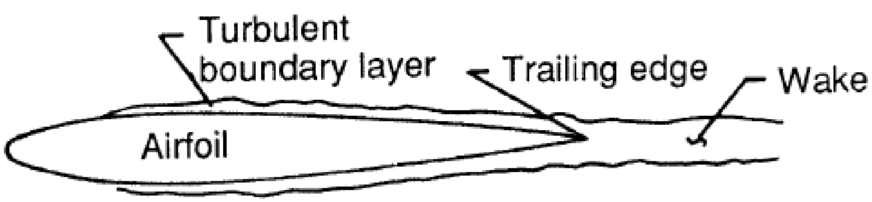
Analyses of the mechanisms of amplitude modulation of aero-acoustic wind turbine sound

Andreas Fischer
Helge Aagaard Madsen
Knud Abildgaard Kragh
Franck Bertagnolio

DTU Wind Energy
Technical University of Denmark
P.O. 49, DK-4000 Roskilde, Denmark
asfi@dtu.dk

(Normal) Amplitude Modulation (NAM) of Wind Turbine Noise [1]

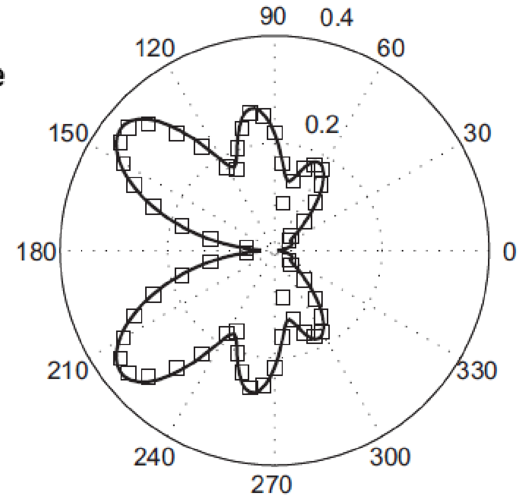
- swishing sound radiated when the blade moves downwards
- Peak to trough level a few dB
- Normally only perceived close to the wind turbine (1-2D)
- Can be explained by the directivity of trailing edge noise



Turbulent-boundary-layer—trailing-edge noise

[2]

Directivity of noise emitted from an airfoil with finite chord length [3]



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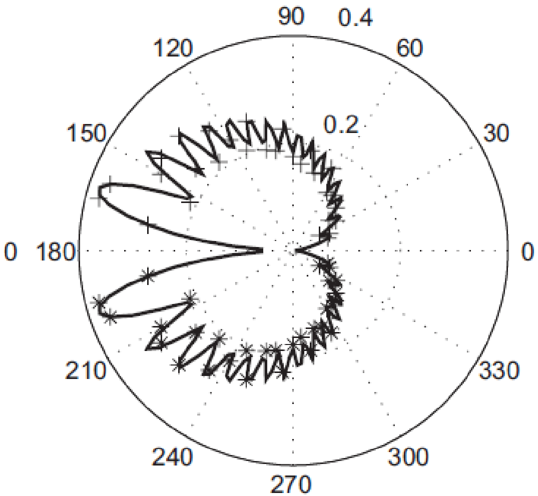

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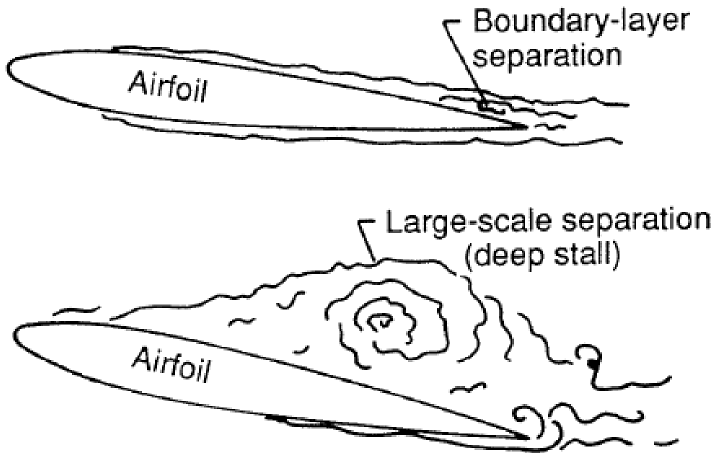
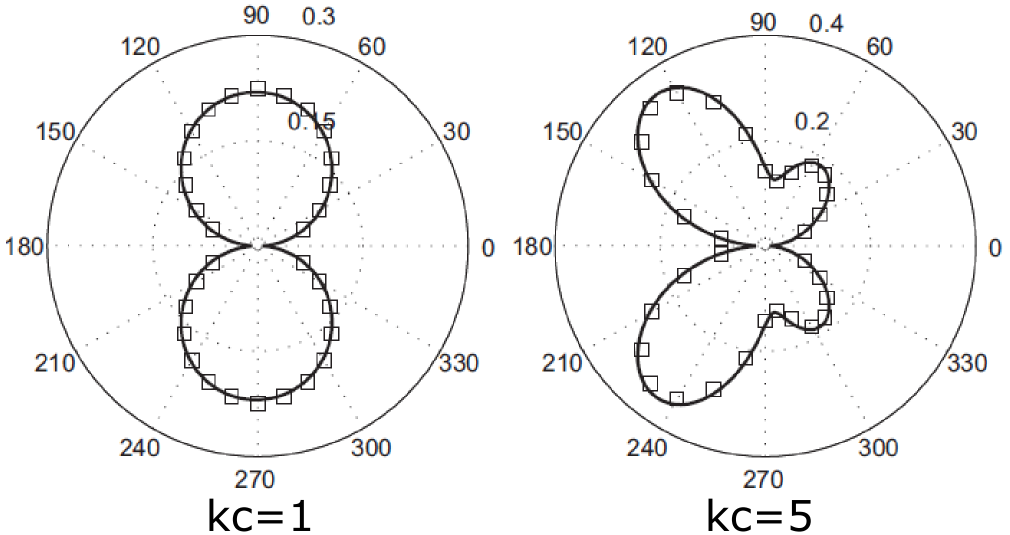
(Other) Amplitude Modulation (OAM) of Wind Turbine Noise [1]

- Described as thumping sound
- More low frequency content and higher peak to trough level than normal AM
- Perceived at larger distance from the wind turbine
- Perceive at up and downwind locations
- Transient stall as a possible explanation



Separation-stall noise [2]

Directivity of noise emitted from an airfoil with finite chord length [3]



Objectives

- Investigate the source of trailing edge noise and stall noise (surface pressure field) on a full scale wind turbine rotor
- Relate surface pressure field to emitted far field sound
- Identify wind conditions which can lead to OAM
- Outline control strategies to alleviate OAM

Outline

- Experimental noise source characterisation on a full scale rotor
  (DAN-AERO MW project)
- Relation between noise source and emitted far field sound
  (measurement in Virginia Tech Wind Tunnel)
- Critical atmospheric conditions to cause (Other)AM
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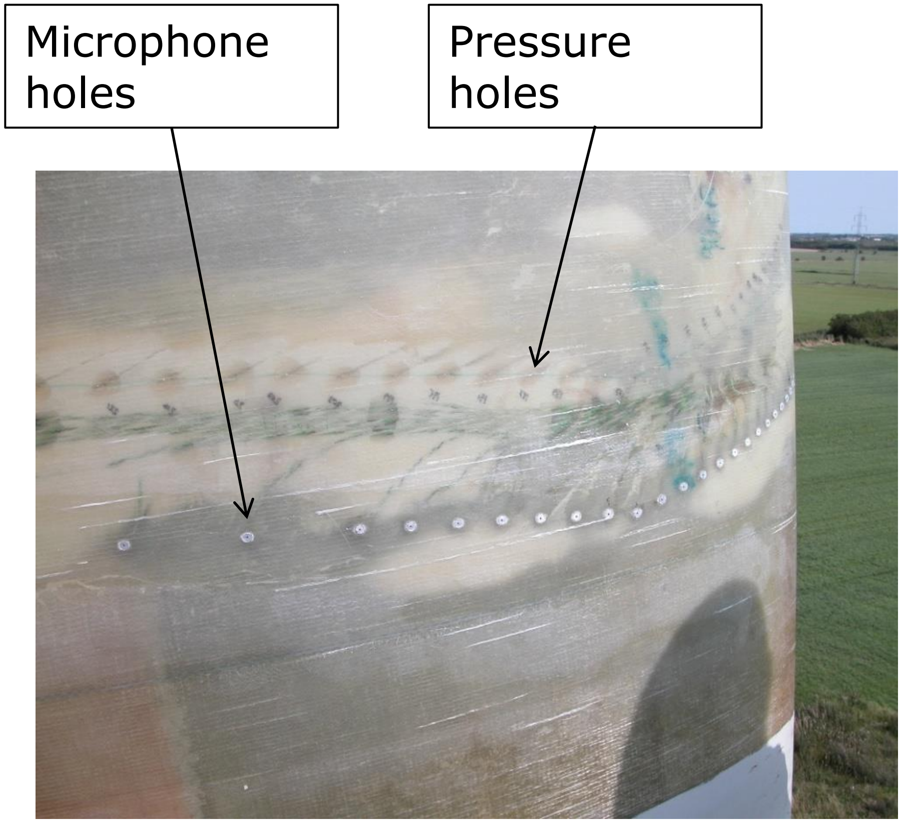
NEG-Micon NM80 Wind turbine with inflow sensors

