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Publication date:
2012

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Citation (APA):
Aagaard Madsen , H., Bertagnolio, F., & Fischer, A. (2012). Measurement of high frequency surface pressure fluctuations for blade noise characterization [Sound/Visual production (digital)]. IQPC Conference on Wind Turbine Noise and Vibration Control, Bremen, Germany, 22/10/2012

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Measurement of high frequency surface pressure fluctuations for blade noise characterization

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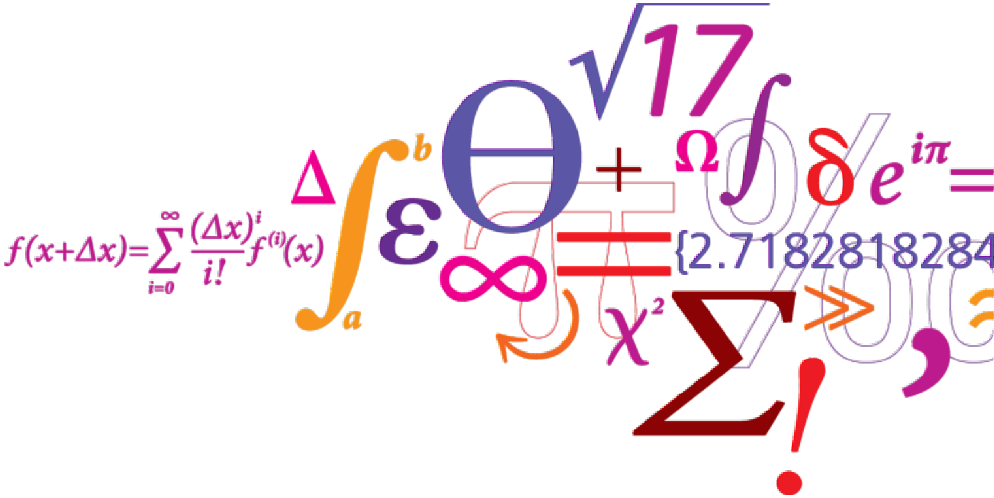


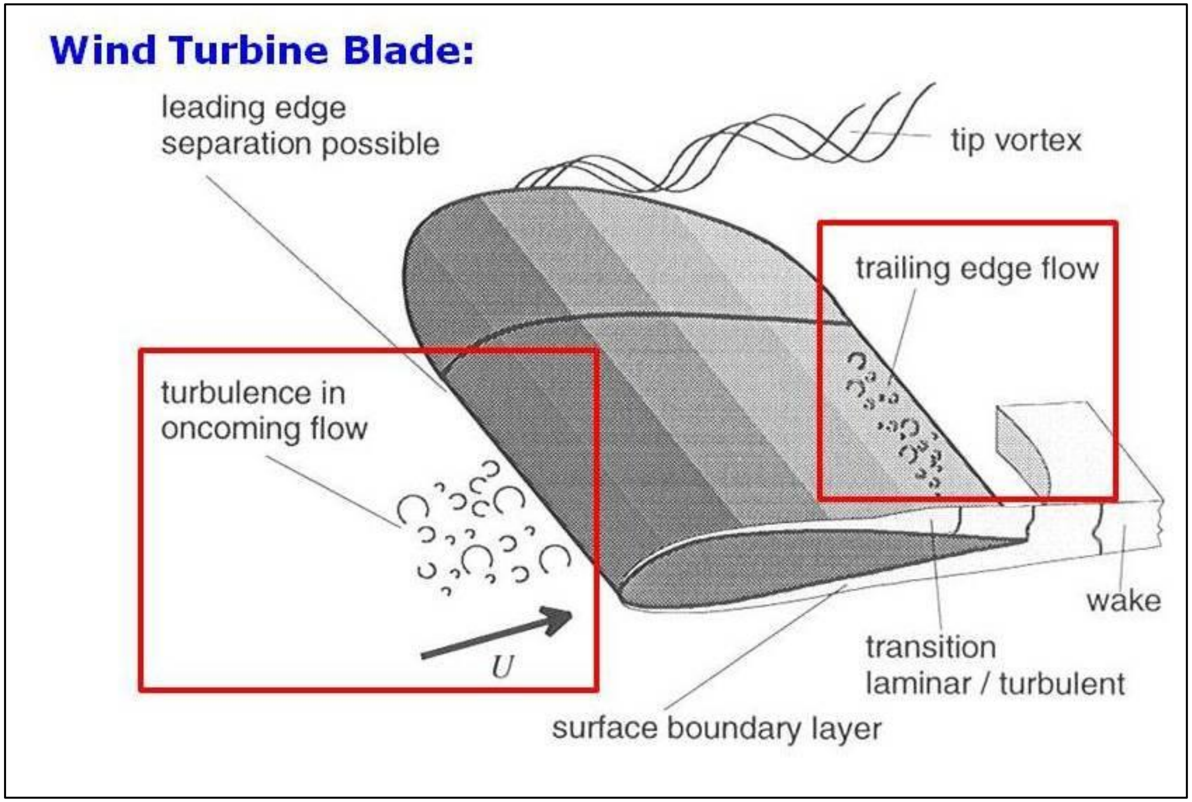
DTU Wind Energy
Department of Wind Energy

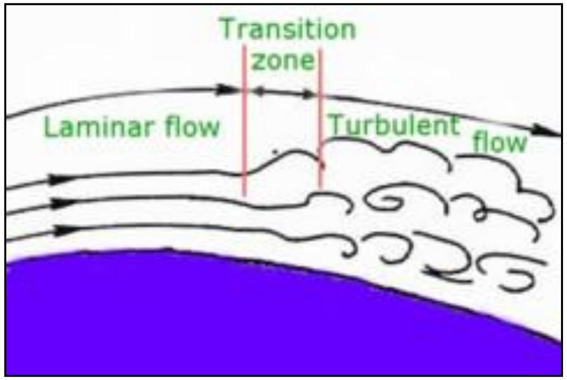
Outline

- Why using high frequency surface pressure measurements ?
- Surface pressure to far field noise
- Measurement technique
- Wind tunnel measurements compared with model results
- Measurements on a full scale 80m diameter rotor
- Influence of different inflow conditions on the noise source
- Perspectives for application of the technique

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

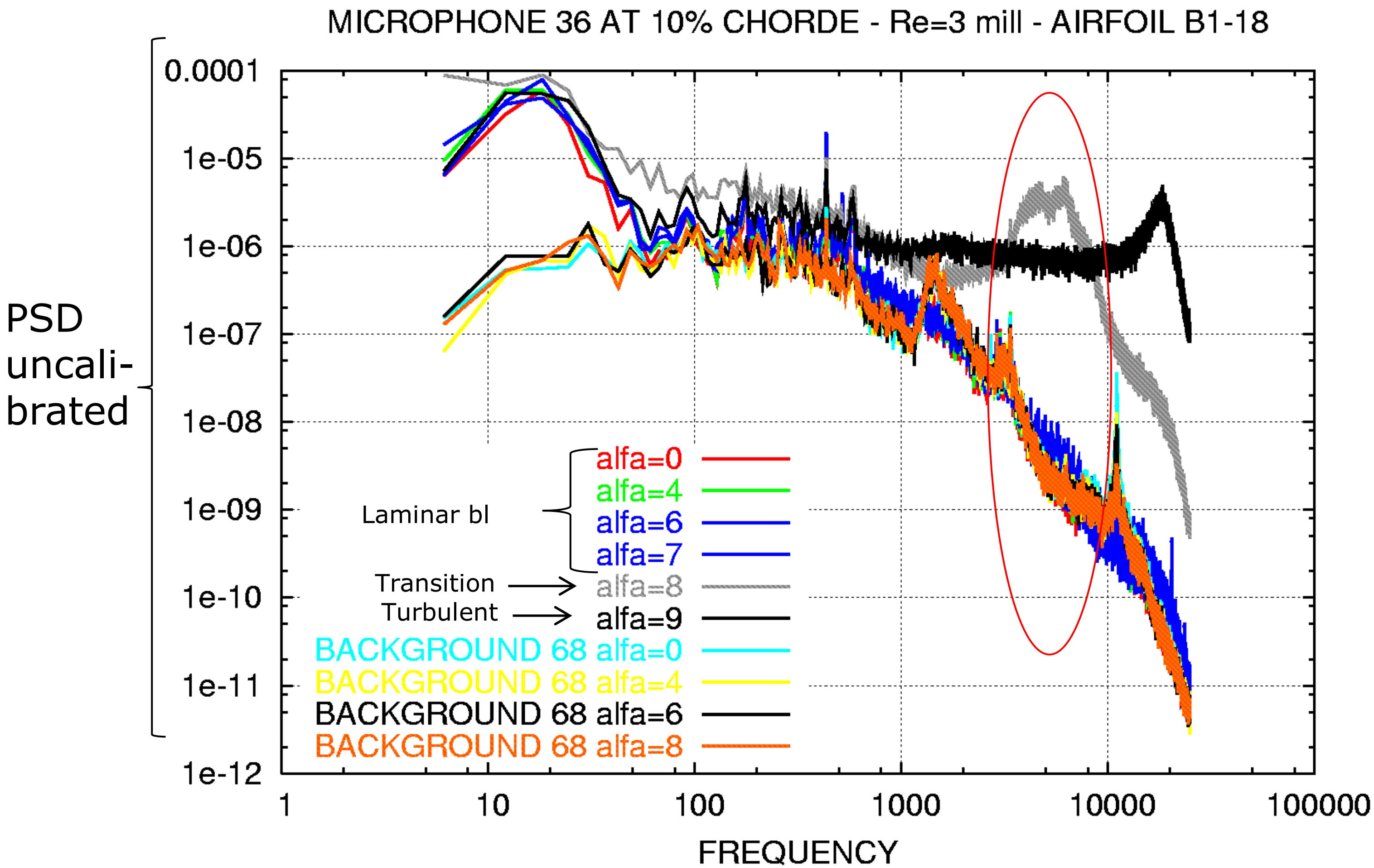
- SP is the source of trailing edge (TE) noise
- SP is the source of turbulent inflow (TI) noise
- SP has a high intensity compared with ambient noise



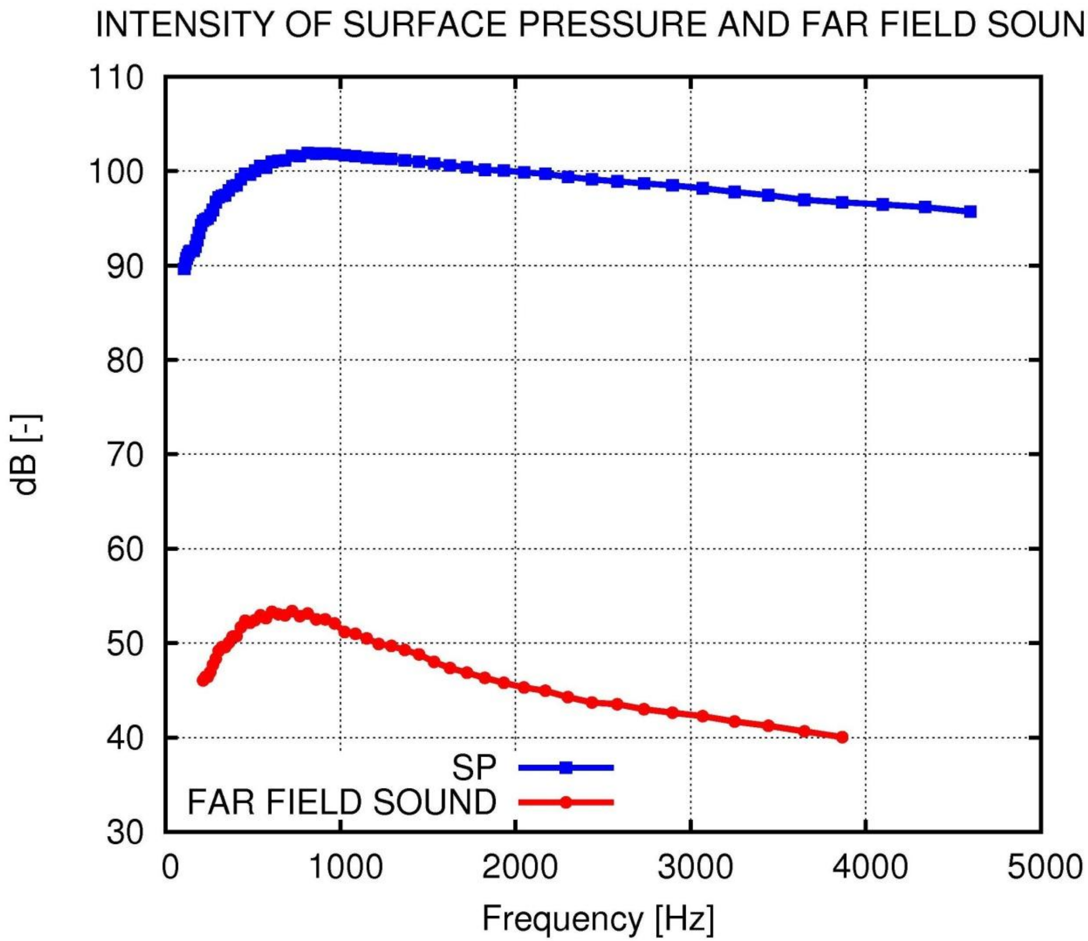


- Measuring SP enables correlation with detailed inflow data from inflow sensors on the blade
- Measuring SP provides more accurate aeroacoustic characterization during design and testing of new low noise airfoil designs
- Measuring SP provides detailed noise source information, enabling continuous, optimal input to the turbine control system for operation within noise constrains

