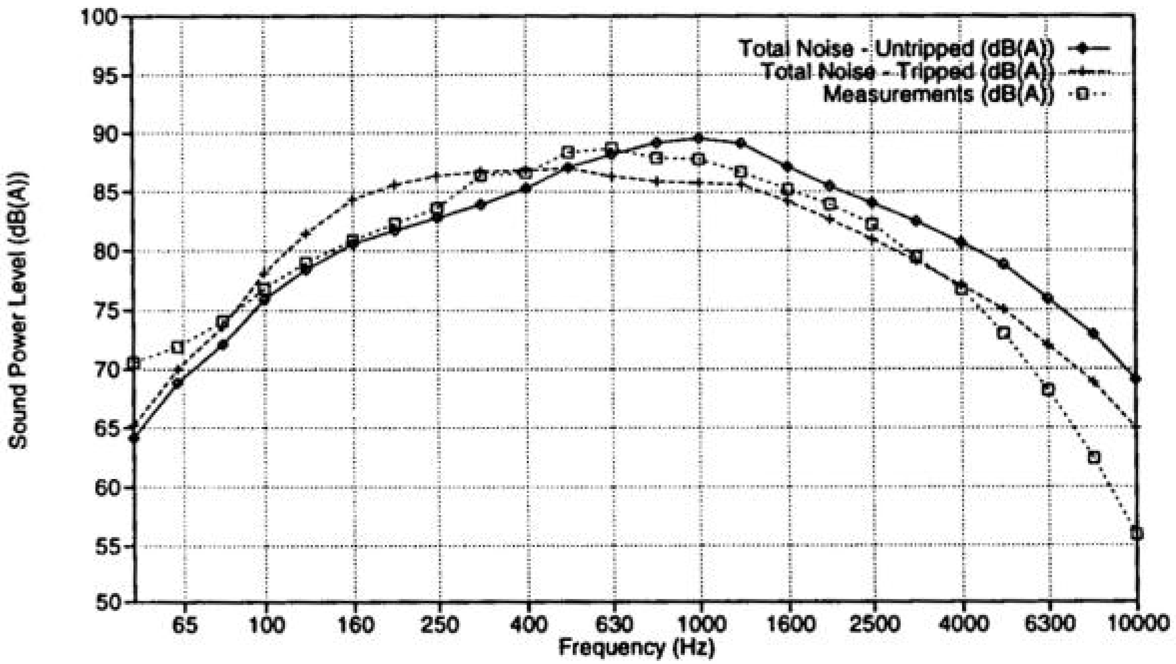


Figure 4-7 *Predicted sound power level in dB(A) compared to experimental results from Jacobsen & Andersen [14] for the Vestas V27 wind turbine at 8 m/s, tip pitch 0.5°.*

Fuglsang and Madsen (1996)

BPM model – influence of tip pitch

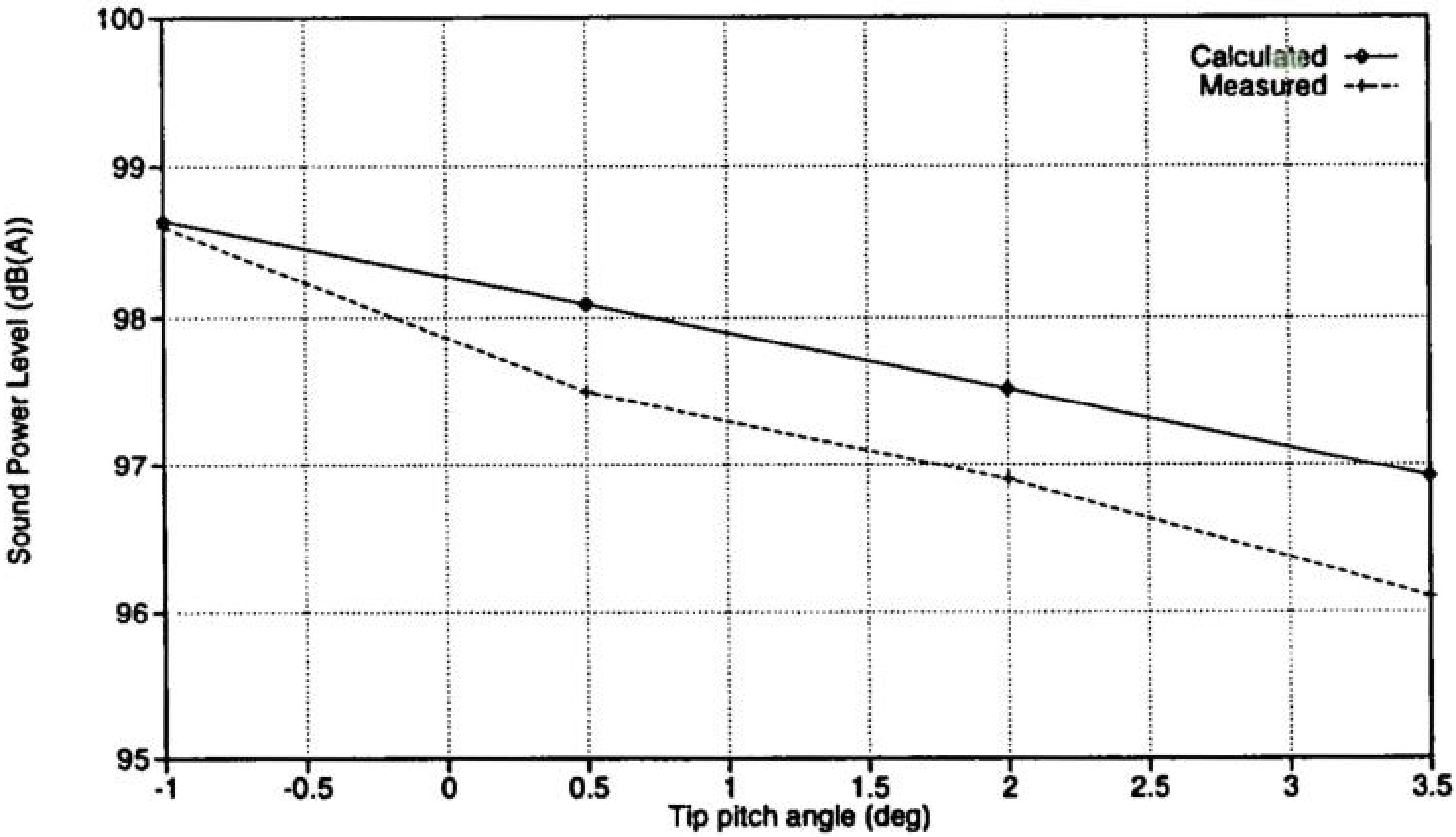


Figure 4-12 *Sound power level in dB(A) predicted for different tip pitch angles, compared with experiment for the Vestas V27 at 8 m/s.*