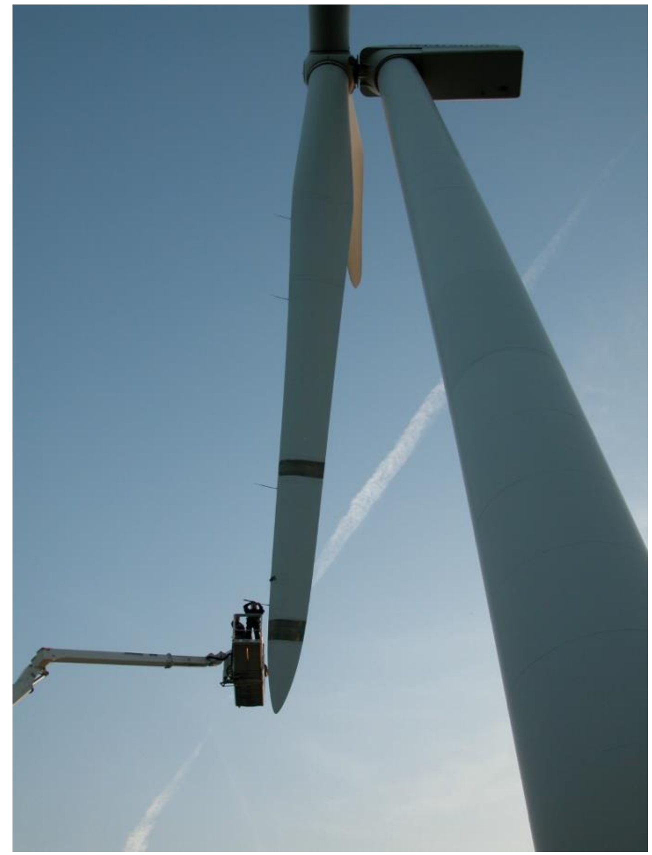
DANAERO MW project [4], Vestas, Siemens, LM Wind Power, DONG Energy, DTU, 2007-2010

- Pressure tabs at r=13m, 19m, 30m and 37m
- Pitot tubes at r= 14.5m, 20.3m, 31m and 36m
- 60 Microphones at r=37m for high frequency surface pressure measurements

Four 5 hole pitot tubes installed on a NM80 turbine

Campaign measurements from June to September 2009 – DANAERO MW project



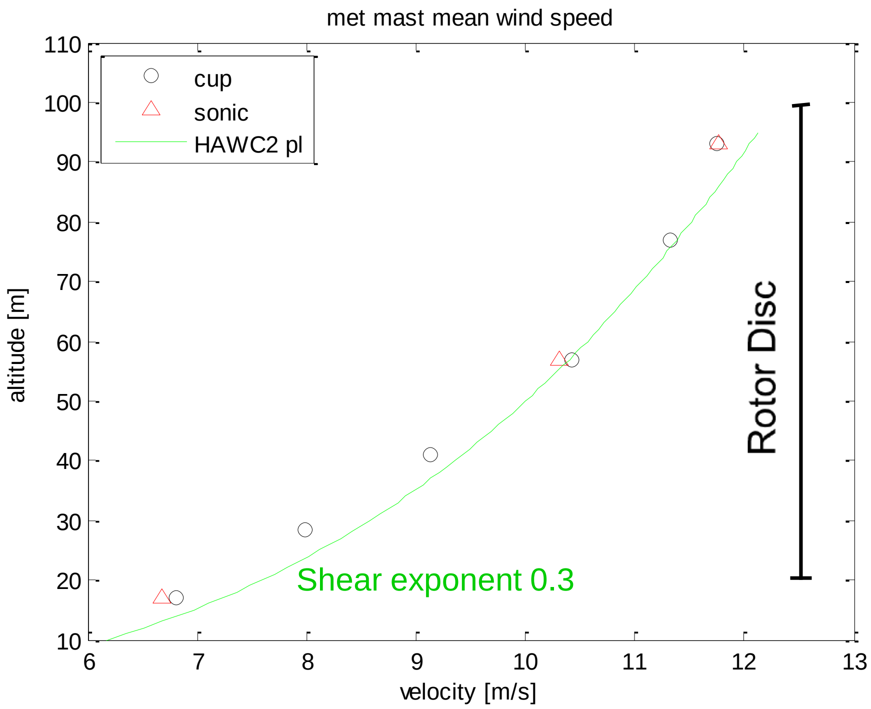


NEG-Micon NM80 Wind Turbine (DANAERO MW project)

- Technical Data:
  - Rated power 2.3MW
  - Hub height 57m
  - Rotor diameter 80m
  - LM38.8 blades
- Unusual operational conditions:
  - Constant rotational speed (16.23rpm = 1.7rad/s)
  - Pitch -4.5° (towards higher AoAs, forced to stall)
  - High wind speed (above 12m/s at hub)
  - Yaw +/-10°

Wind velocity profile measured at the met mast on Sept. 1, 2009 (10min average)

10:00



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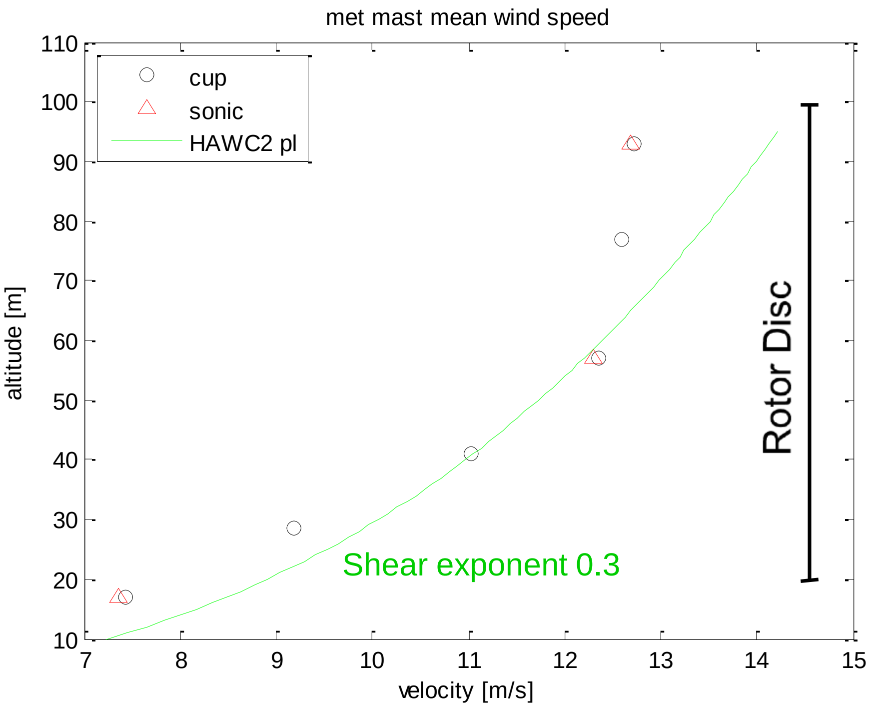

Wind velocity profile measured at the met mast on Sept. 1, 2009 (10min average)