SP in a turbulent boundary layer has a high intensity compared with ambient noise



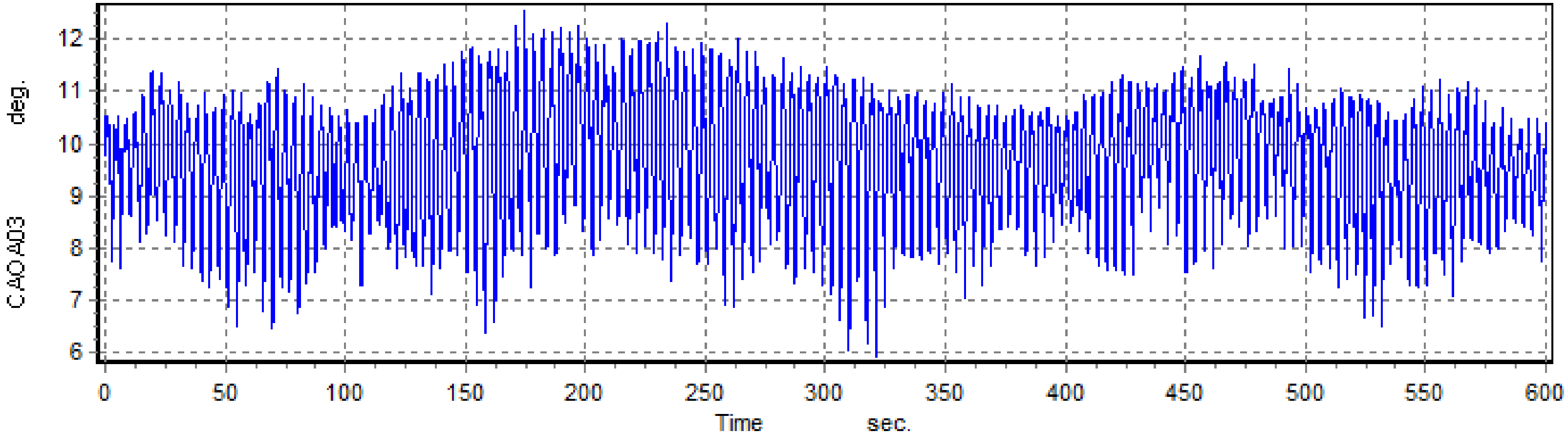
SP in the turbulent boundary layer has a high intensity compared with the farfield sound

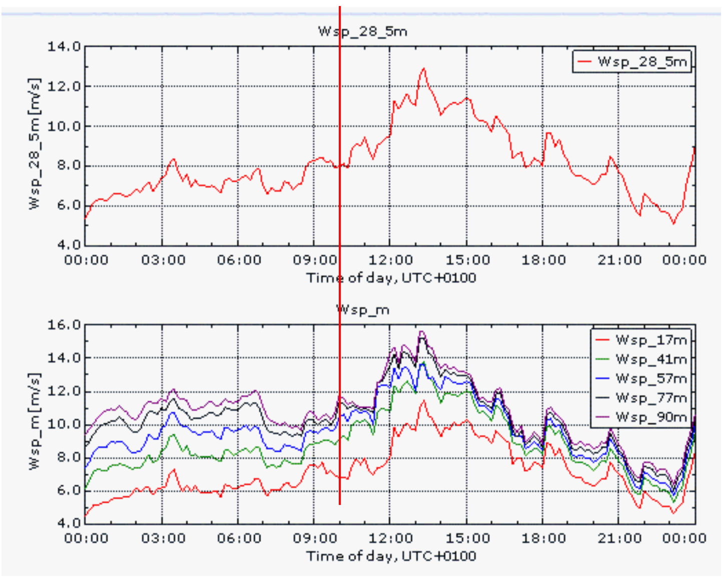


Based on set-up in the Virginia-Tech Wind Tunnel 2011 – NACA64-618 airfoil at 1.5 mill Re

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



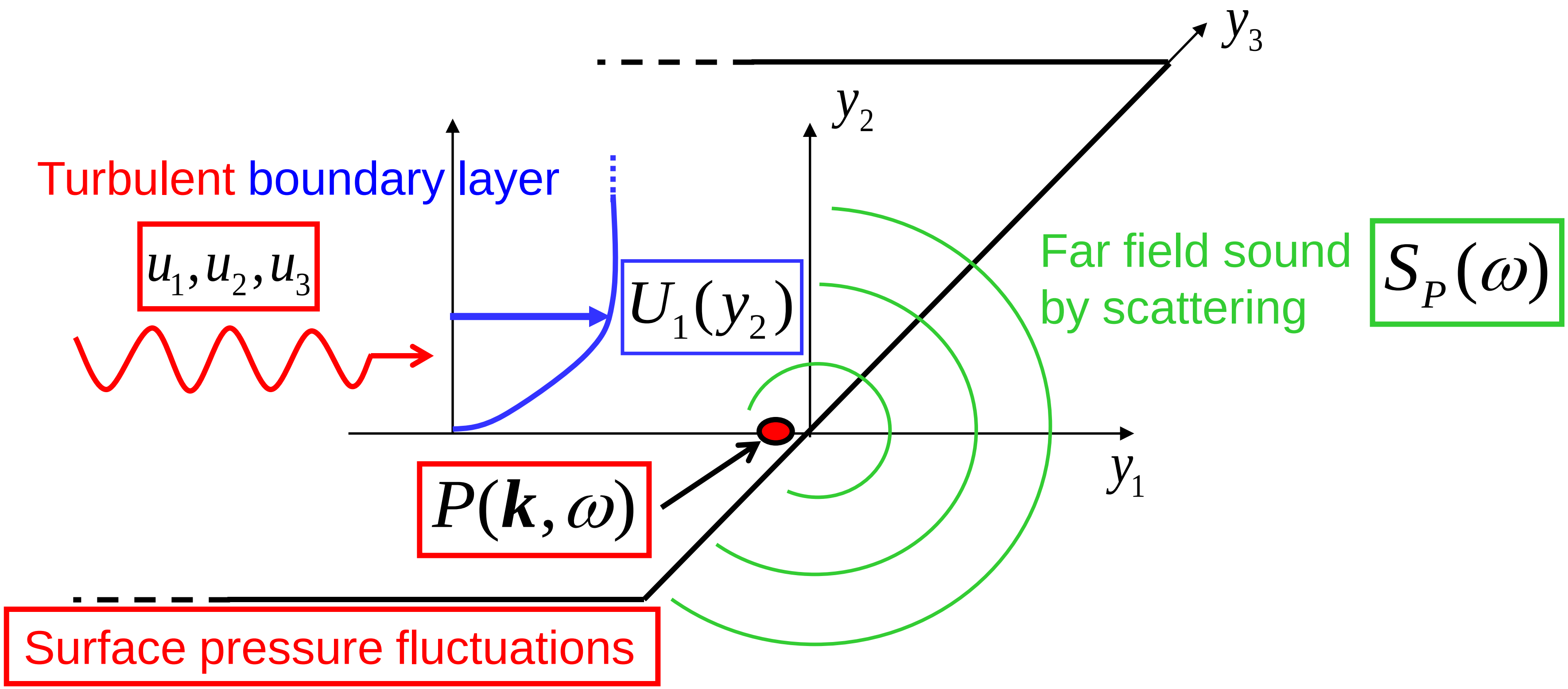


Drawbacks with the SP technique compared with traditional far field measurements

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

Surface pressure to far field noise

TE Noise Mechanism



Using TNO model & CFD to evaluate: $P(\boldsymbol{k} = \{k_1, k_3\}, \omega)$

TNO model* + CFD RANS Calculation

...yield SP spectrum (Blake, 1986):

$$P(\mathbf{k},\omega)=4\rho_0^{\,2}\,\frac{k_1^{\,2}}{k_1^{\,2}+k_3^{\,2}}\int_0^{+\infty} L_2(y_2)\left(\frac{\partial U_1}{\partial y_2}\right)\overline{u_2^{\,2}}\cdot\Phi_{22}(\mathbf{k},\omega)\cdot\Phi_m\left[\omega-U_c k_1\right]\cdot \mathrm{e}^{-ky_2}\,\mathrm{d}y_2$$

Isotropic turbulence ($L_2(y_2)$):

$$\frac{L_2}{0.745}=\Lambda=0.519\cdot\frac{k_T^{3/2}}{\varepsilon}$$

Empirical approx. ($\overline{u_2^{\,2}}$):

$$\overline{u_2^2}=0.45\cdot k_T$$

Von Karman Isotropic Spectrum ($\Phi_{22}(\mathbf{k},\omega)$):

$$\Lambda=0.519\cdot\frac{k_T^{3/2}}{\varepsilon}$$

$\frac{\partial U_1}{\partial y_2}$, $\frac{k_T^{3/2}}{\varepsilon}$, k_T → **In-house CFD RANS code EllipSys2D**

* modified TNO model:

F. Bertagnolio, Experimental Investigation and Calibration of Surface Pressure Modeling for Trailing Edge Noise, in: Proc. of Inter-Noise 2011 Conf., Osaka, Japan.