Fuglsang and Madsen (1996)

BPM model – used in rotor optimization

Baseline rotor

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

Fuglsang and Madsen (1996)

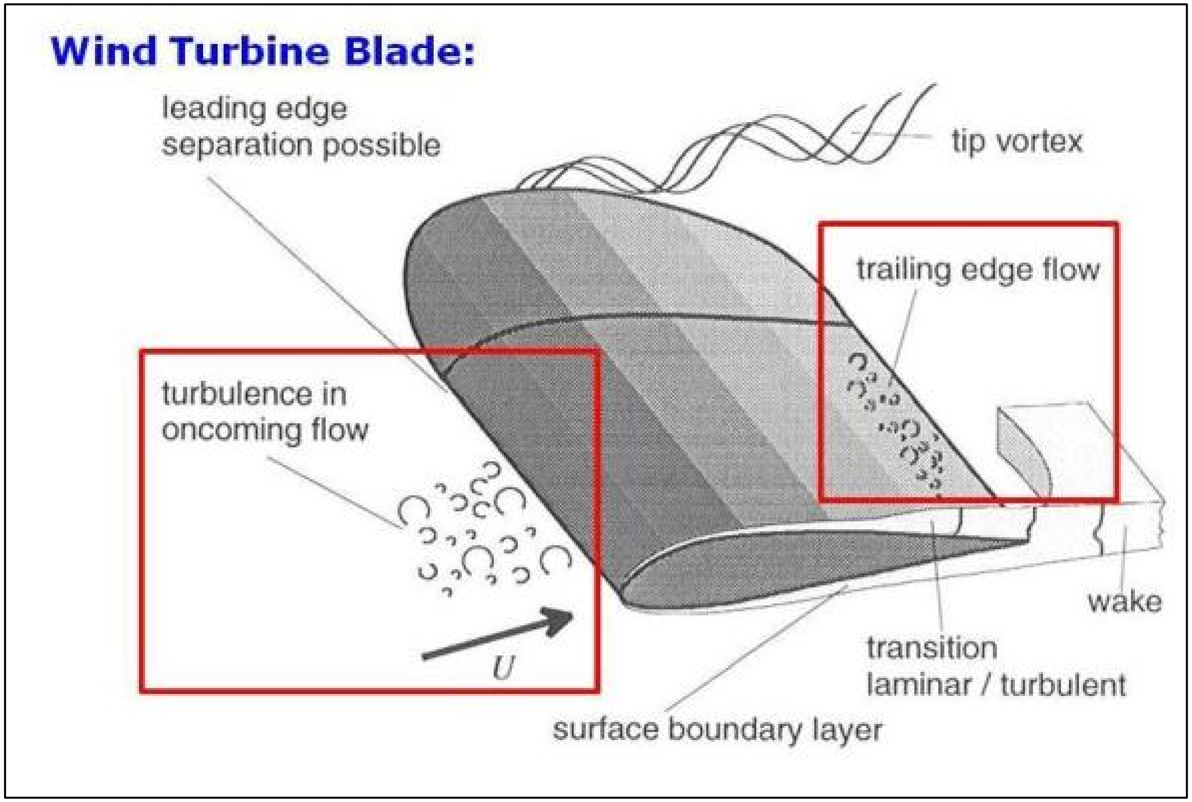
Outline – Part2

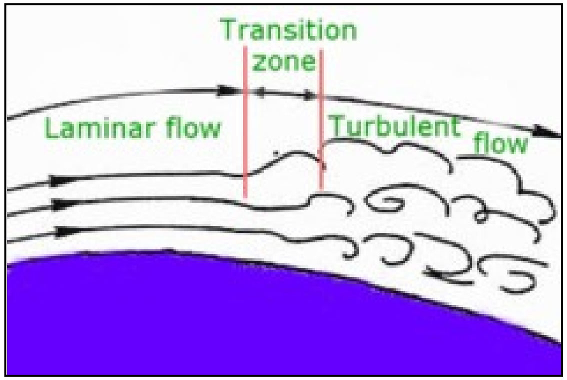
Measurement of high frequency surface pressure fluctuations for blade noise characterization

- ❑ Why using high frequency surface pressure measurements ?
- ❑ The measurement technique
- ❑ Measurements on a full scale 80m diameter rotor
- ❑ Perspectives for application of the technique

Why using high frequency surface pressure (SP) measurements for aeroacoustic characterization ?