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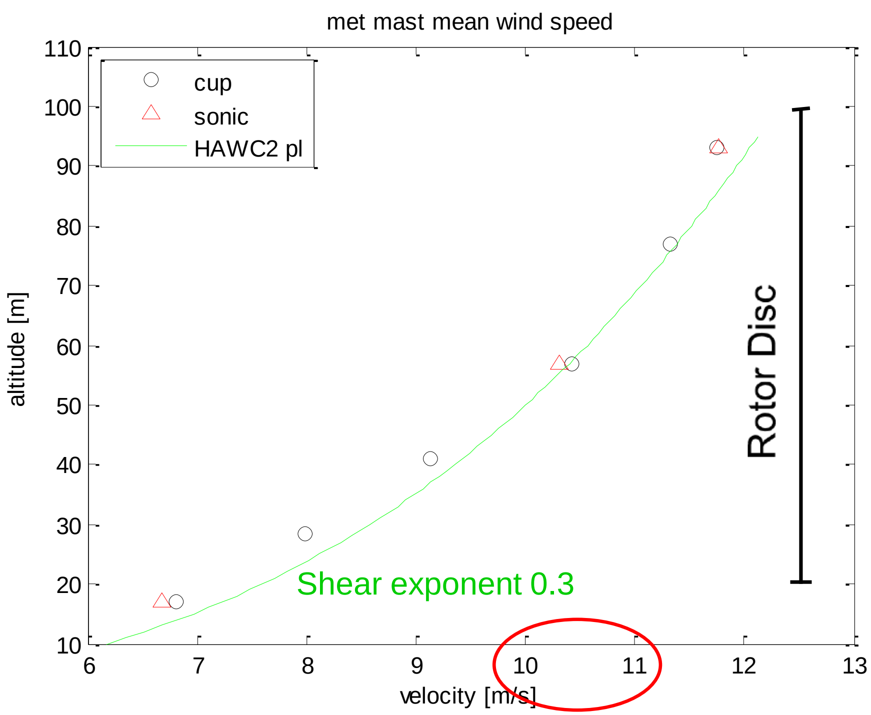

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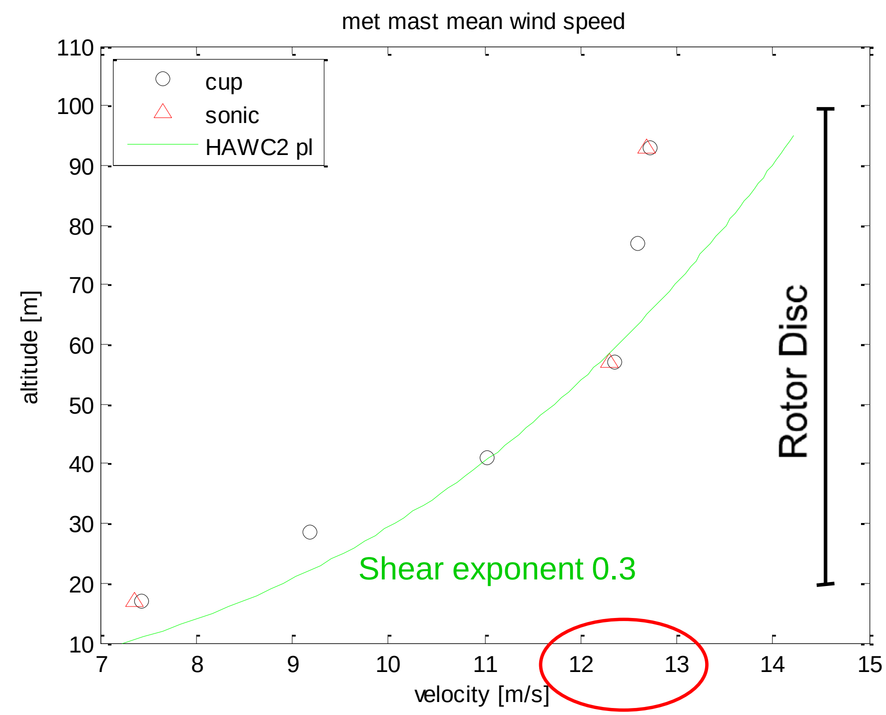
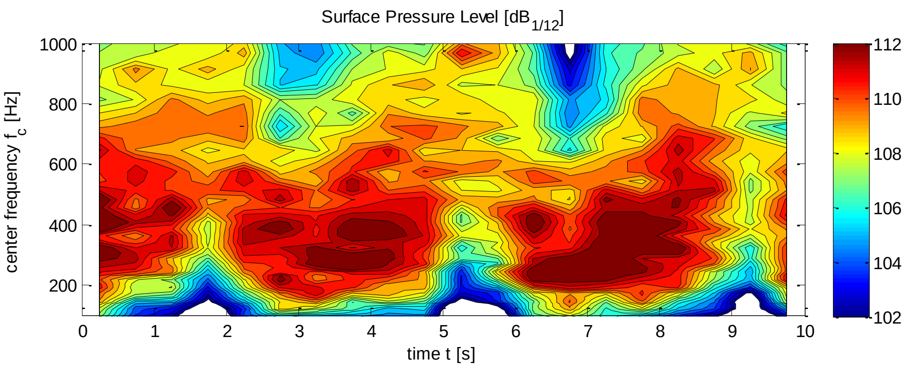
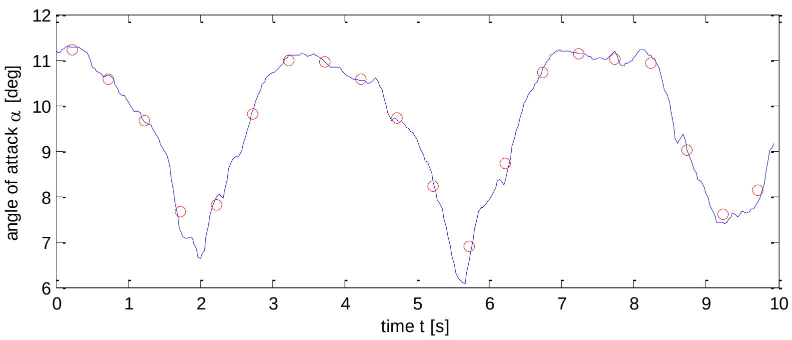


Surface pressure level on suction side at x/c=0.84, Sept. 1, 2009 (evaluated every 0.5sec)