TE Noise Evaluation from SP Spectra

- **Far-Field Noise (Howe, 1978):**

$$S_P(\omega) = \frac{L_{span}}{4\pi R^2} \int_{-\infty}^{+\infty} \frac{\omega}{c_0 k_1} \cdot \underline{P(k_1, k_3 = 0, \omega)} \, \mathrm{d}k_1$$

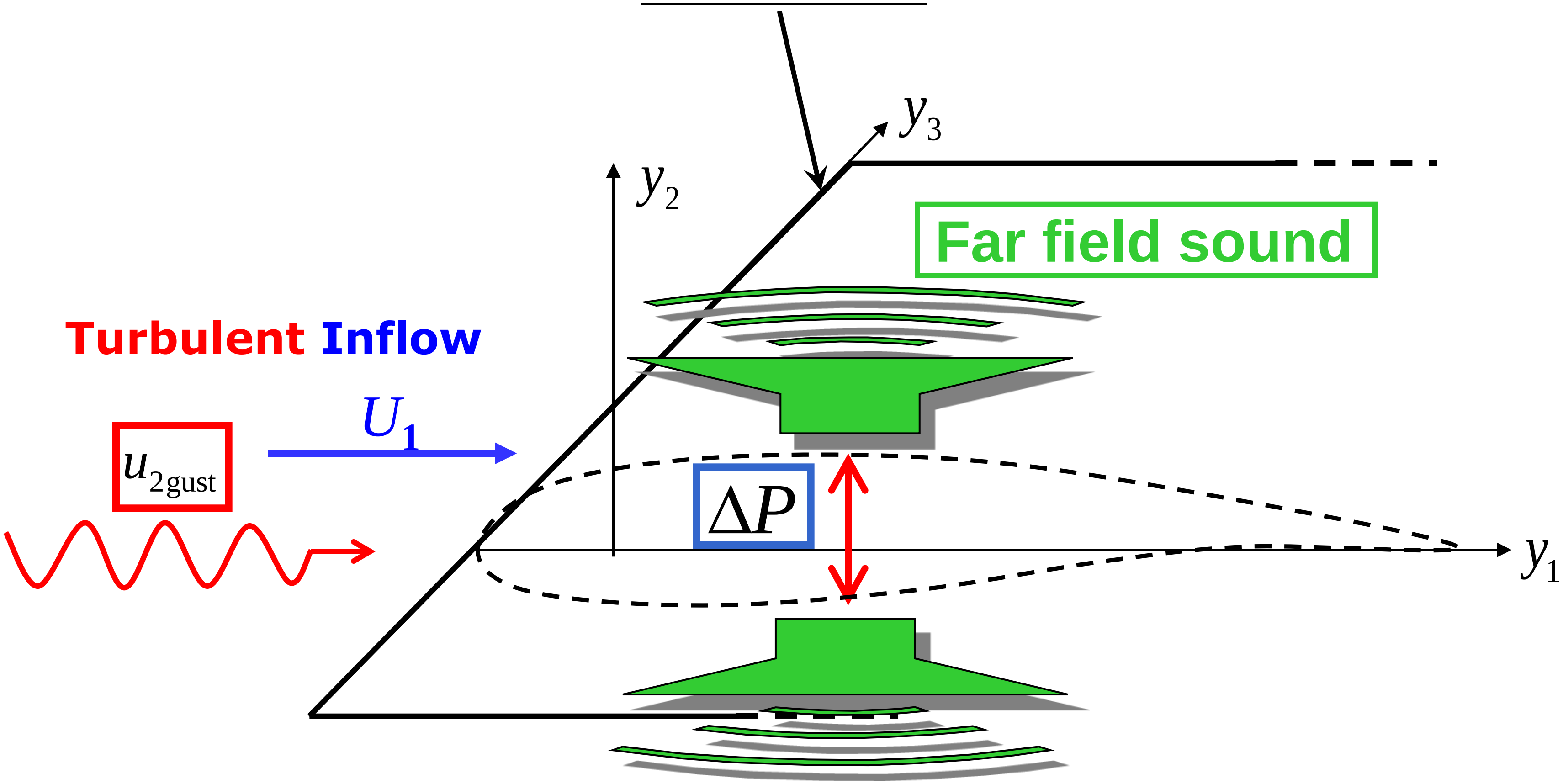
- **Surface Pressure *Frequency-*Spectrum:**

$$P(\omega) = \iint_{-\infty}^{+\infty} \underline{P(k_1, k_3, \omega)} \, \mathrm{d}k_1 \mathrm{d}k_3$$

Measured by HF mics.

Turbulent Inflow Noise

Idealized Airfoil as an Half-Plane

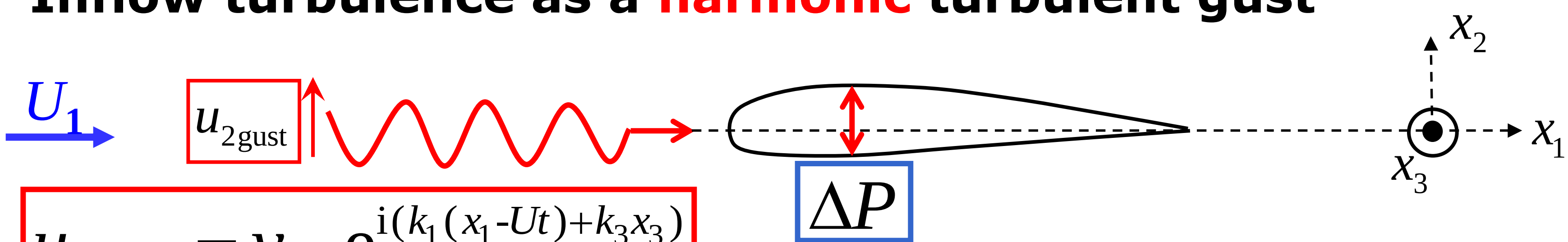


Turbulent Inflow Noise Model

Amiet's Theory (1976)

Linearized Inviscid Theory *for* *flat plate* *with* *0-mean loading*

- **Inflow turbulence as a harmonic turbulent gust**



$$u_{2,gust} = v_0 \cdot e^{i(k_1(x_1 - Ut) + k_3 x_3)}$$

- **Surface pressure response using Sears' theory:**

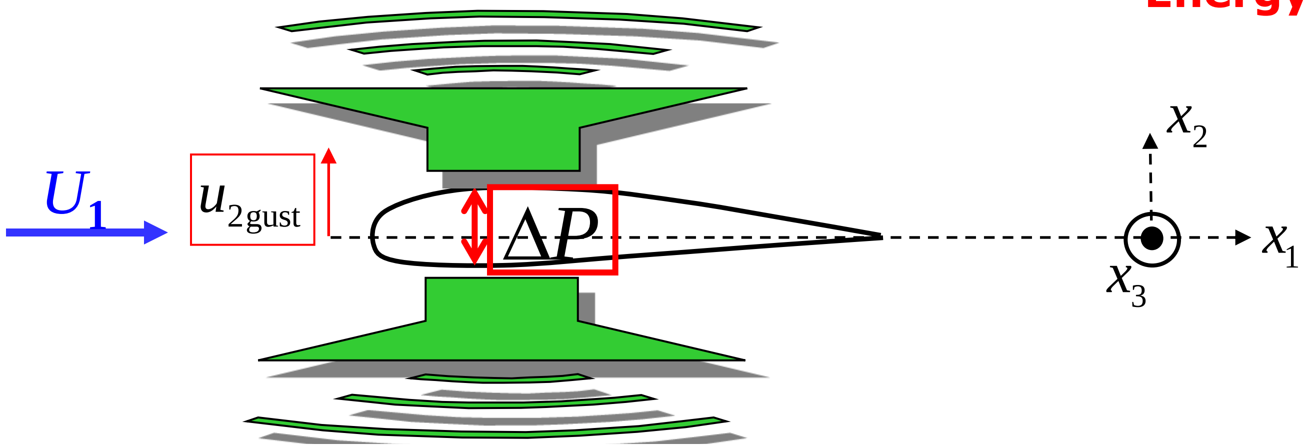
$$\Delta P(x_1, x_3, t, k_1, k_3) = 2\pi\rho_0 v_0 g(x_1, k_1, k_3) \cdot e^{i(k_1 U t - k_3 x_3)}$$

where *g* is the transfer response function

Turbulent Inflow Noise Model

The energy spectrum of the local airfoil surface pressure jump fluctuations then reads:

$$\Phi_p(x,\omega) = 2U(\pi\rho)^2 \int_0^\infty g^*(\xi,K_1,k_3)\cdot g(\xi,K_1,k_3)\underbrace{\Phi_{22}(K_1,k_3)}_{\text{Energy spectrum of } u_{2gust}}dk_3$$



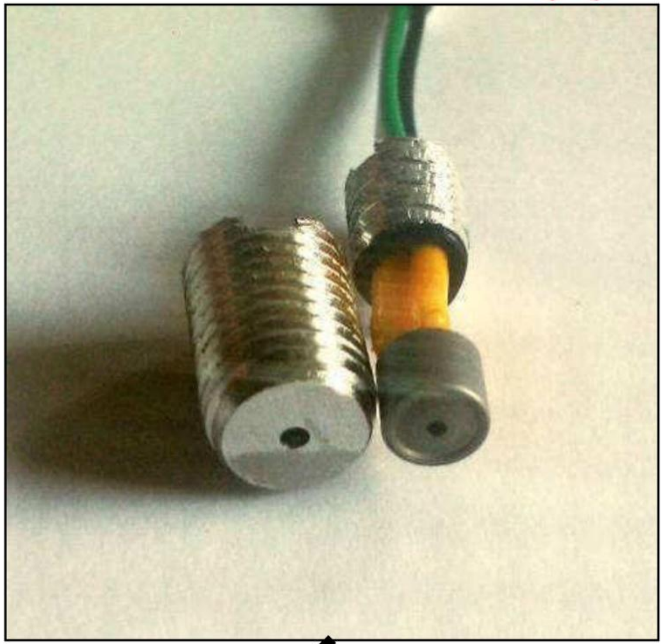
Pressure jump fluctuations radiate as dipole to far field noise

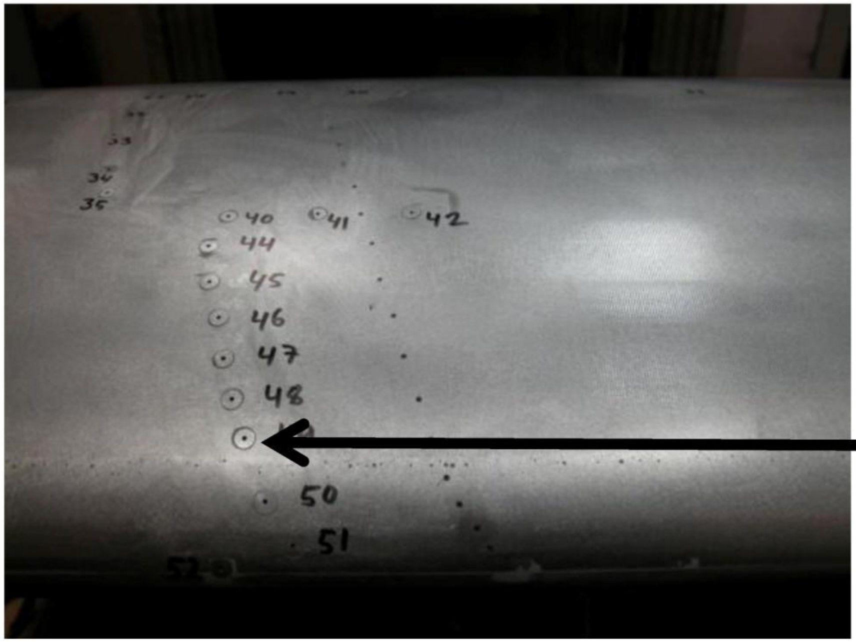
$$S(r,\omega) = \left(\frac{\omega\rho b y}{c_0\sigma^2}\right)^2 \pi U d \left|L(r,K_1,K_3)\right|^2 \Phi_{22}(K_1,K_3)$$