- SP is the source of trailing edge (TBLTE) noise
- SP is the source of turbulent inflow (TI) noise
- SP has a high intensity compared with ambient noise (an example will be shown)





- Measuring SP enables correlation with detailed inflow data from inflow sensors on the blade, resolving 1p variations causing amplitude modulation (an xample will be shown)

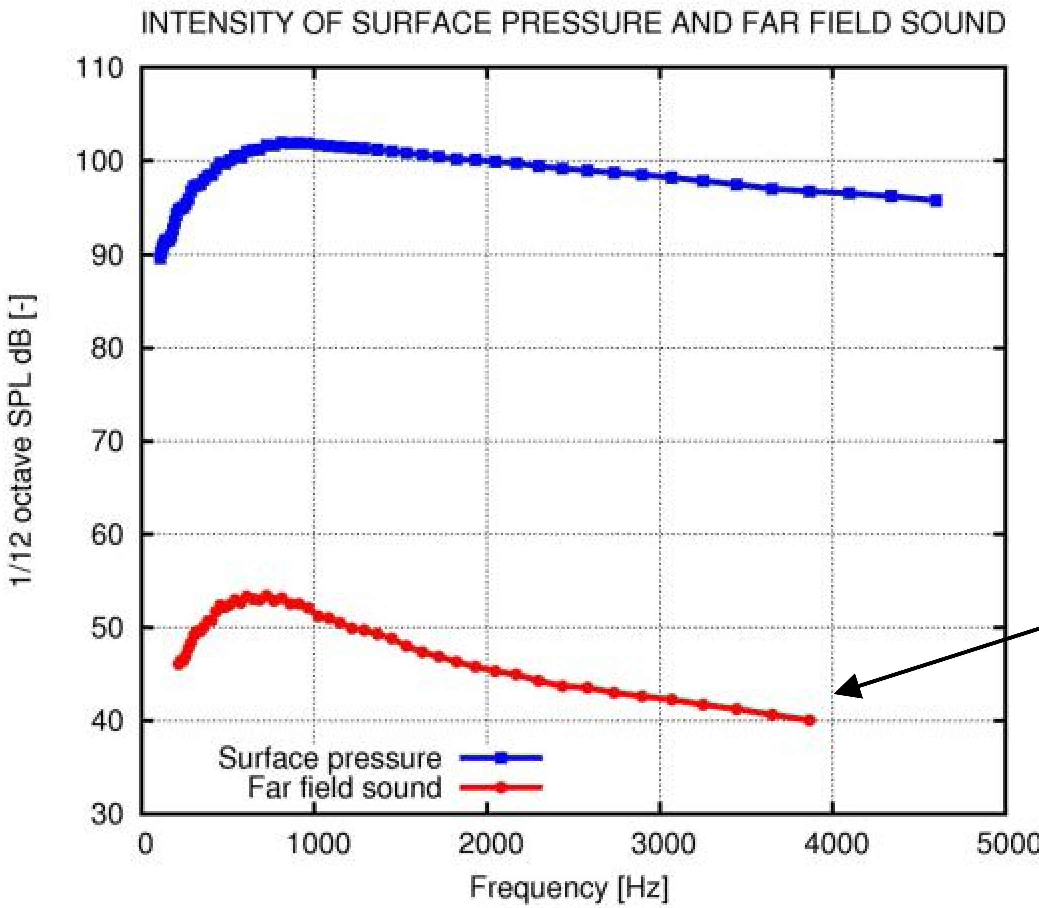
- Measuring SP provides more accurate aeroacoustic characterization during design and testing of new low noise airfoil designs

- Measuring SP provides detailed noise source information, enabling continuous, optimal input to the turbine control system for operation within noise constrains

Drawbacks with the SP technique compared with traditional far field measurements

- it is measurements at a cross section of a blade
- uncertainty in converting the SP to the far field noise
- ....

SP in the turbulent boundary layer has a high intensity compared with the far field sound

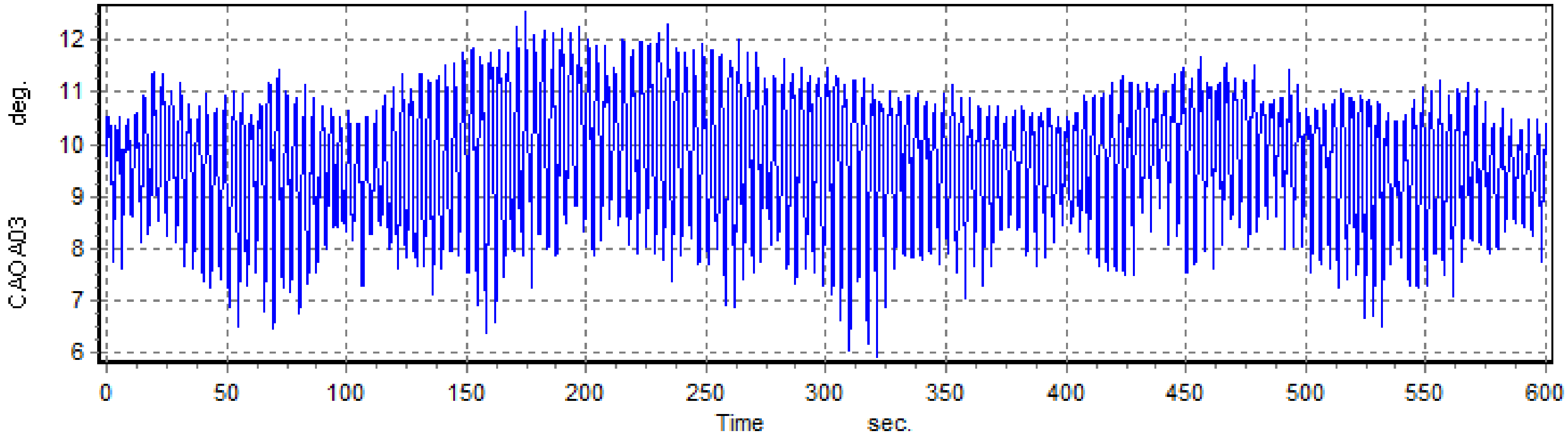


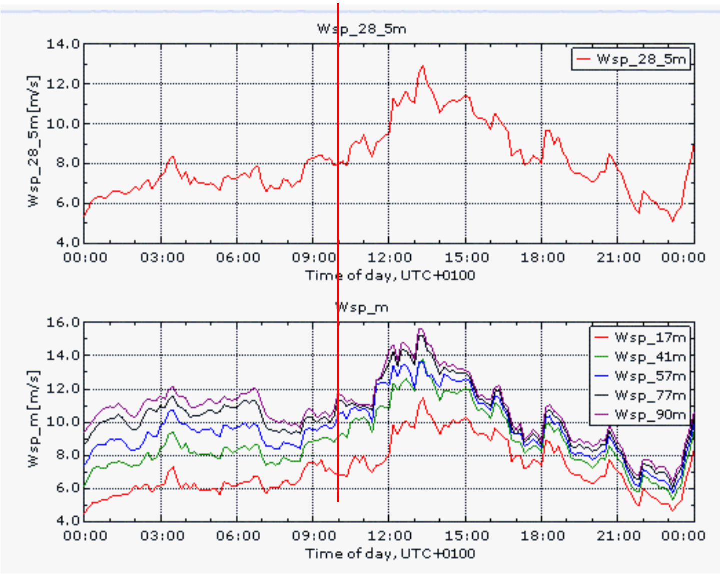
Based on set-up in the Virginia-Tech Wind Tunnel 2011 – NACA64-618 airfoil at 1.5 mill Re