10:05





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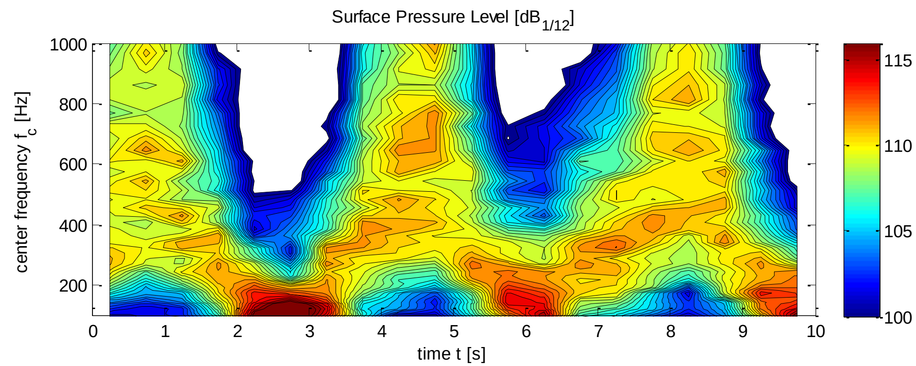
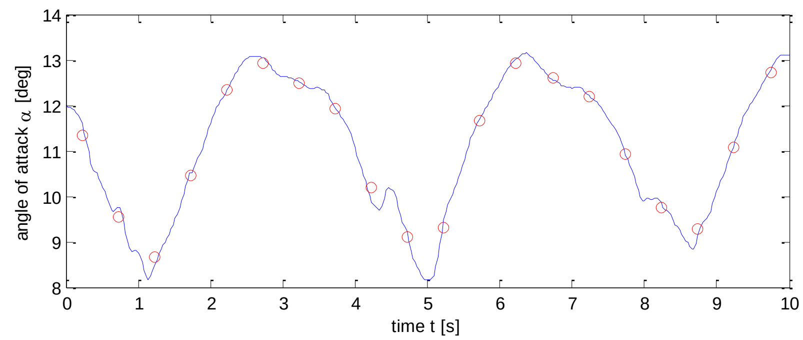
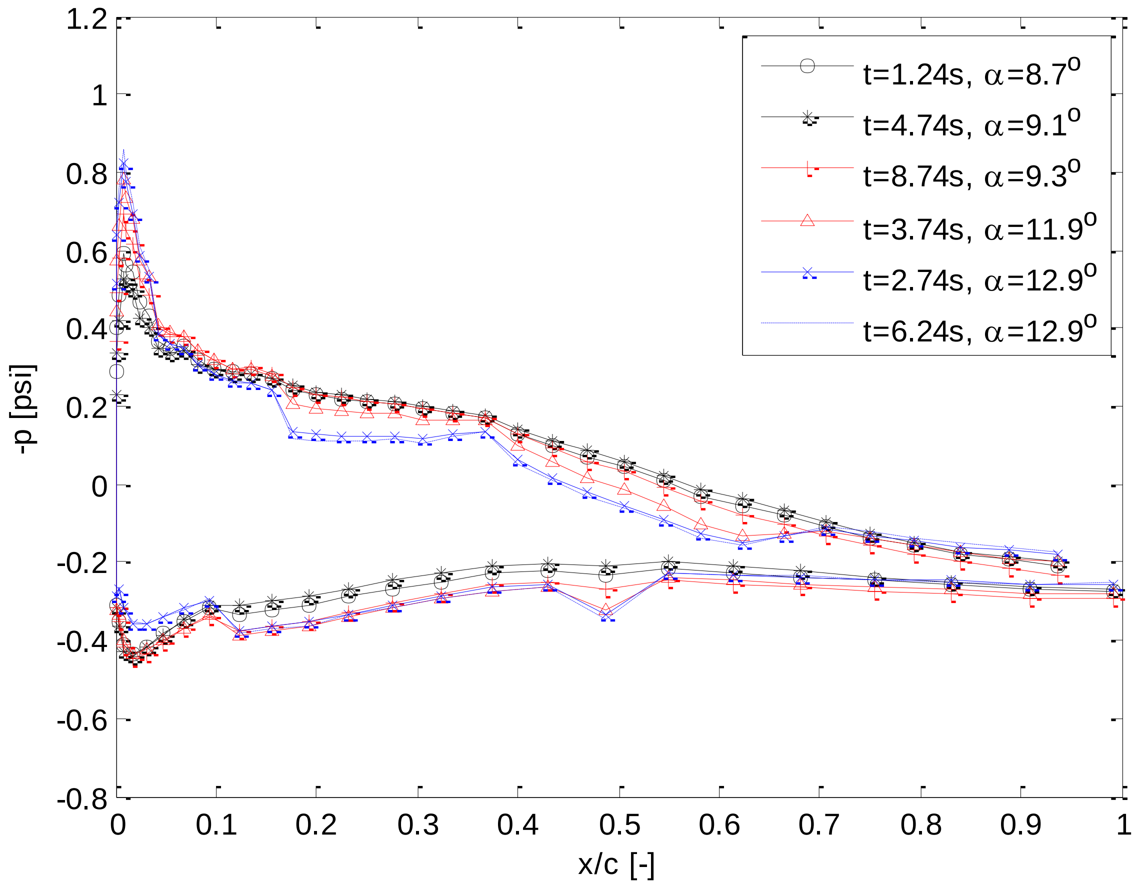
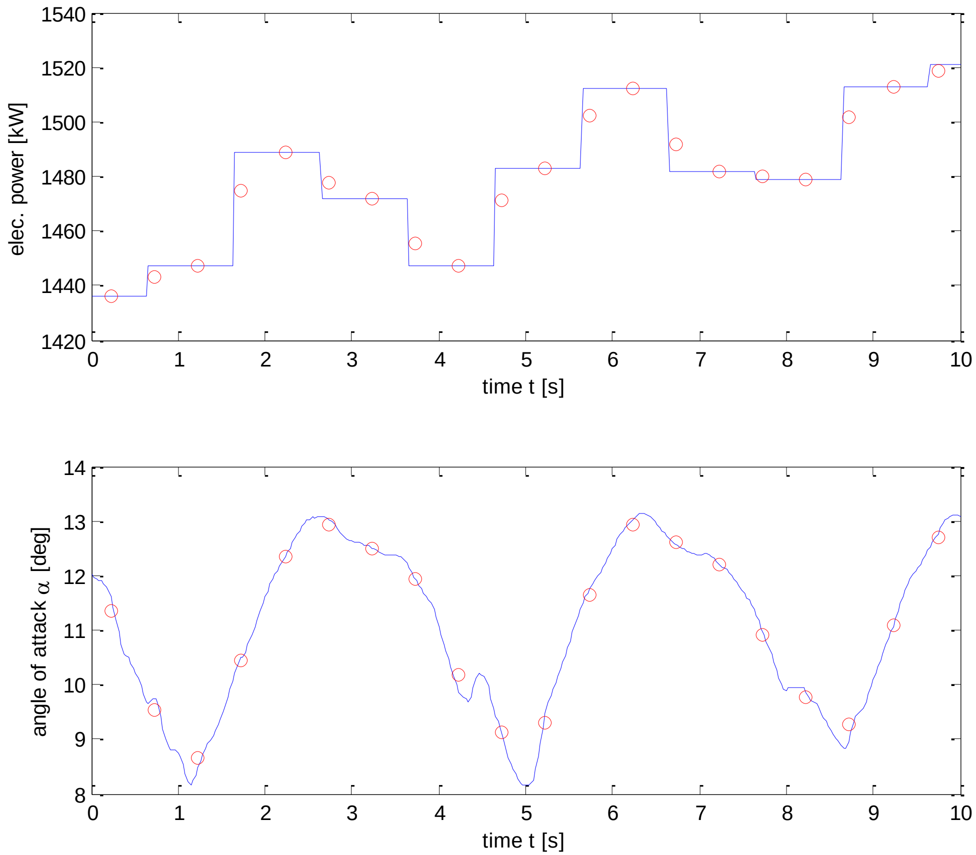




Aerofoil Pressure distribution Sept 1, 2009, 11:48



Electrical Power and Angle of Attack, Sept 1, 2009, 11:48



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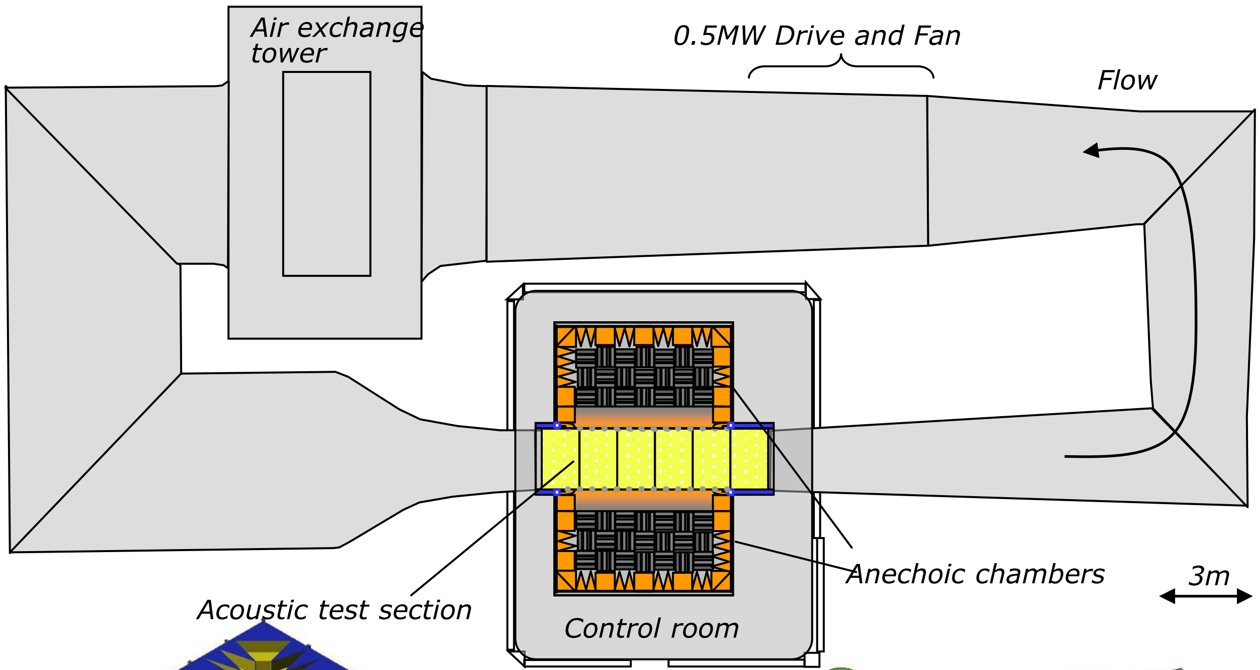
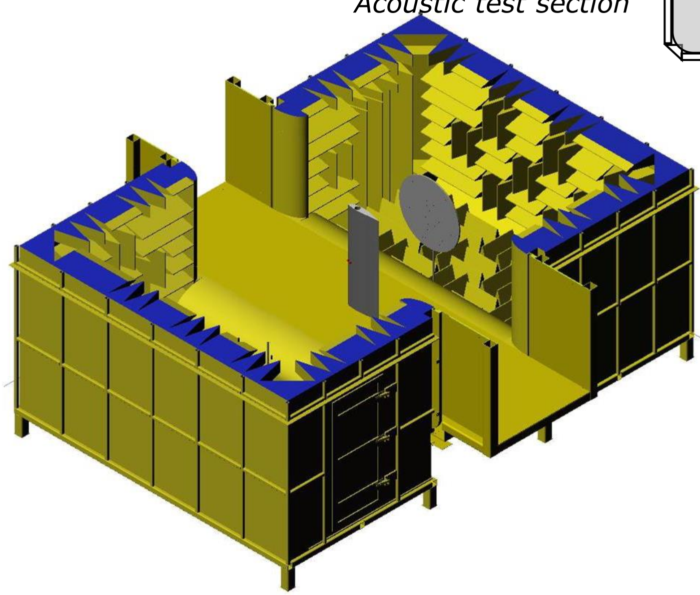
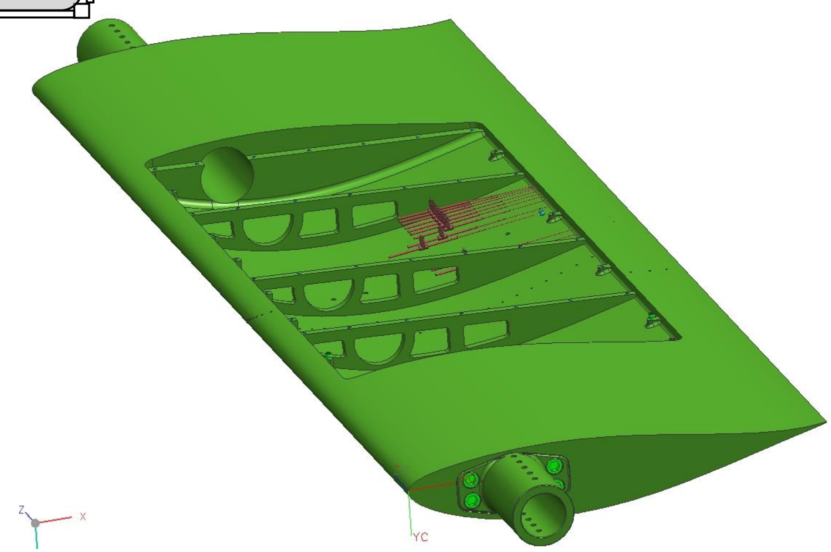
Virginia Tech Stability Wind Tunnel