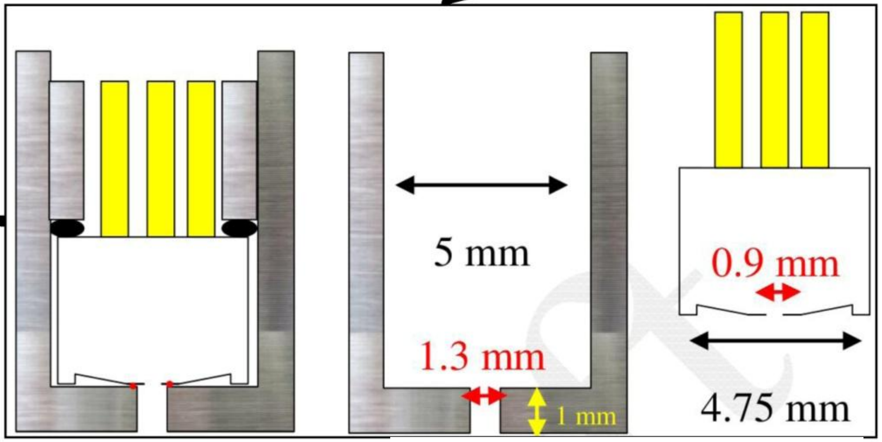
The measurement technique

SURFACE PRESSURE – Meas. Technique

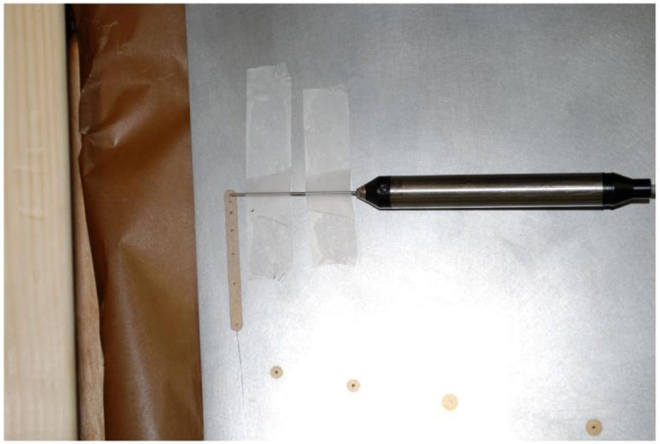
Flush-mounted HF microphones







Calibration of microphones in cooperation with B&K



(a) reference microphone and pinhole

(b) Sennheiser headphone HD650 source

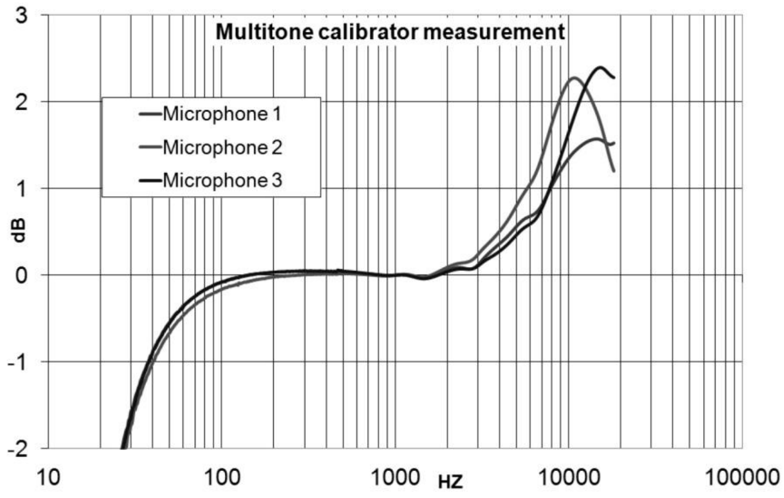
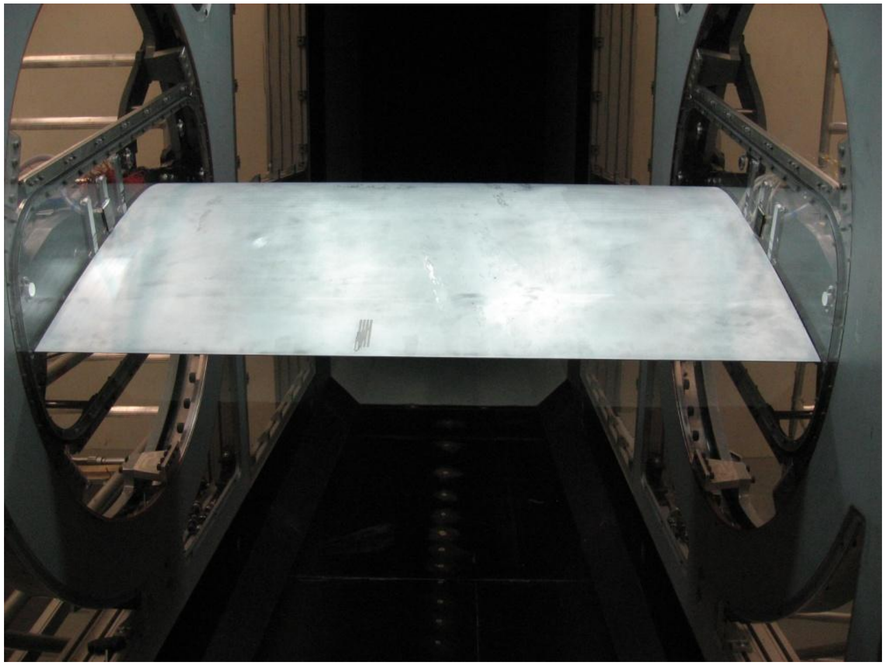


Figure 4: High-Frequency Microphones Deviations [Figure courtesy of Brüel & Kjær]

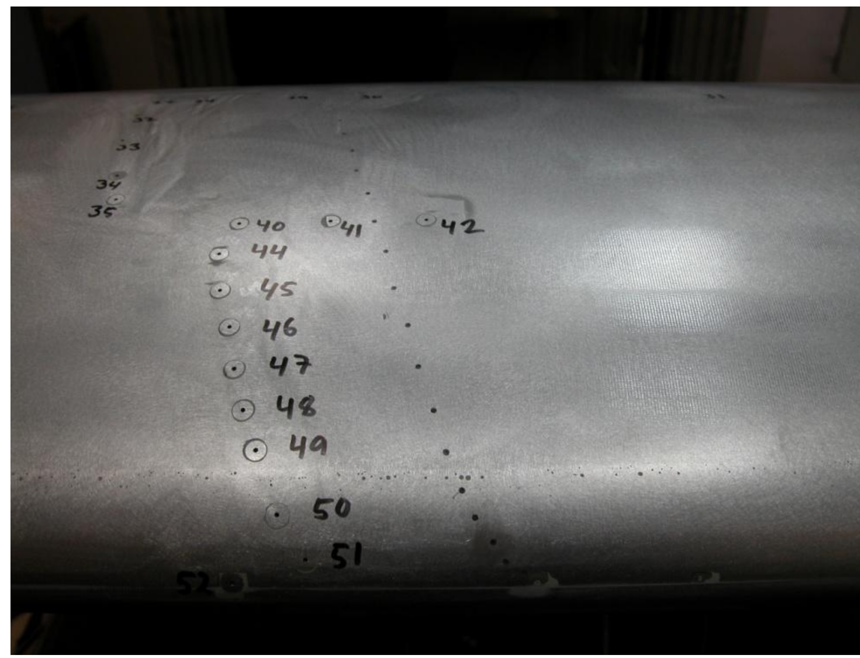
Wind tunnel measurements compared with model results

Test in the LM Wind Tunnel - 2007

Aerodynamic Test Facility

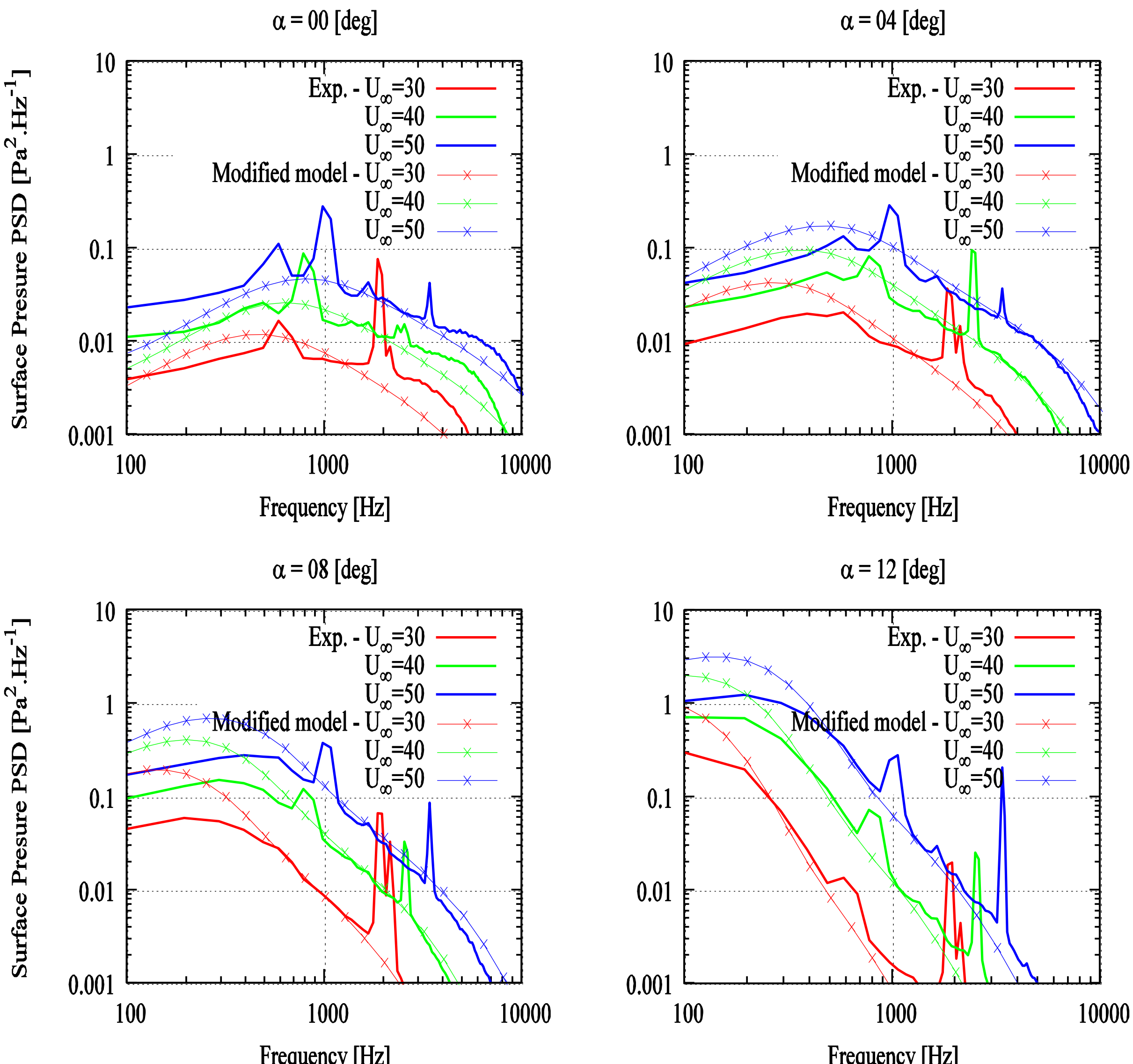


NACA0015 Airfoil Section

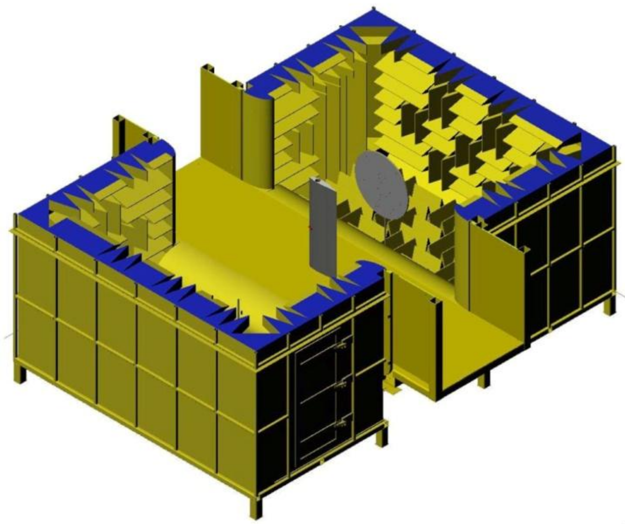


Surface Pressure Measurement Holes

Surf. Pres. Measurements near TE



Virginia Tech measurements 2011*
- NACA64-618 airfoil with microphones



Can we transfer SP to far field sound ?