Far field sound measured about 2m from the airfoil section

The inflow to the blade is varying considerably in time, in particular over 1p -the same is the noise source

Measured inflow angle at radius 30m on a 2MW turbine

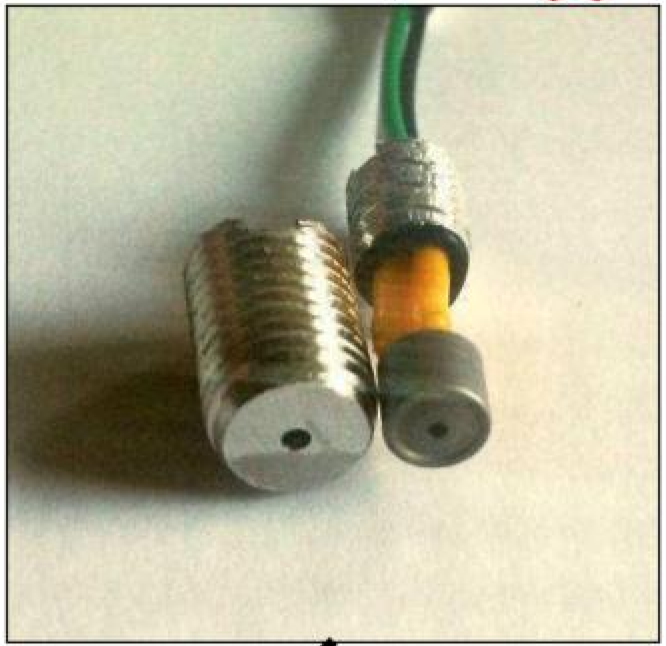


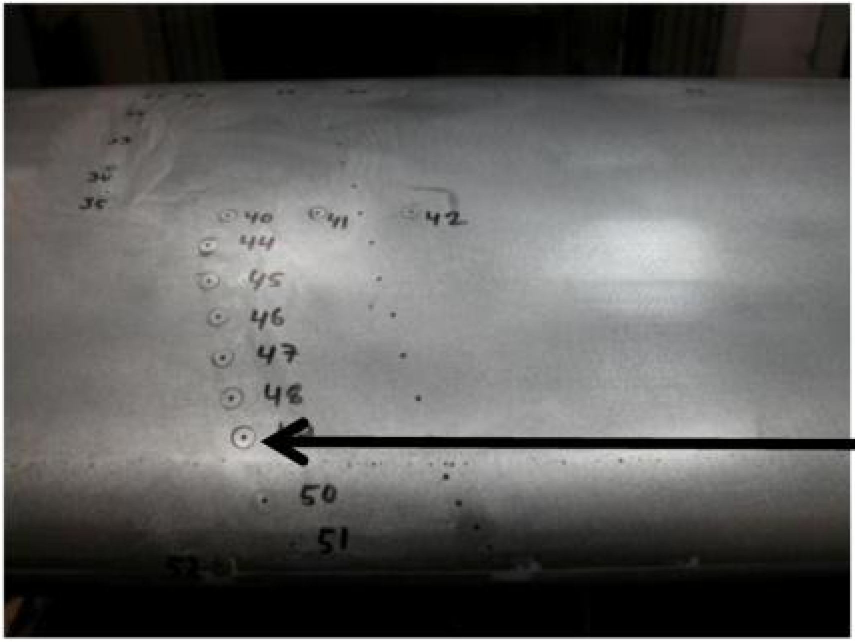


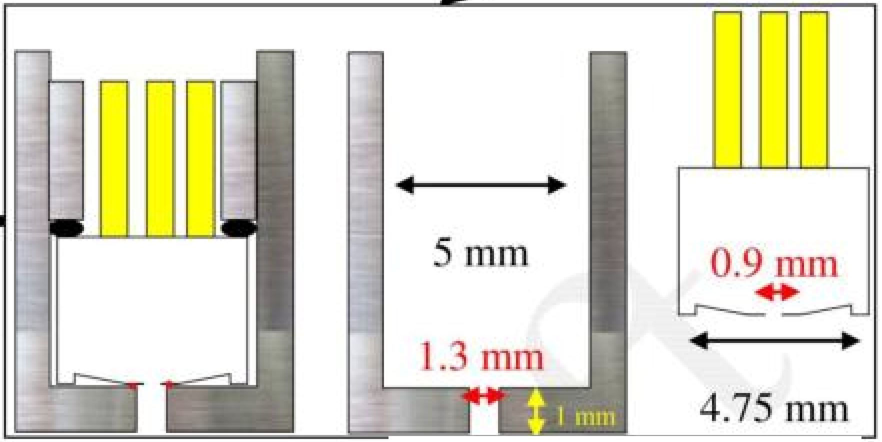
The measurement technique