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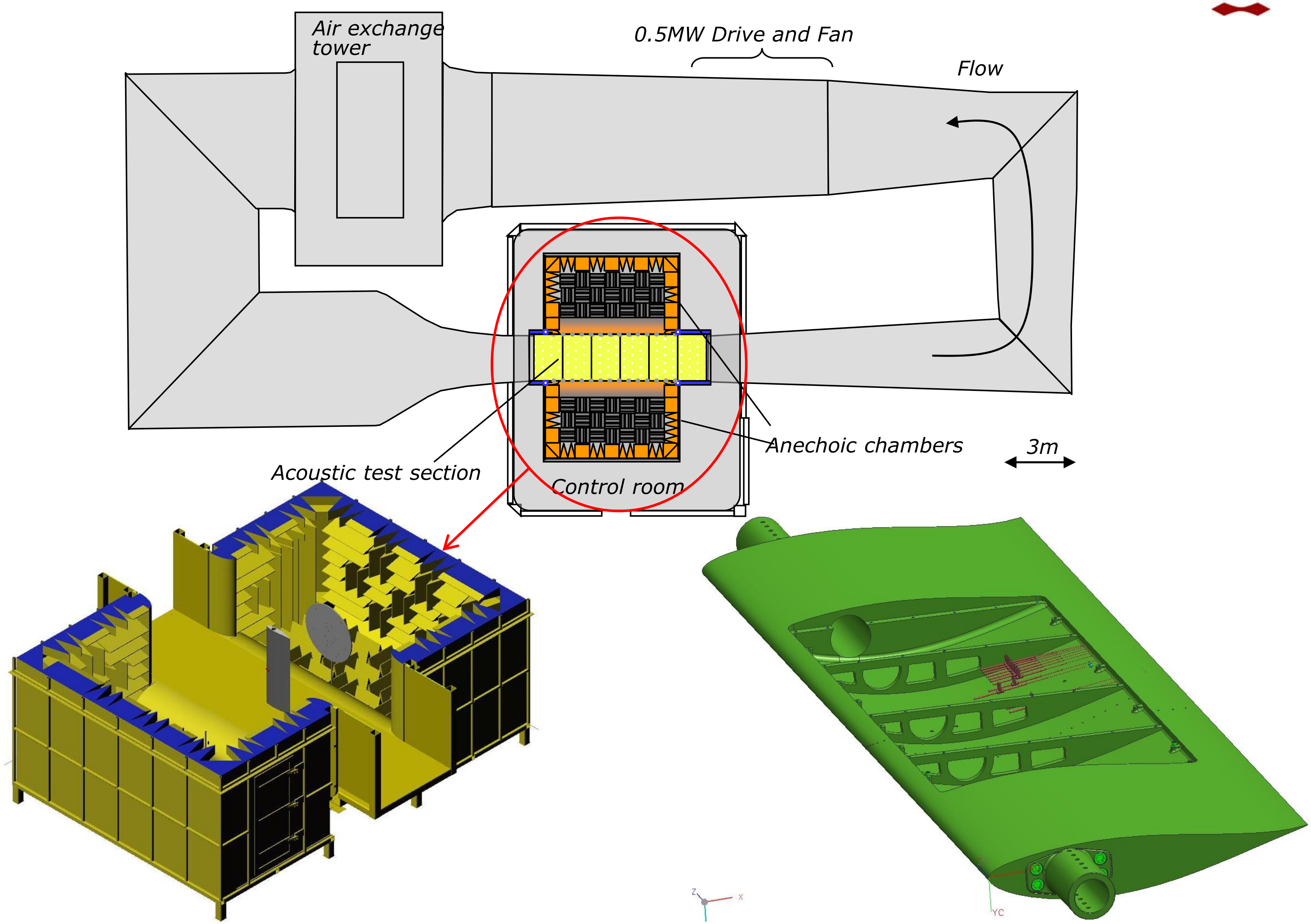

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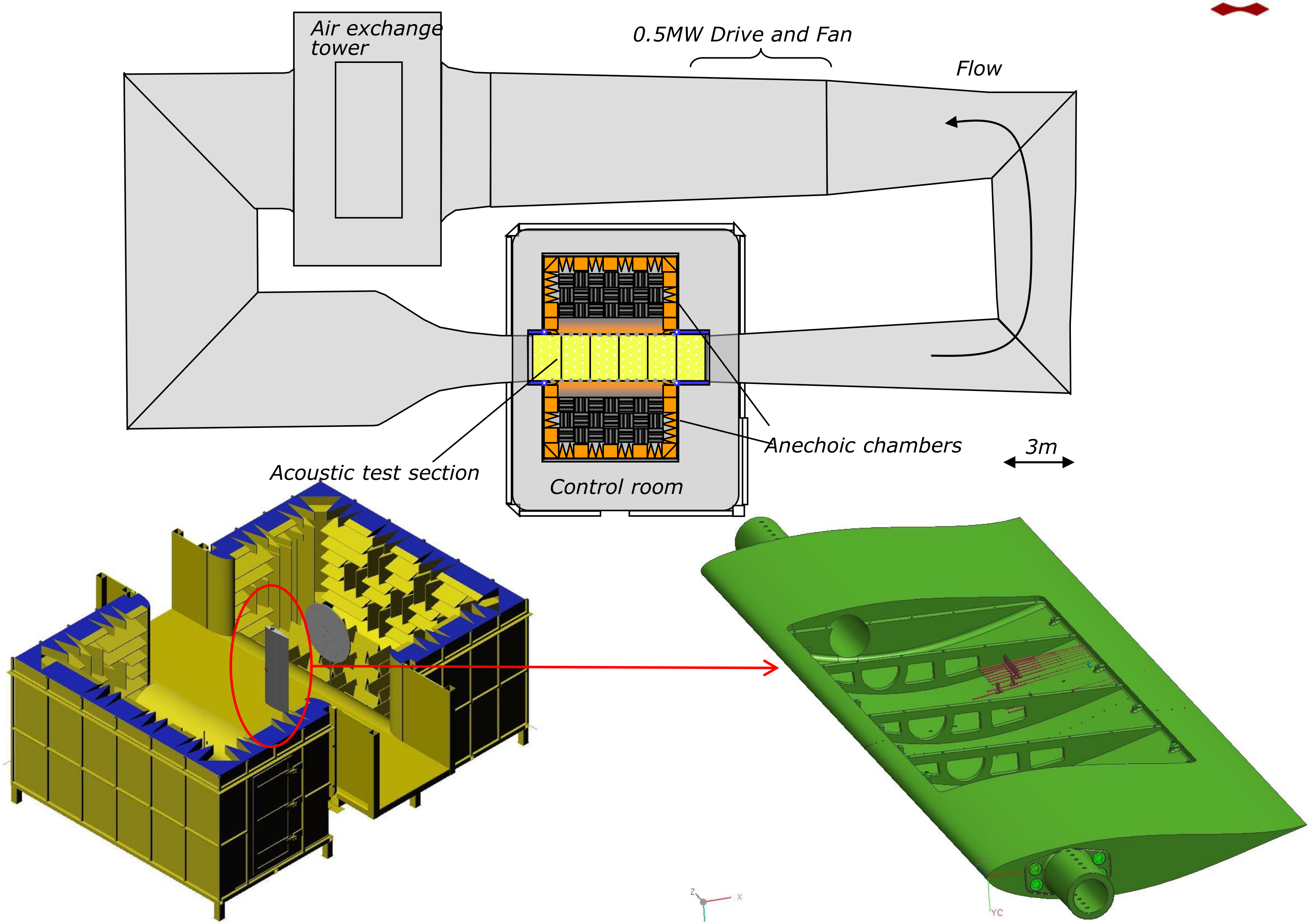
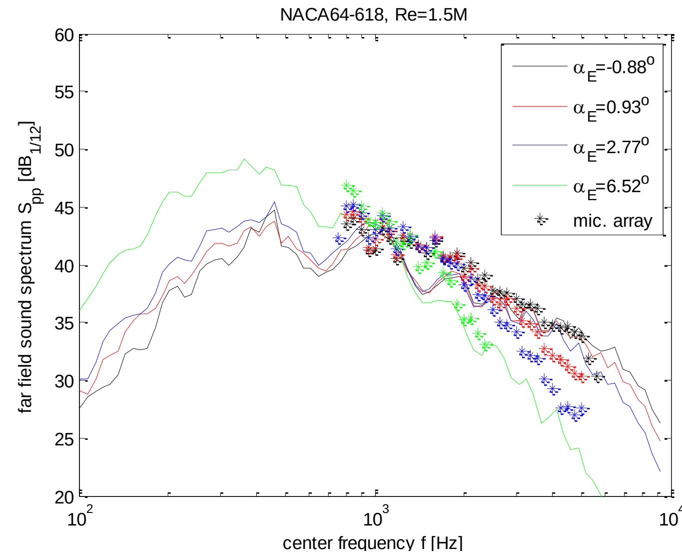