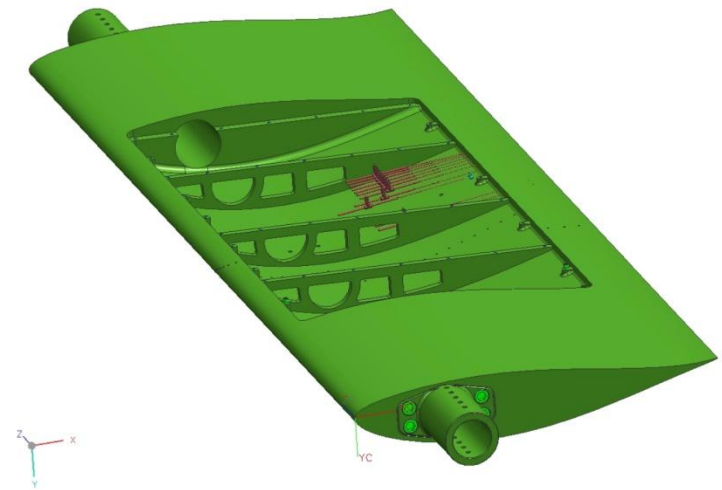


Figure 3.6: CAD rendering of NACA64-618 airfoil with open lid and view on the instrumentation (red: microphone tube adapters)

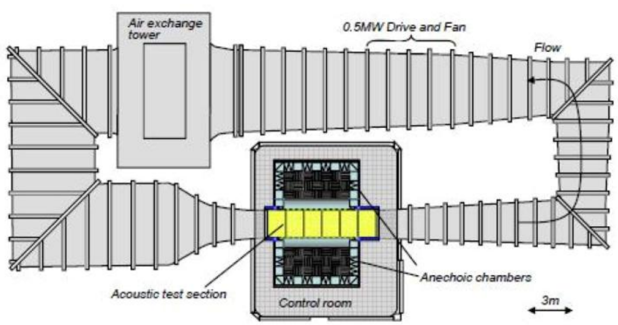
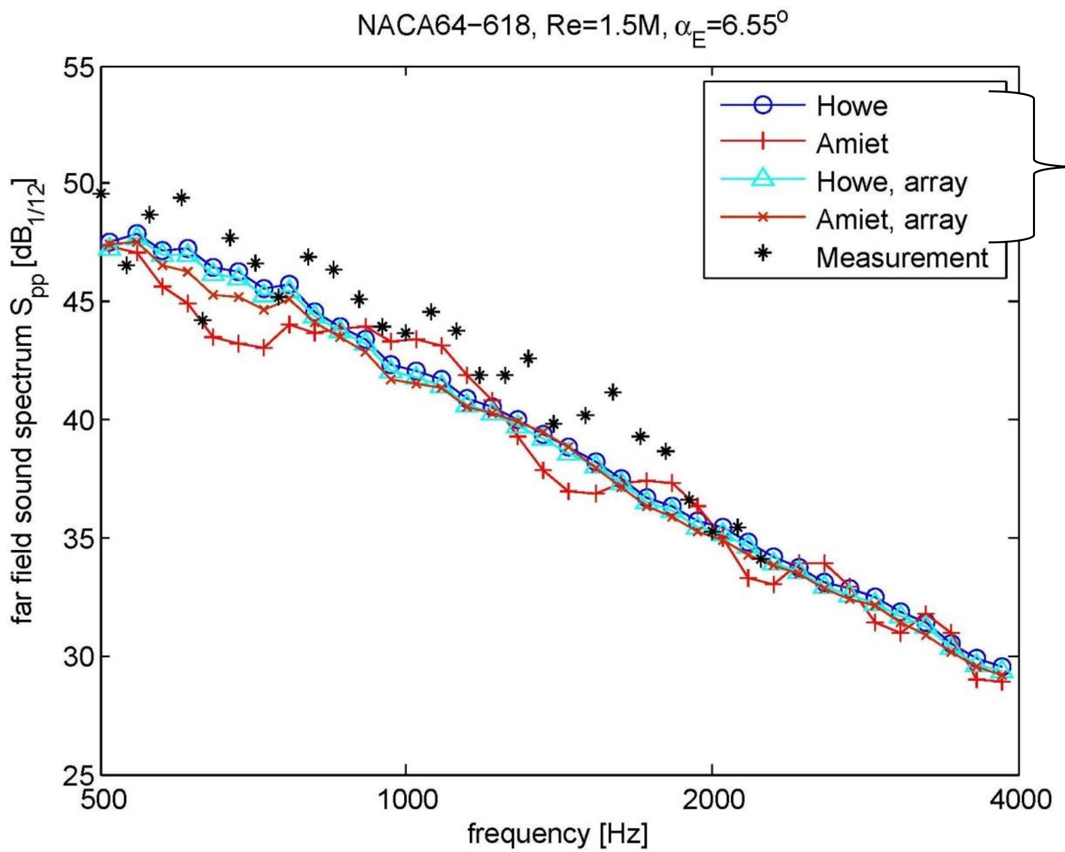


Figure 3.4: Schematic of the Virginia Tech Stability Wind Tunnel in acoustic configuration from [37]

* PhD thesis report by Andreas Fischer (2011) "Experimental characterization of airfoil boundary layers for improvement of aeroacoustic and aerodynamic modeling "

Virginia Tech measurements 2011*
- NACA64-618 airfoil with microphones



Derived from SP measurements

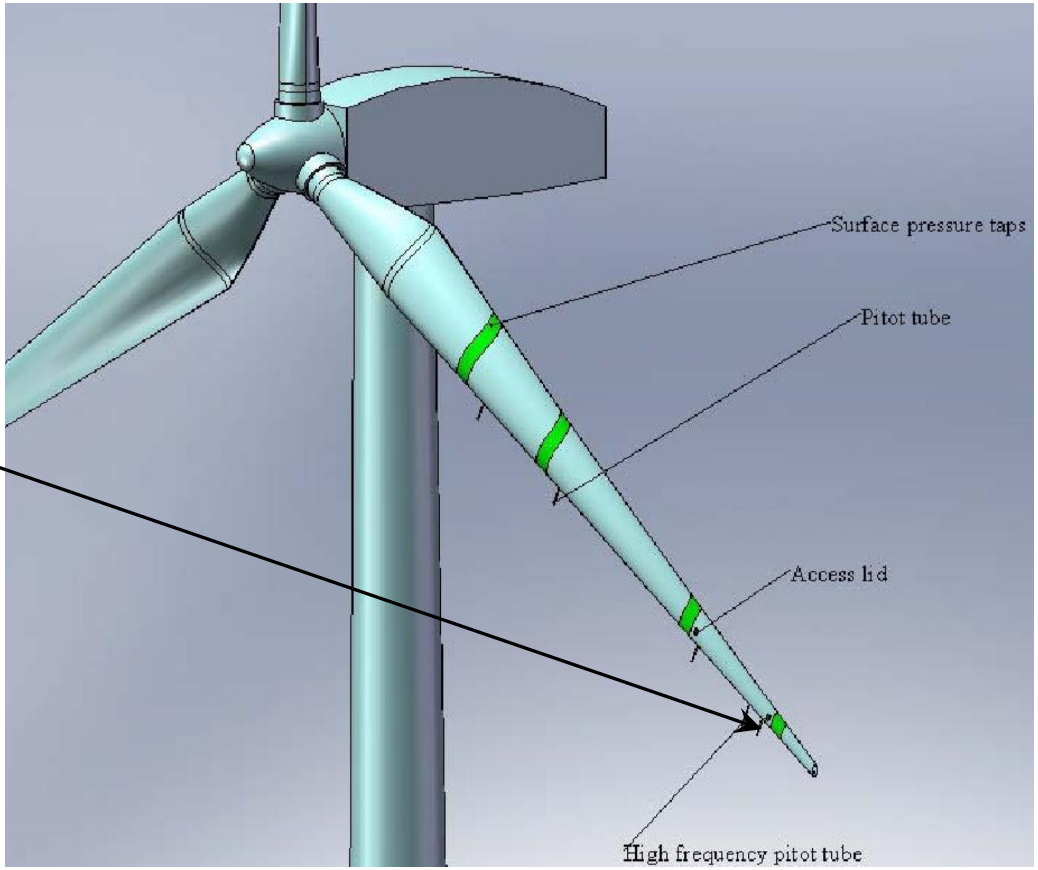
* PhD thesis report by Andreas Fischer (2011) "Experimental characterization of airfoil boundary layers for improvement of aeroacoustic and aerodynamic modeling "

Measurements on a full scale 80m diameter rotor

- From the DAN-AERO project -

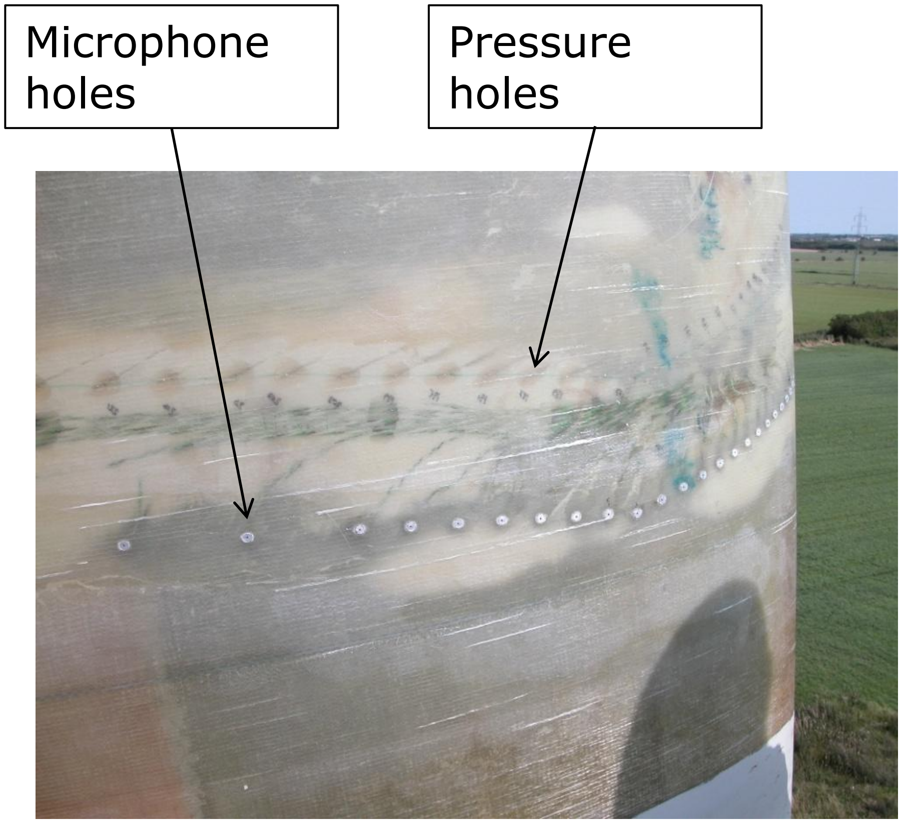
Measurement of SP on a full scale rotor blade, 80m diameter rotor, 2MW - - DAN-AERO MW project

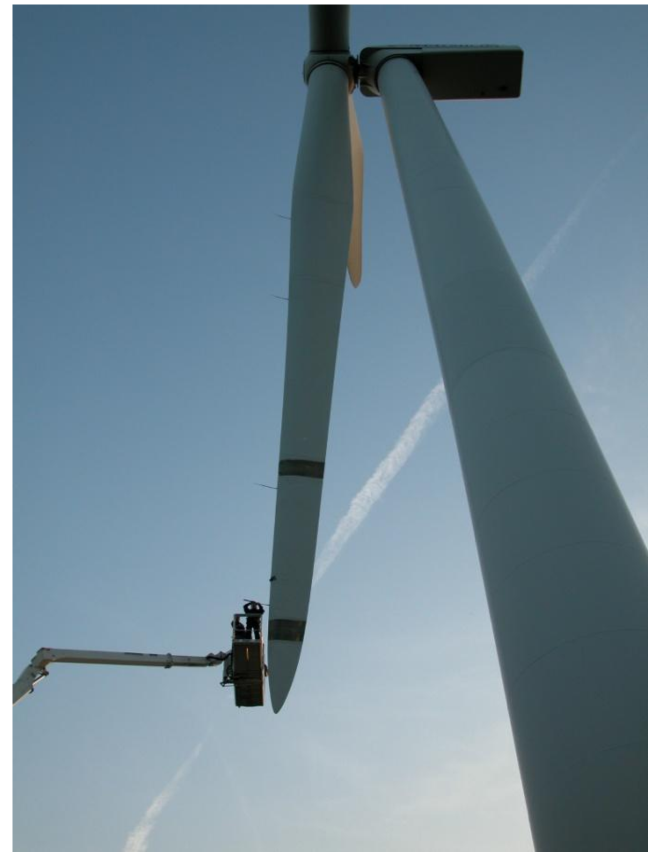
- surface pressure and inflow measured at 4 radial stations
- **the outboard station also instrumented with around 60 microphones for high frequency surface pressure measurements**
- high frequency measurements of the inflow
- measurements from June to September 2009