SURFACE PRESSURE – Meas. Technique

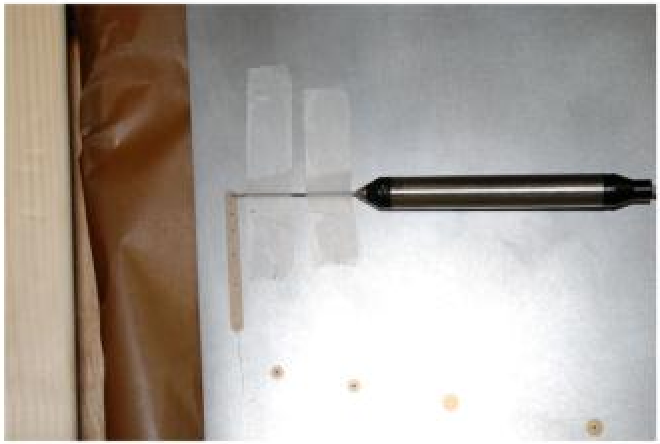
Flush-mounted HF microphones







Calibration of microphones in cooperation with B&K



(a) reference microphone and pinhole

(b) Sennheiser headphone HD650 source

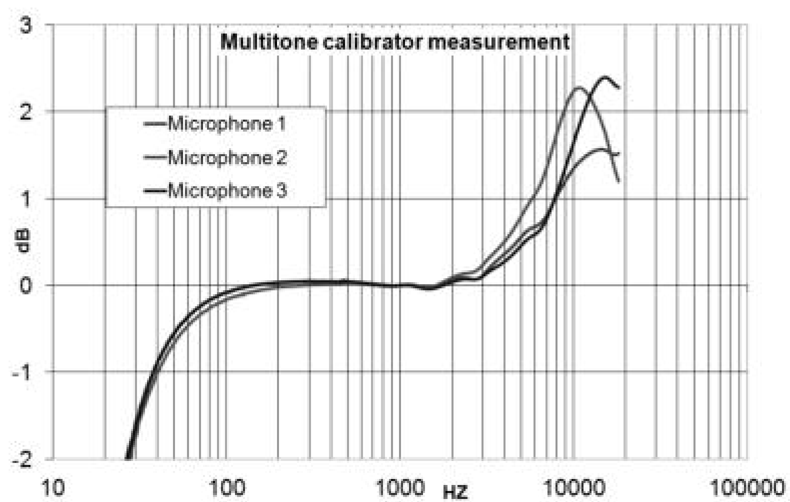


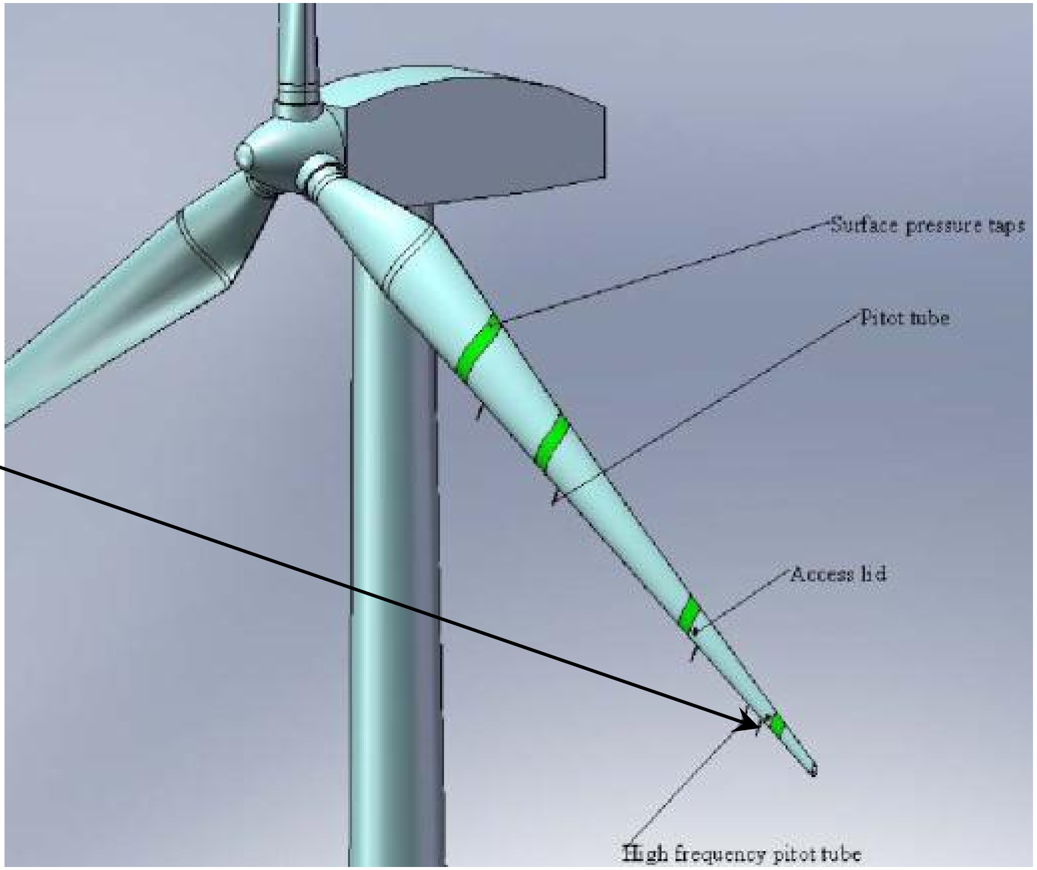
Figure 4: High-Frequency Microphones Deviations [Figure courtesy of Brüel & Kjær]