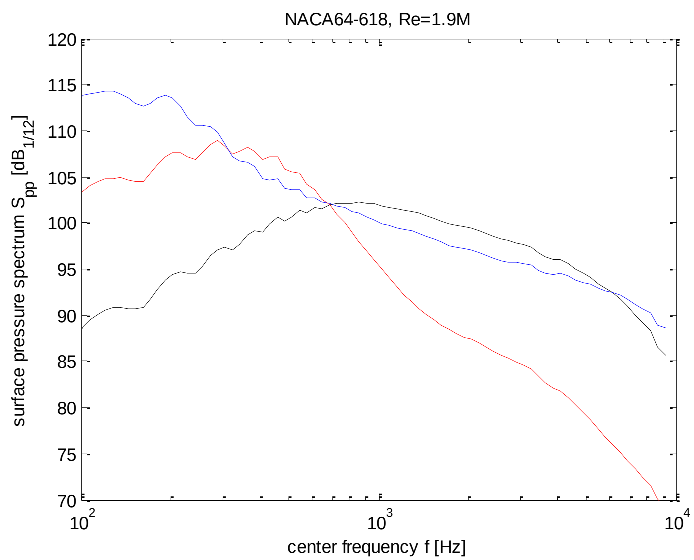
Prediction of far field sound pressure with measured surface pressure

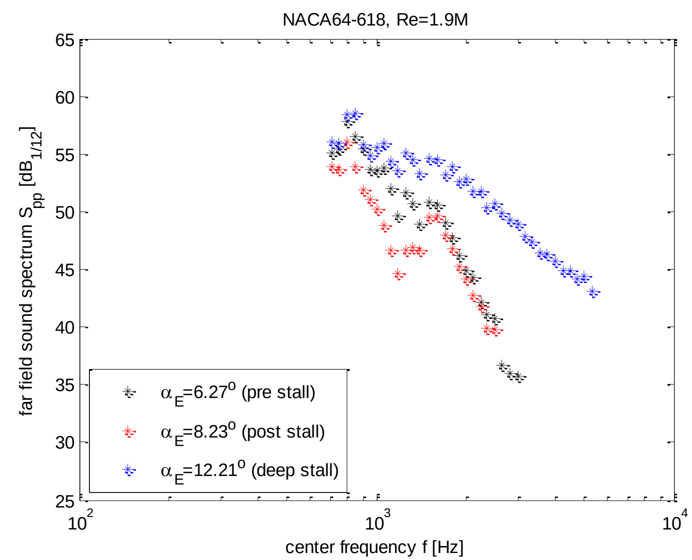
Trailing edge noise [5] :

$$S_f(\vec{y},\omega) = \left(\frac{\omega y_2 b}{2\pi c_0 S_0^2}\right)^2 2\pi L \left| I\left(\frac{\overline{\omega}}{U_c}, \overline{K}_3\right)\right|^2 \Pi_0\left(\frac{\omega}{U_c}, k_0 \frac{y_3}{S_0}\right)$$



The effect of stall on noise emission:





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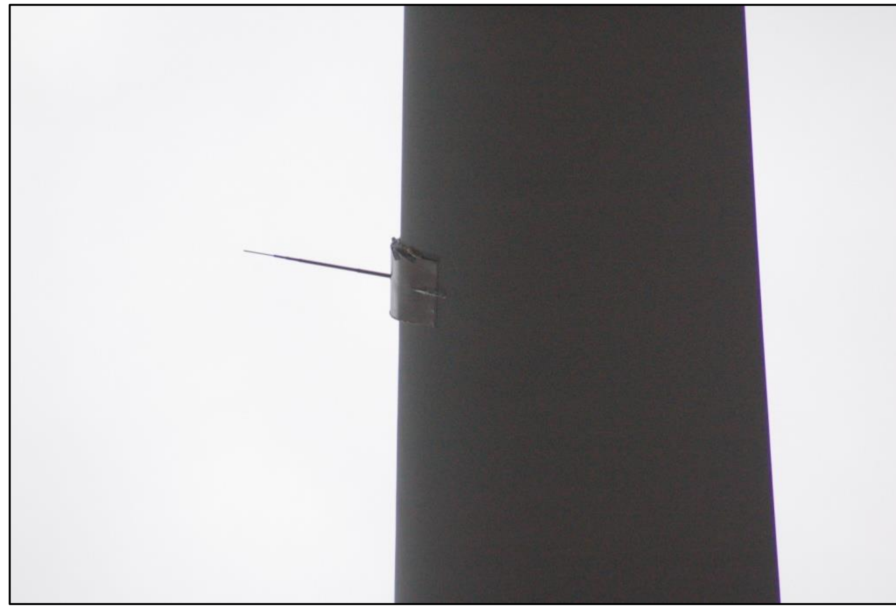
DANAERO MW Project 2009

Vestas, Siemens, LM Wind Power, DONG Energy, DTU

Pitot tube mounted at radial position r=36m



Siemens 3.6 MW Turbine

DANAERO MW Project 2009

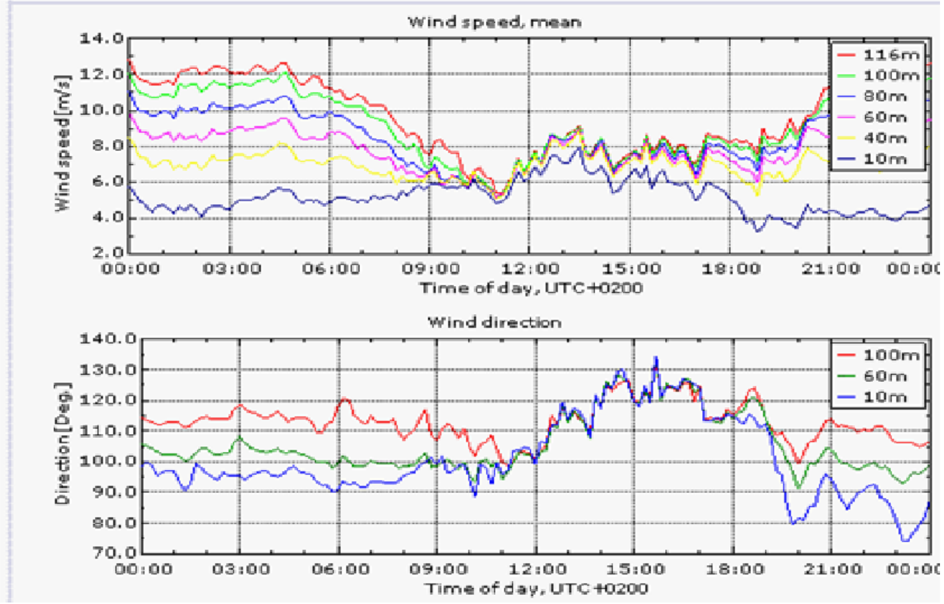
Vestas, Siemens, LM Wind Power, DONG Energy, DTU