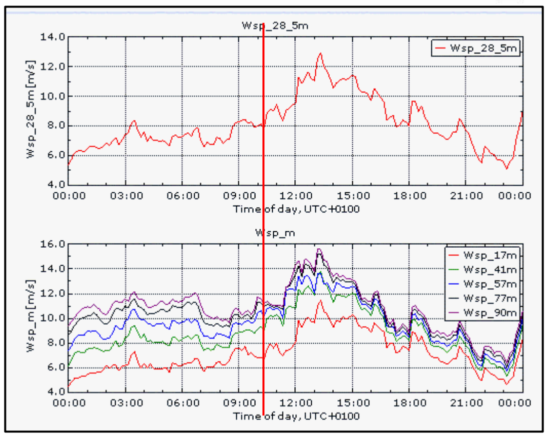
Installation of the 38.8m instrumented blade in May 2009

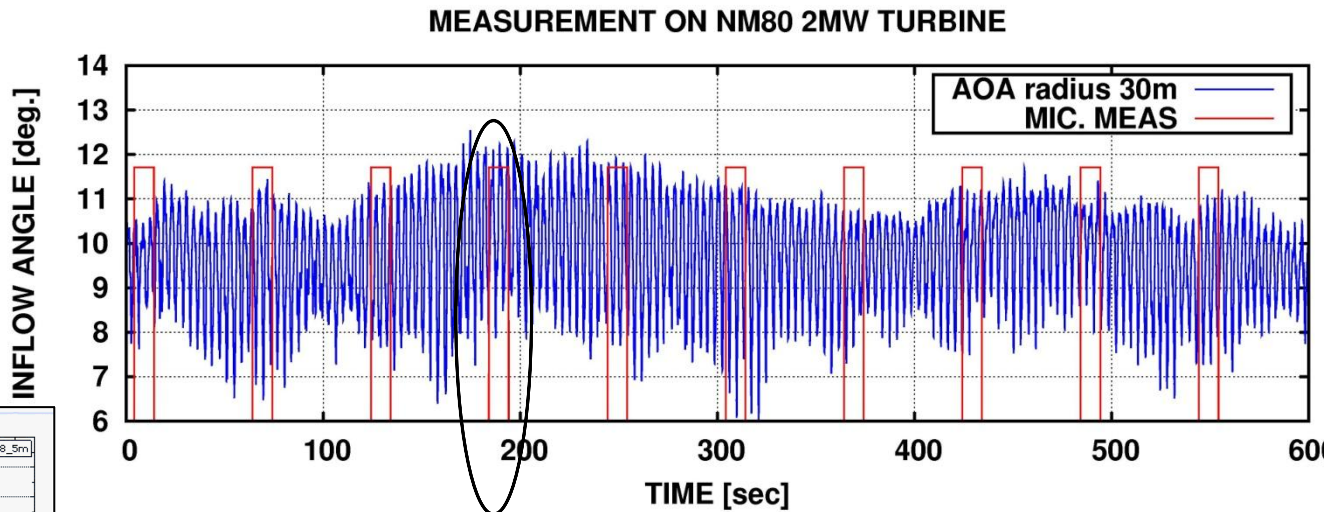
Campaign measurements from June to September 2009

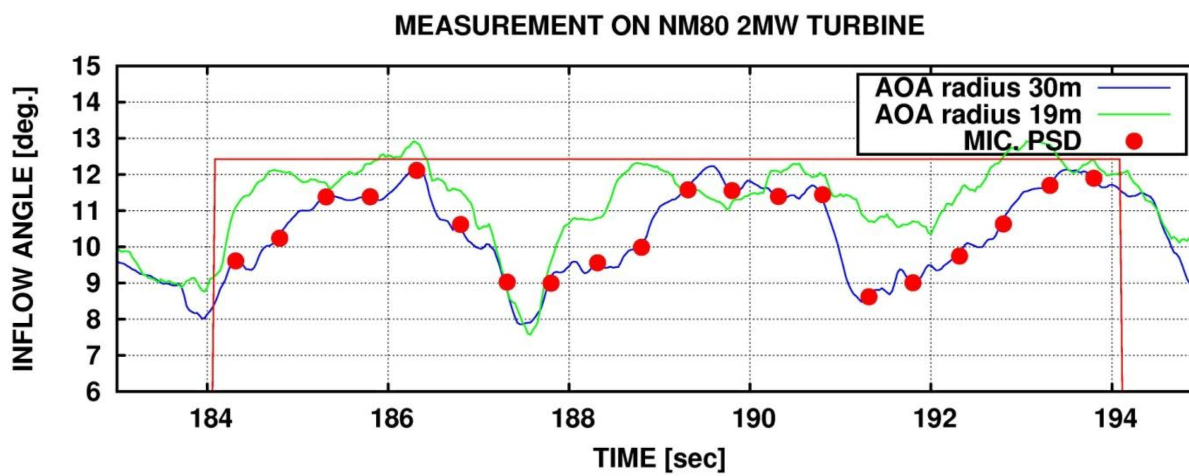




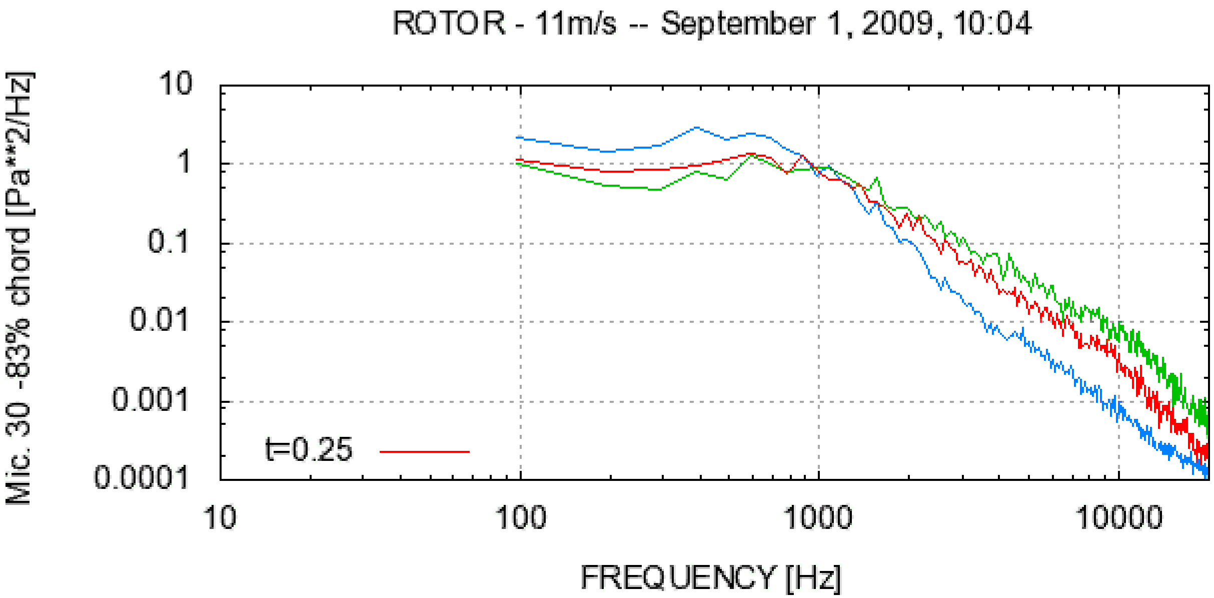
Measurement of SP on a full scale rotor blade, 80m diameter rotor, 2MW