Measurements on a full scale 80m diameter rotor

- From the DAN-AERO project -

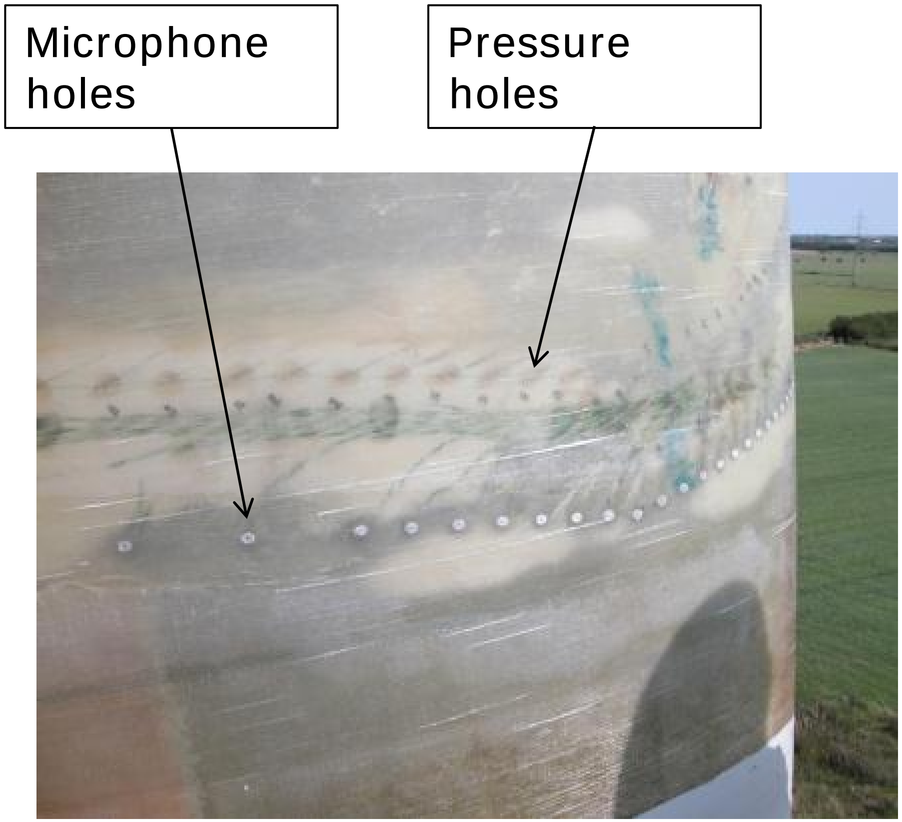
Measurement of SP on a full scale rotor blade, 80m diameter rotor, 2MW - - DAN-AERO MW project

- surface pressure and inflow measured at 4 radial stations
- **the outboard station also instrumented with around 60 microphones for high frequency surface pressure measurements**
- high frequency measurements of the inflow
- measurements from June to September 2009



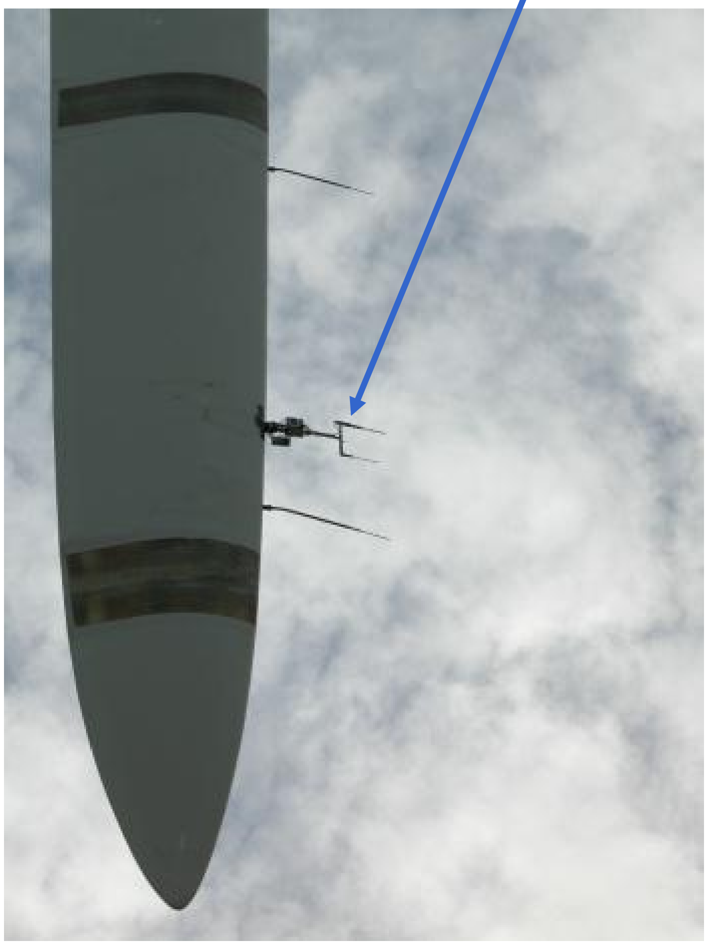
Installation of the 38.8m instrumented blade in May 2009