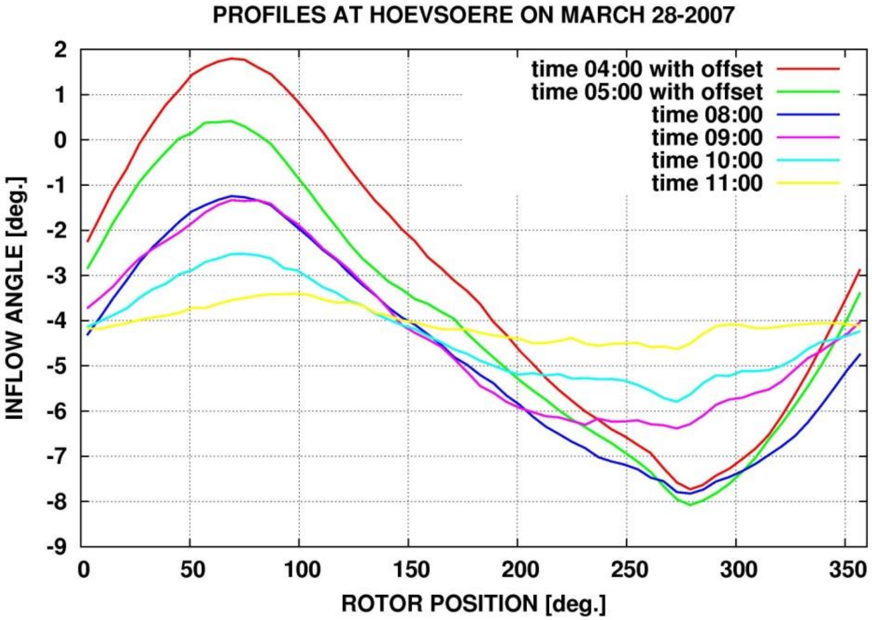
Høvsøre Test Site

Sensor	Position
Cup anemometer, boom mounted on aviation met mast	160m
Cup anemometer top mounted	116.5m
Cup anemometer, wind vane, sonic anemometer, temperature, differential temperature, relative humidity, air pressure	100m
Cup anemometer, sonic anemometer, differential temperature	80m
Cup anemometer, sonic anemometer, differential temperature, wind vane	60m
Cup anemometer, sonic anemometer, differential temperature	40m
Sonic anemometer	20m
Cup anemometer, sonic anemometer, differential temperature, wind vane	10m

Correlation of wind shear to variations in angle of attack

March 28, 2007





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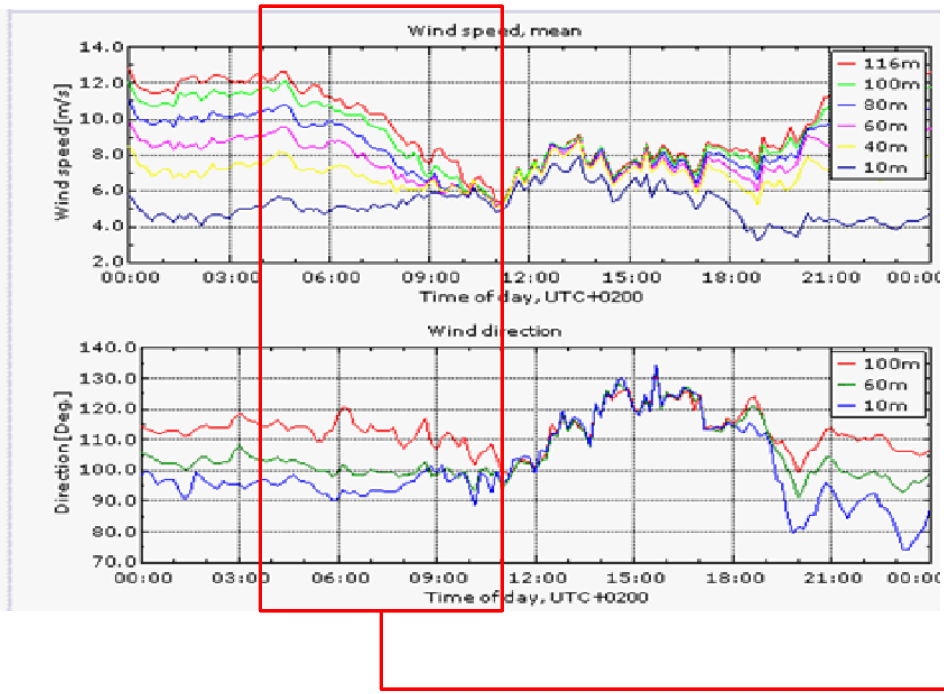

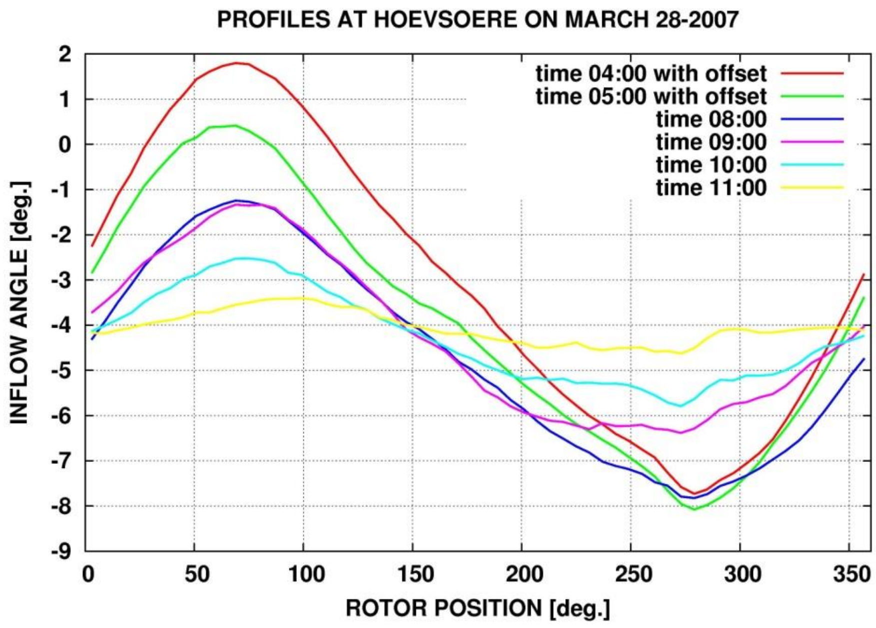

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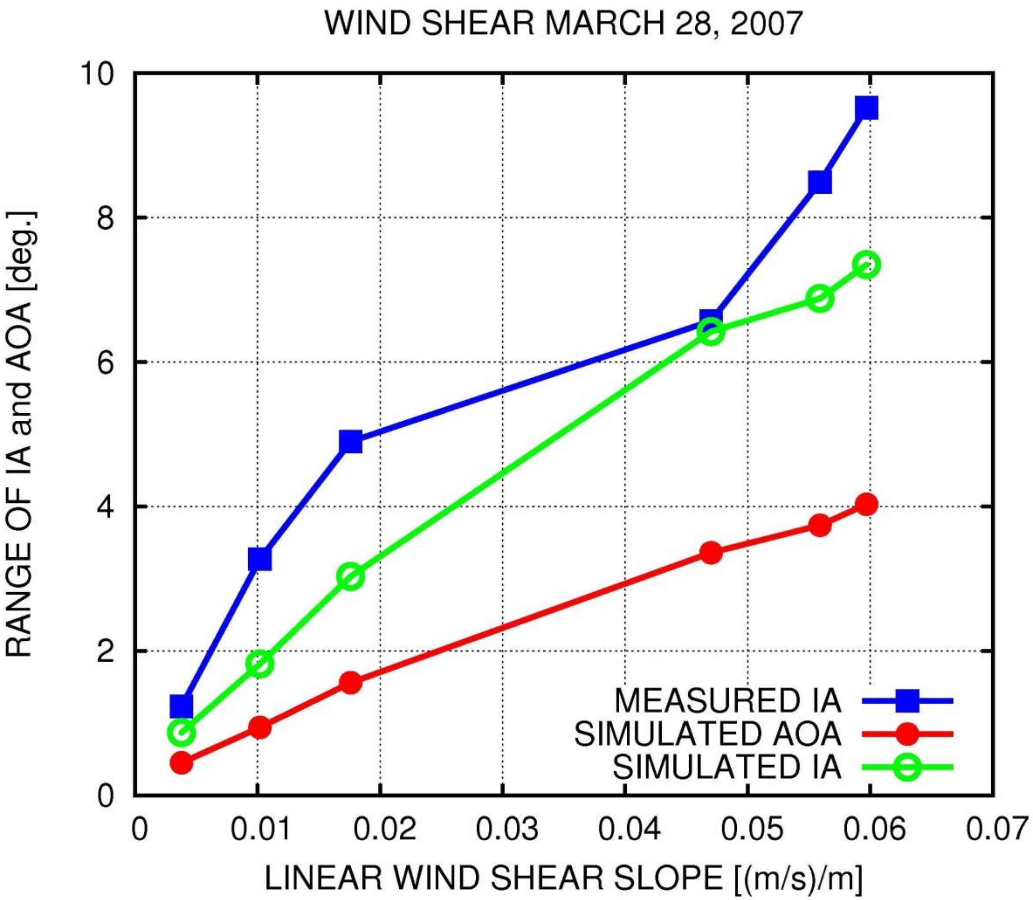
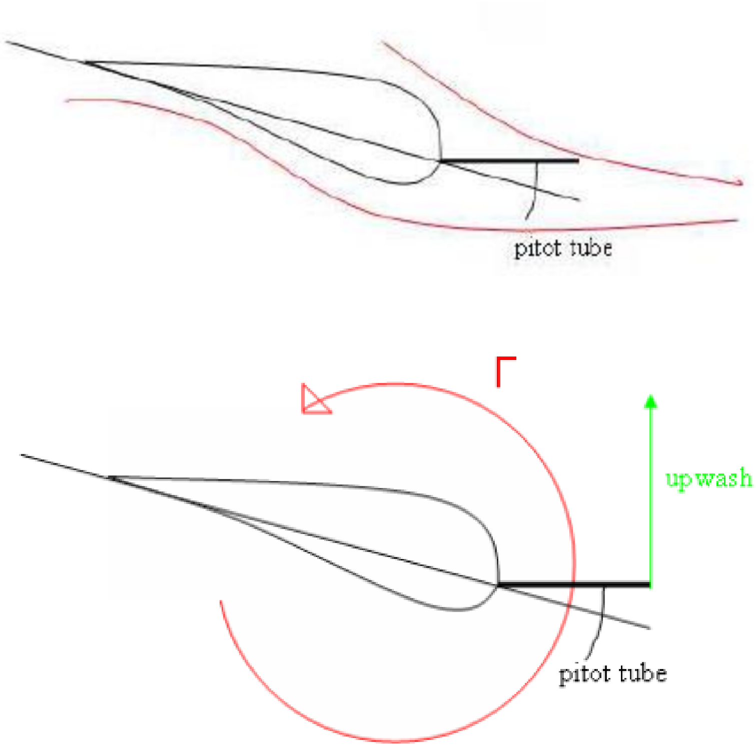