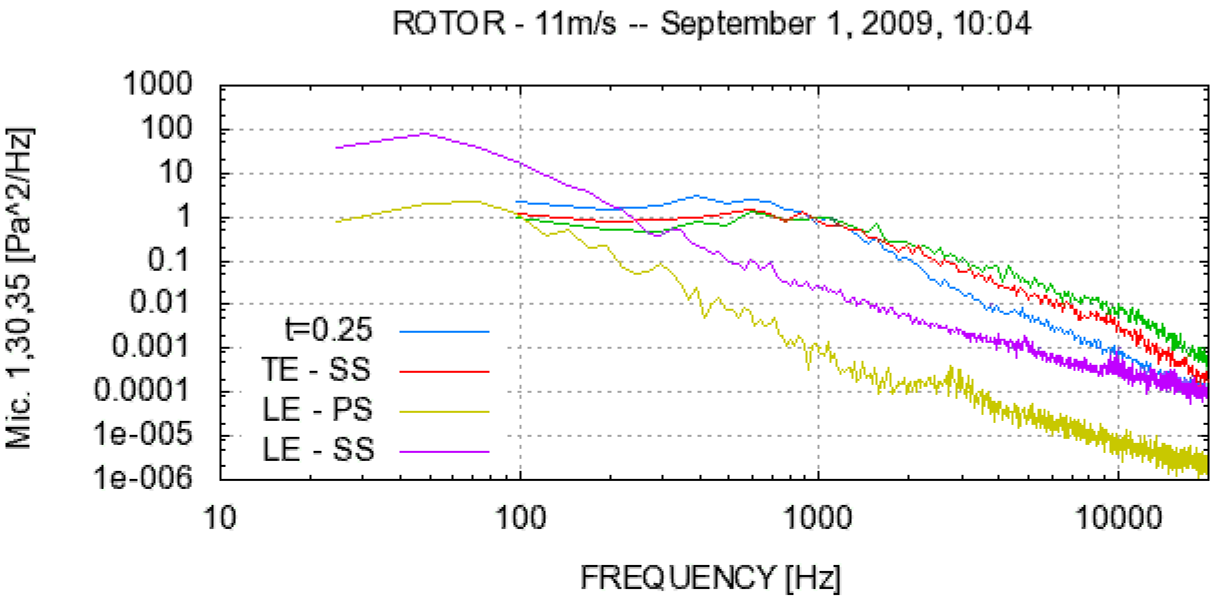


TE spectra measured during free inflow at 9-11m/s



Each spectrum is based on 0.5sec

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



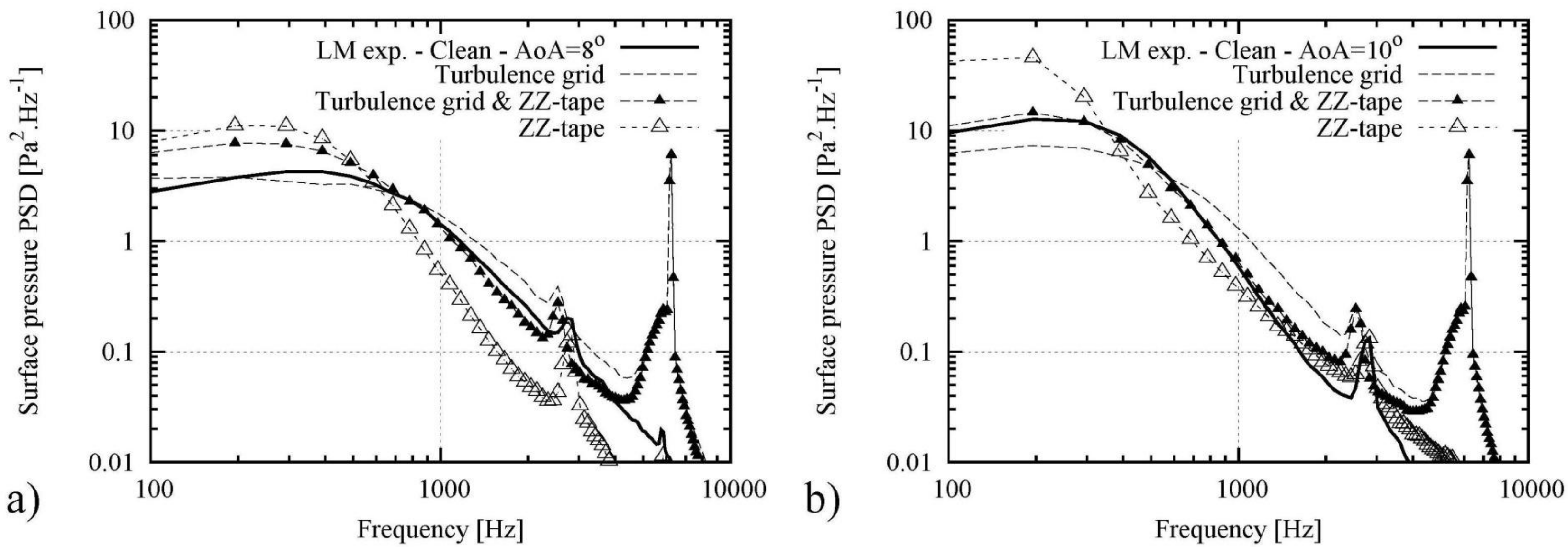
Each spectrum is based on 0.5sec

Influence of different inflow conditions on the noise source

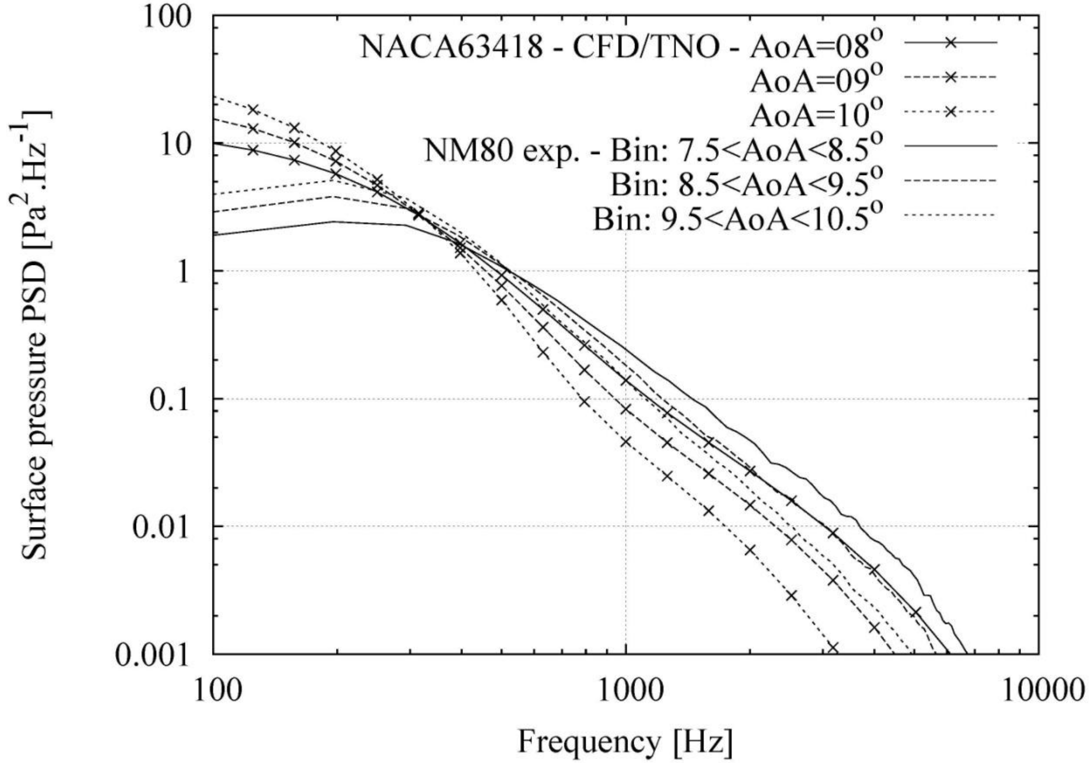
Influence of turbulence in inflow ?

- turbulence grid in wind tunnel
- increased turbulent inflow to rotor due to wake operation

Influence of turbulence in inflow ?



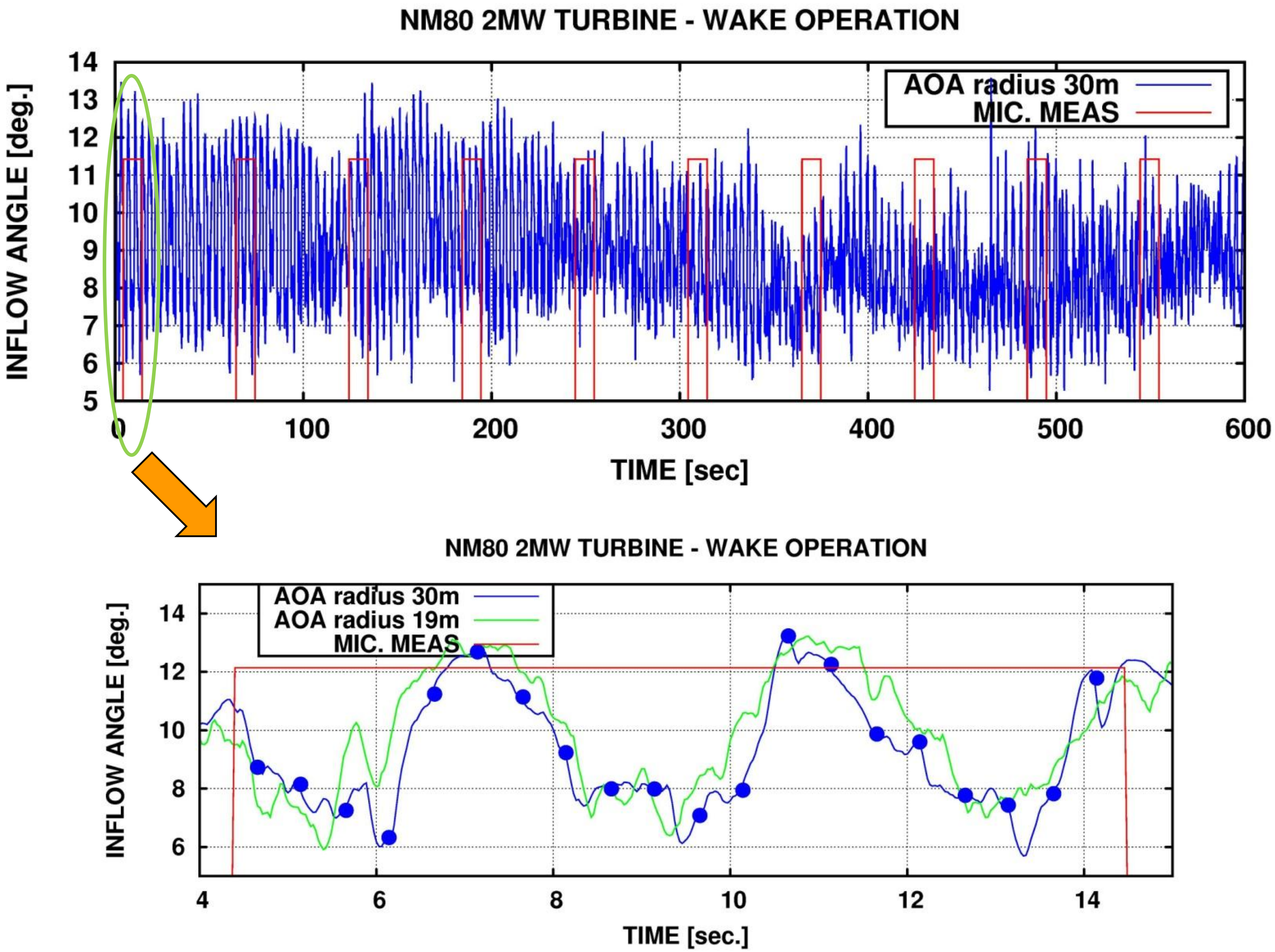
Deviations due to influence of turbulence in inflow ?



(b) SP Spectra near TE ($x/C = 93\%$, Suction side)

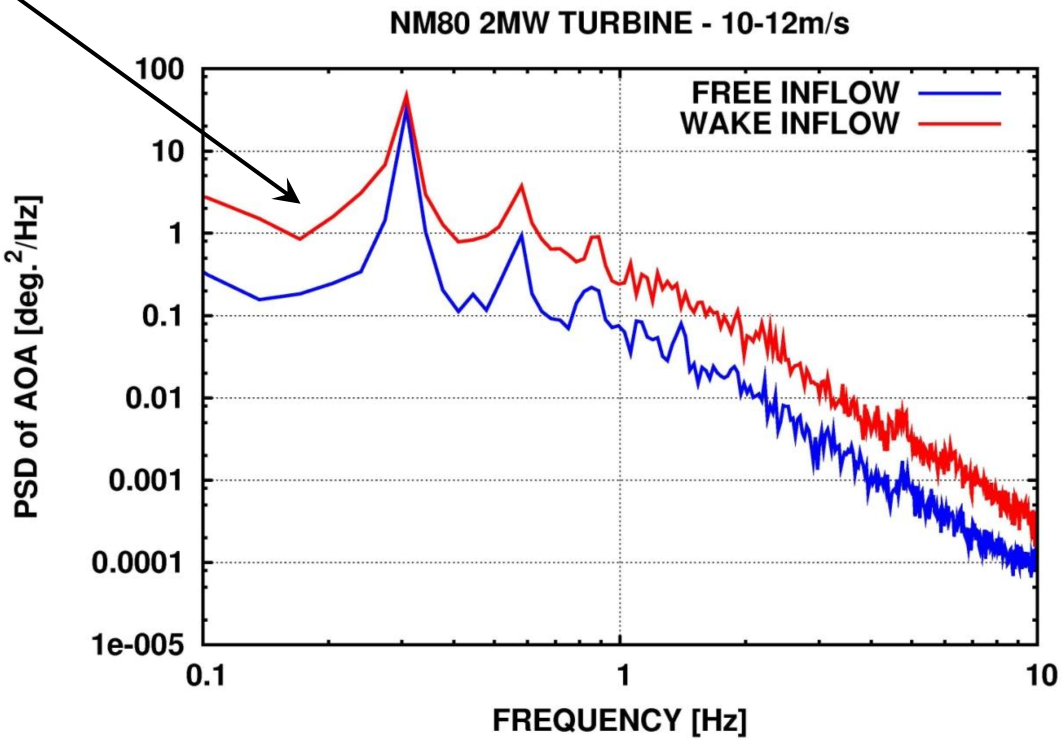
Figure 9: NM80 Rotor (vs. CFD/TNO Model for SP near TE) - Influence of AoA