Campaign measurements from June to September 2009



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

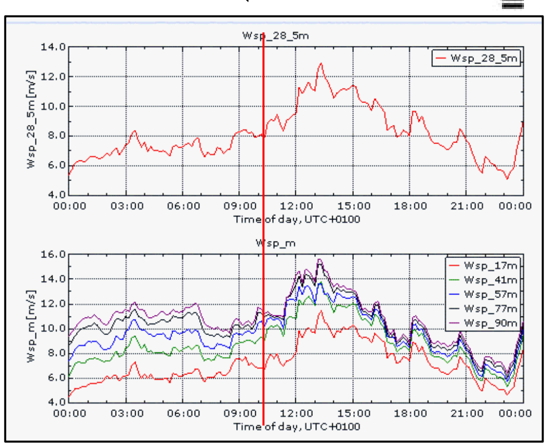
high frequency inflow sensors

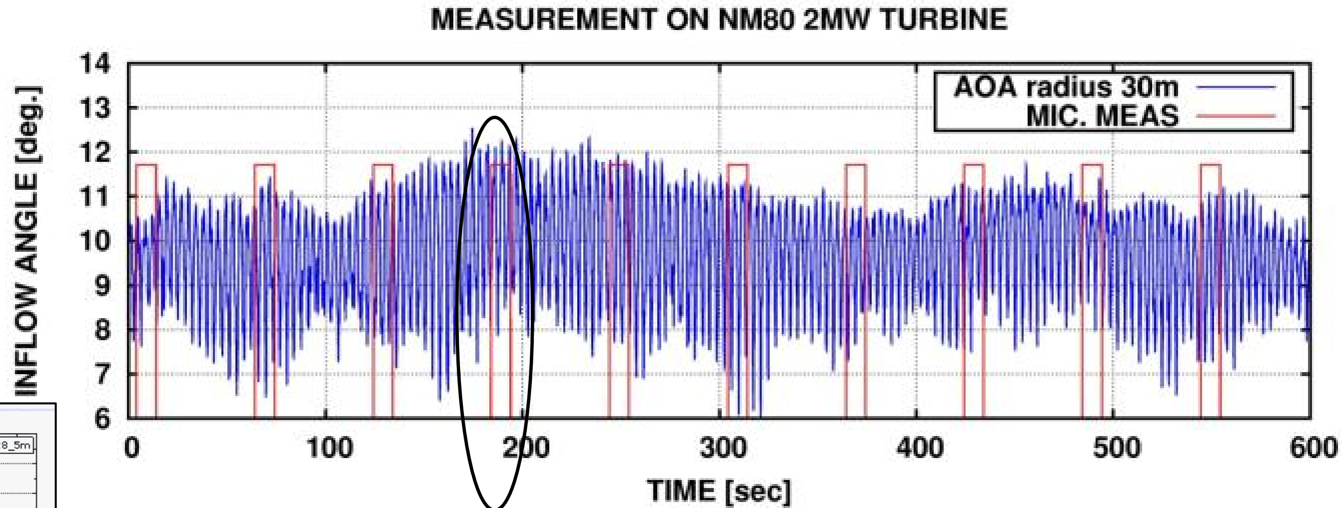


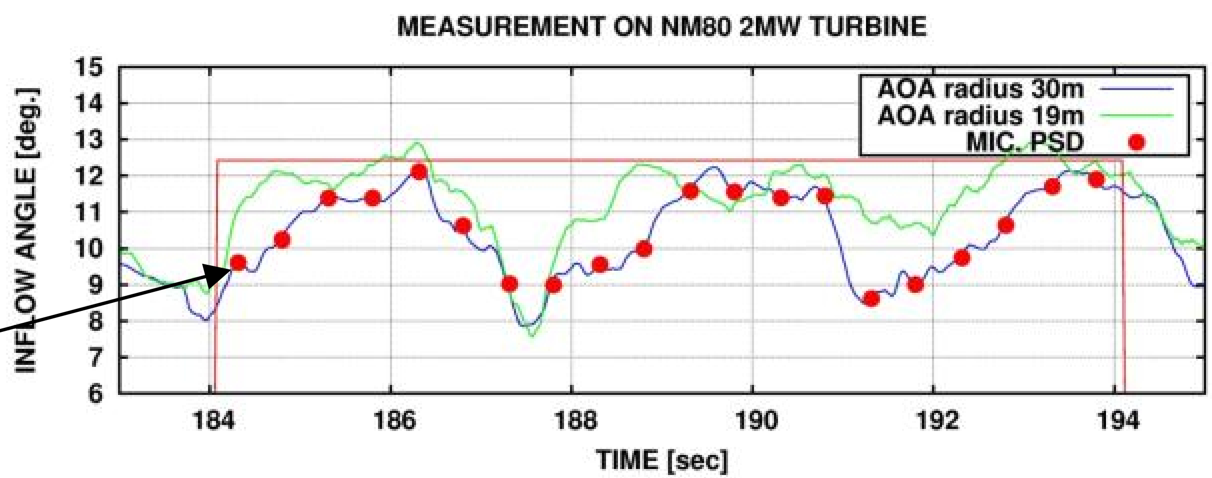
five hole pitot tubes

Measurement of SP on a full scale rotor blade, 80m diameter rotor, 2MW

Wind shear measured in the met mast

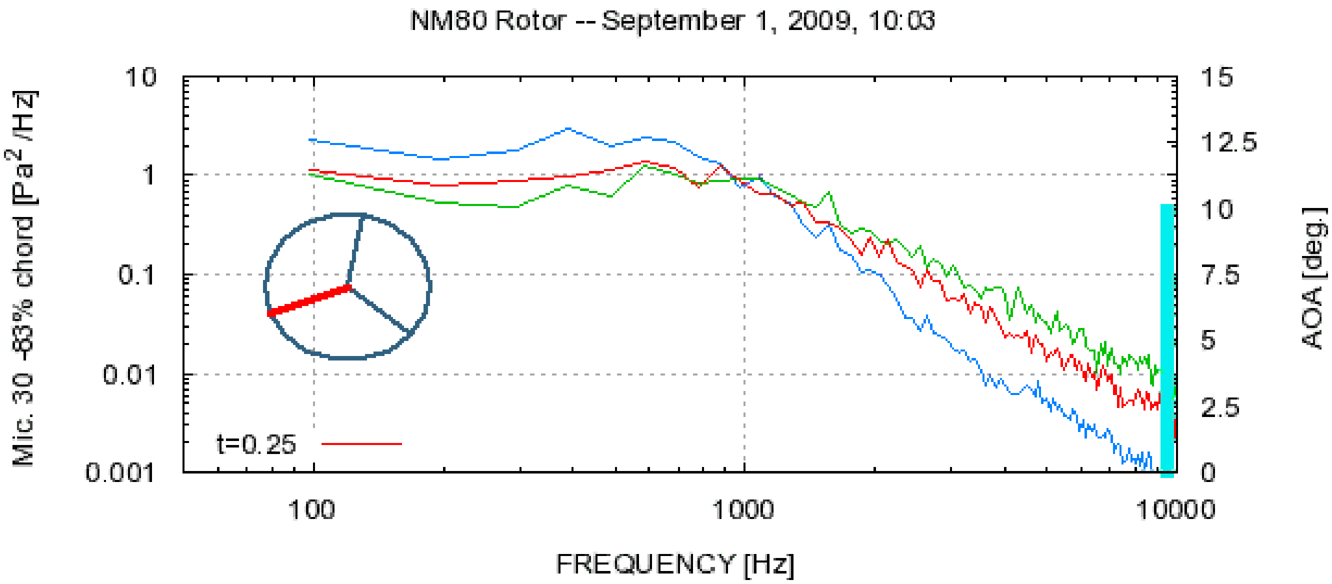






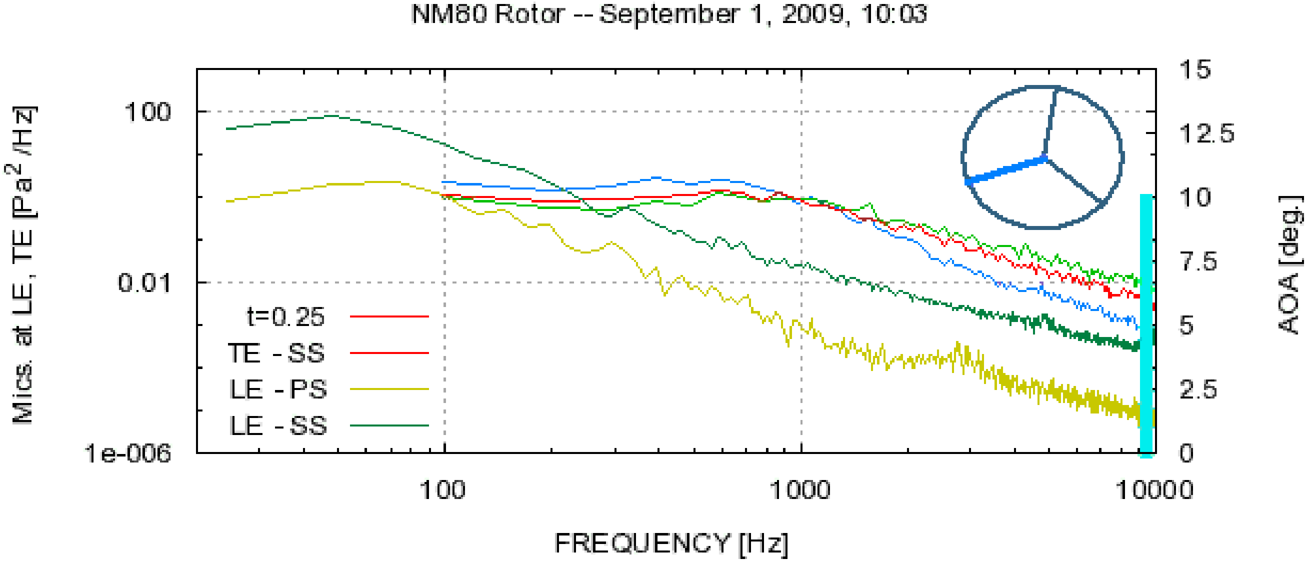
SP spectra derived at each red dot

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



Each spectrum is based on 0.5sec

TE + LE spectra measured during free inflow at 9-11m/s



Each spectrum is based on 0.5sec

Perspectives for application of the technique

A blade mounted sensor system for aeroacoustic noise source monitoring and control