Influence of wake operation
- distance to upstream turbine 3.5D

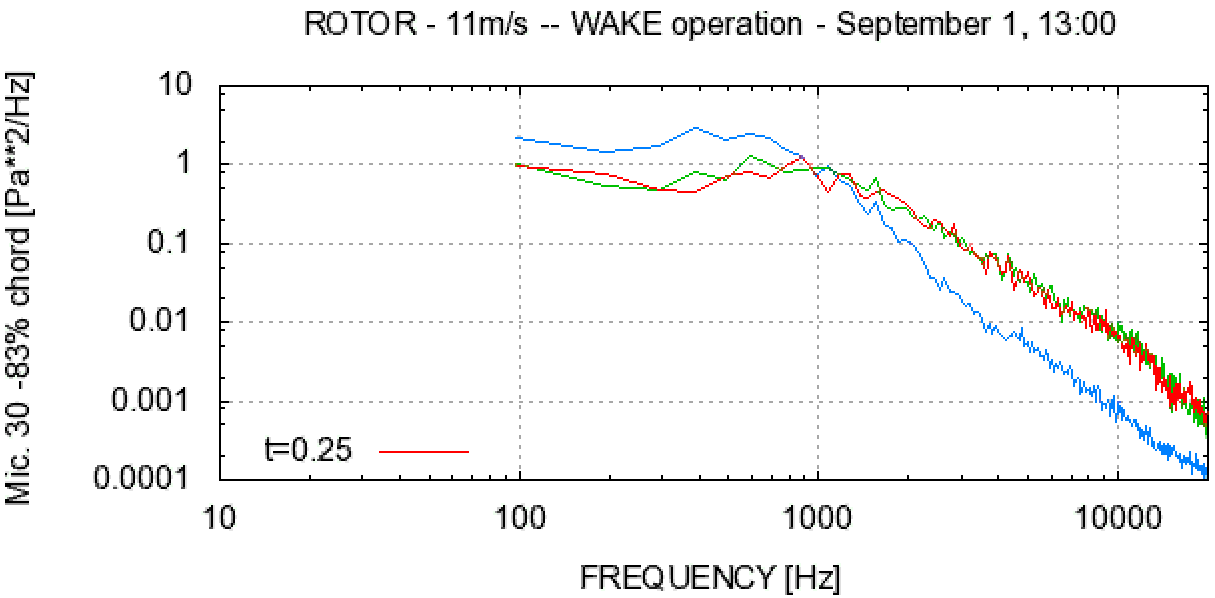


Influence of wake operation
- distance to upstream turbine 3.5D

Increased turbulence level increases AOA variations

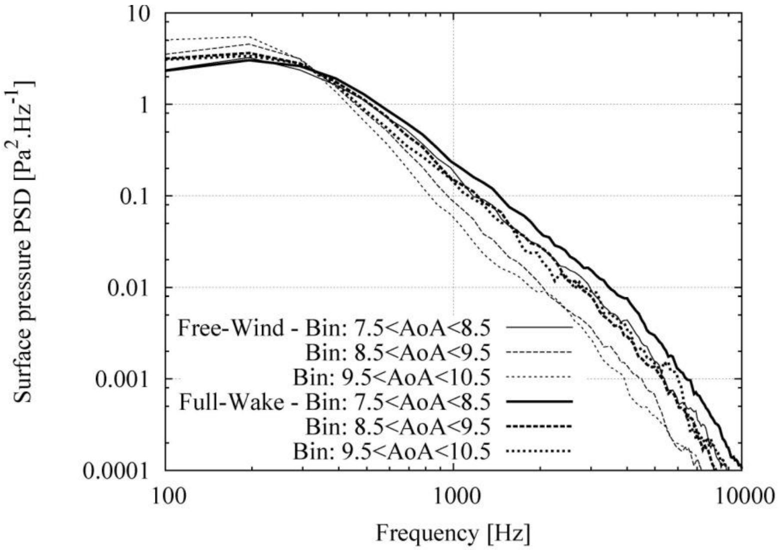


Influence of wake operation
- distance to upstream turbine 3.5D



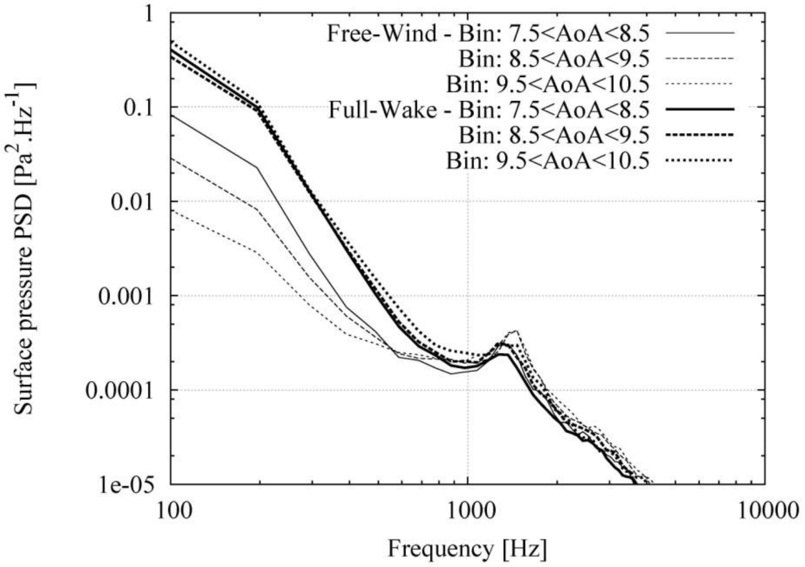
Influence of wake operation
- distance to upstream turbine 3.5D

Trailing edge



(b) TE Microphone - $x/C = 93\%$ (Suction side)

Leading edge



(a) LE Microphone - $x/C = 2.2\%$ (Pressure side)

Perspectives for application of the technique

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

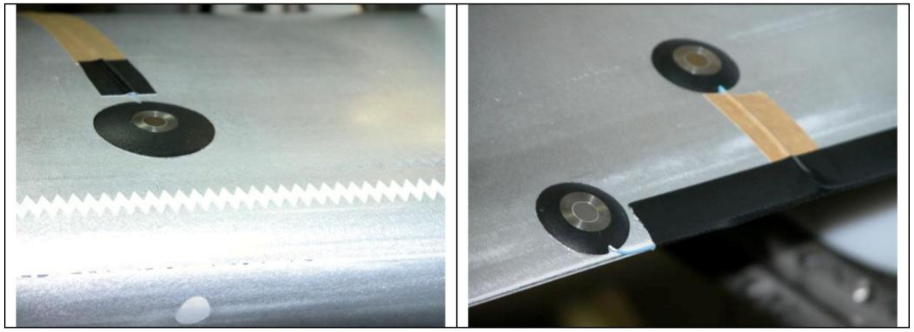
Objectives of blade mounted monitoring system:

- 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

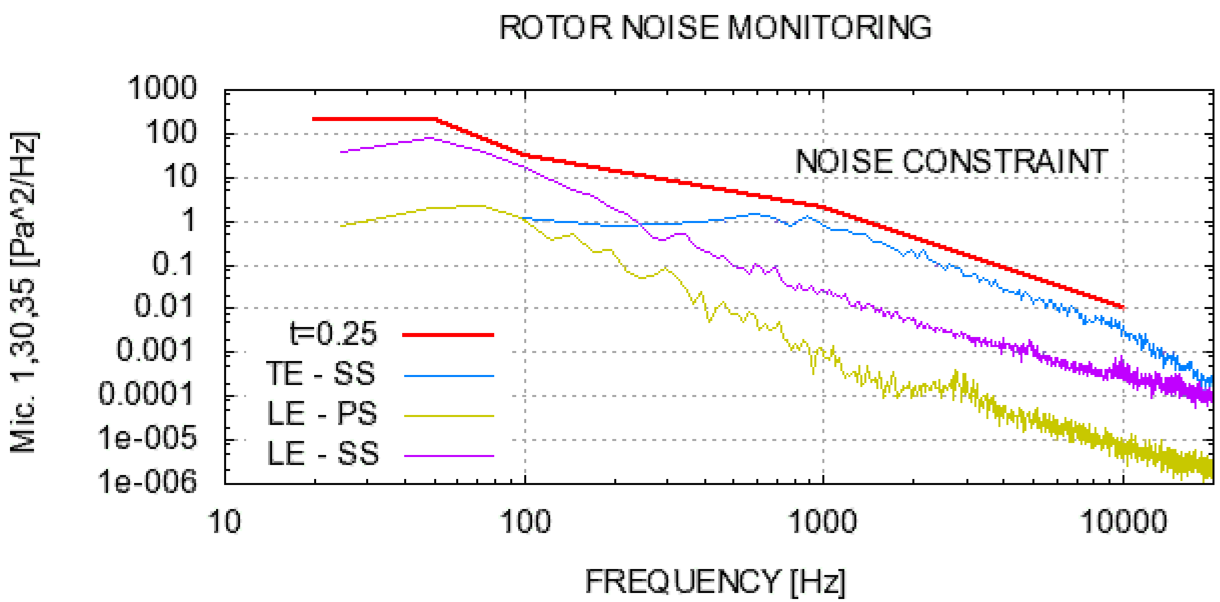
Proposed system



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



Acknowledgements

The work has been carried out within the projects **DAN-AERO** and **DAN-AERO II**

Funded partly by **EUDP**; contracts ENS-33033-0074 and ENS-64009-0258

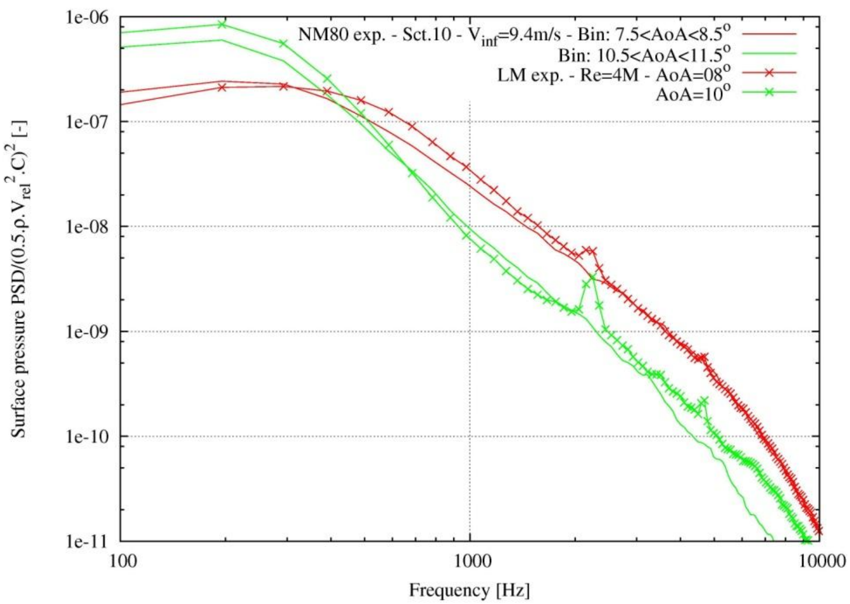
Partly by the project participants:

- Siemens
- Vestas
- LM Wind Power
- Dong Energy
- DTU Wind Energy

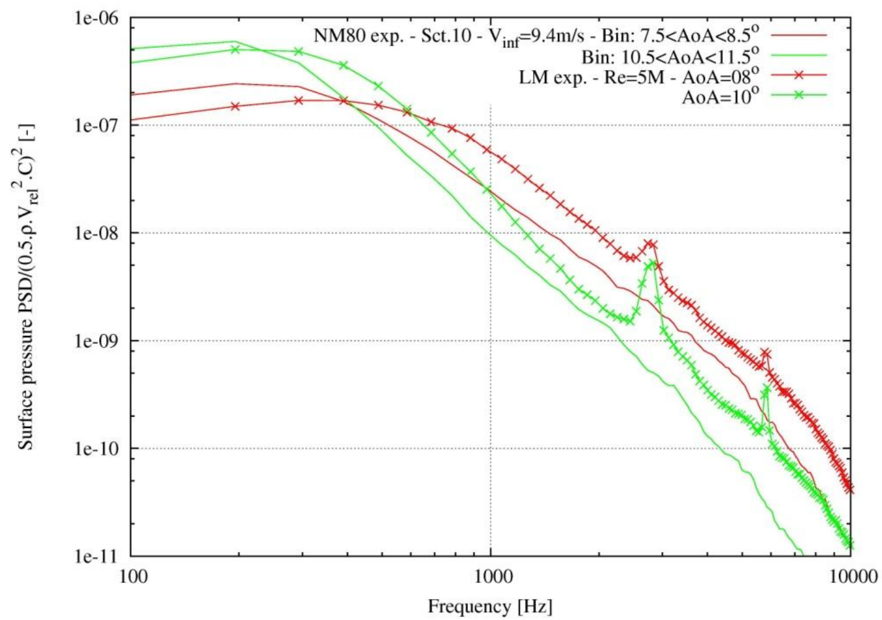

Thank you for
your attention

Comparison of SP measured in wind tunnel and on the NM80 2MW rotor - preliminary

difference in Re number



same Re number



c=0.9m – wind tunnel airfoil model
c=1.2m - rotor