Objectives of blade mounted monitoring system:

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

Advantages of system

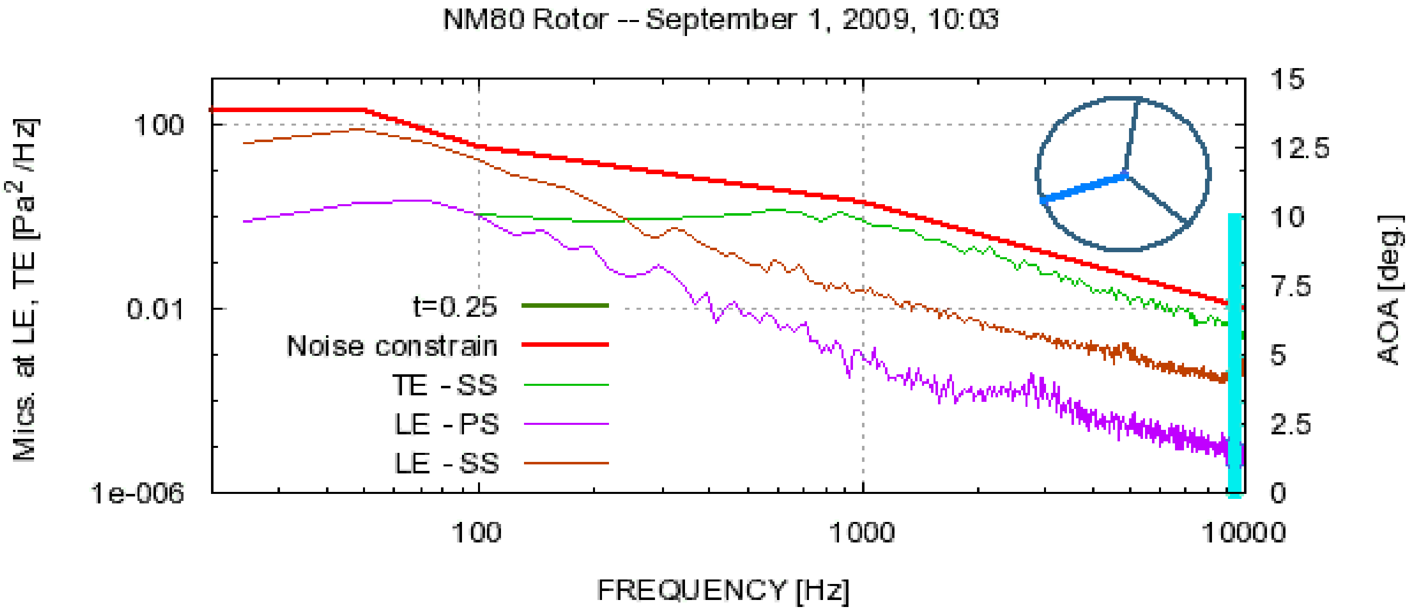
- Detailed and continuous source monitoring enables changes of turbine control system only when necessary
- Detailed source monitoring can provide input to the control system on an azimuth level, e.g. for individual pitch control to reduce/avoid amplitude noise modulation

Proposed system

Surface mounted microphones from B&K

Data processing and analysis system

One output screen from the system could be continuously updated PSD spectra of surface pressure fluctuations and **a noise constrain line**



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- DTU Wind Energy


Thank you for
your attention