Difference between inflow angle (IA) and angle of attack (AOA)



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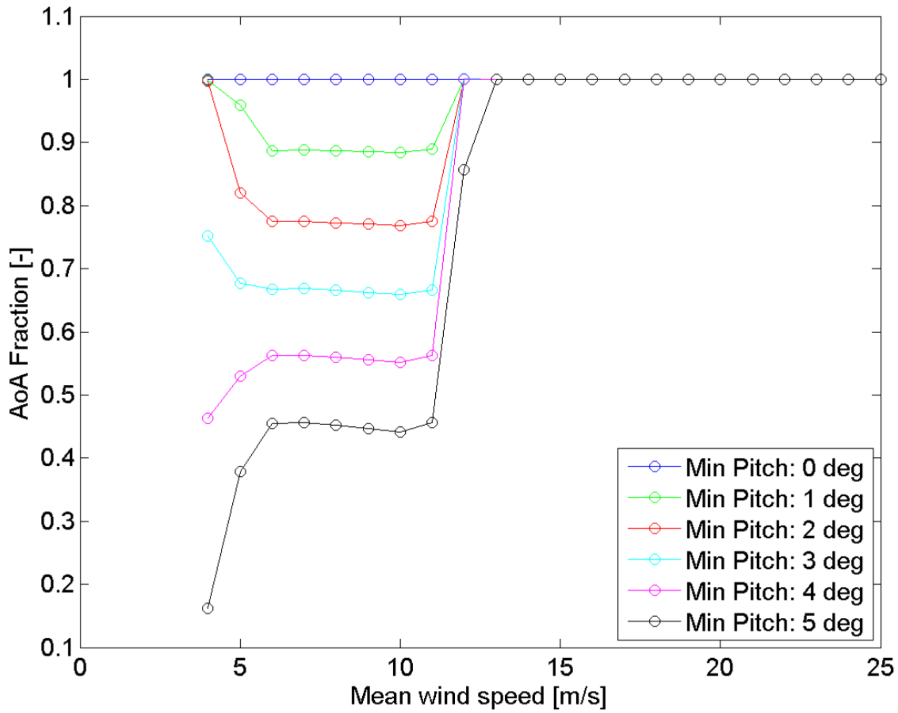
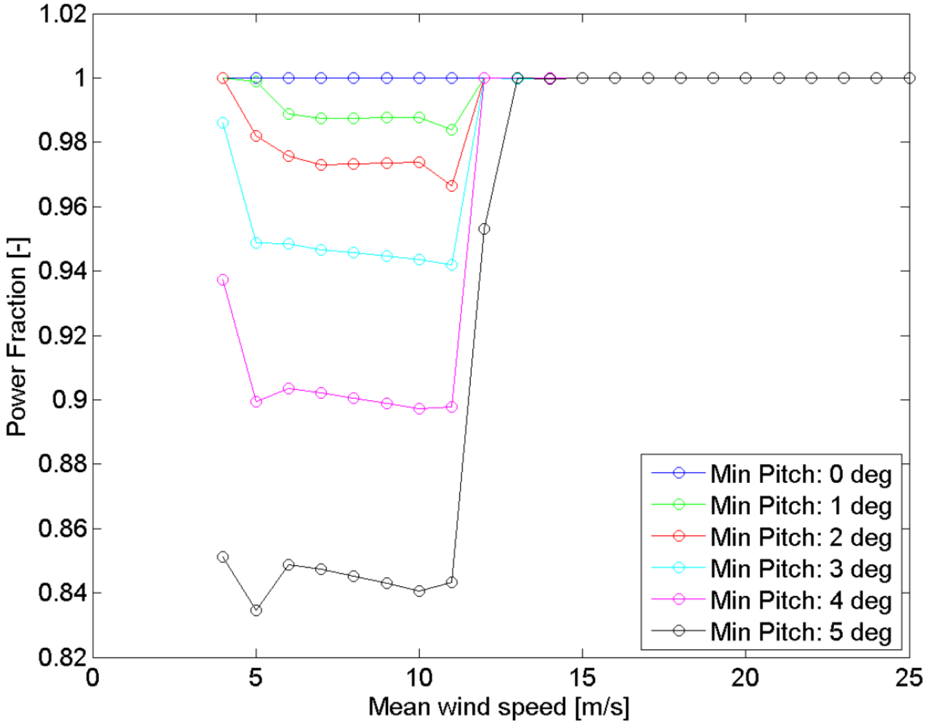
Mitigation - Decreasing mean angle of attack

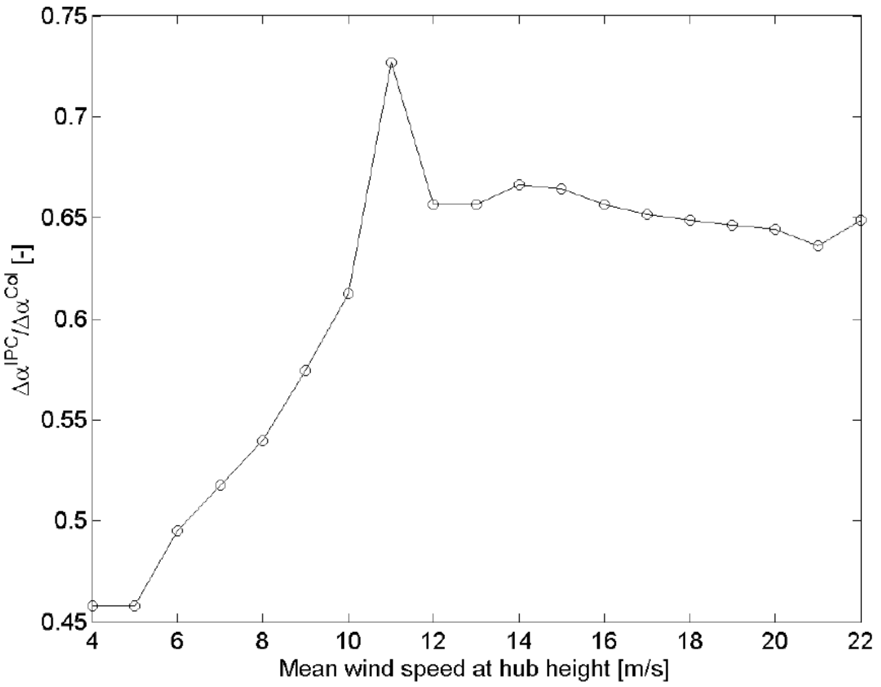
- HawcStab2 simulations with varying min pitch angle

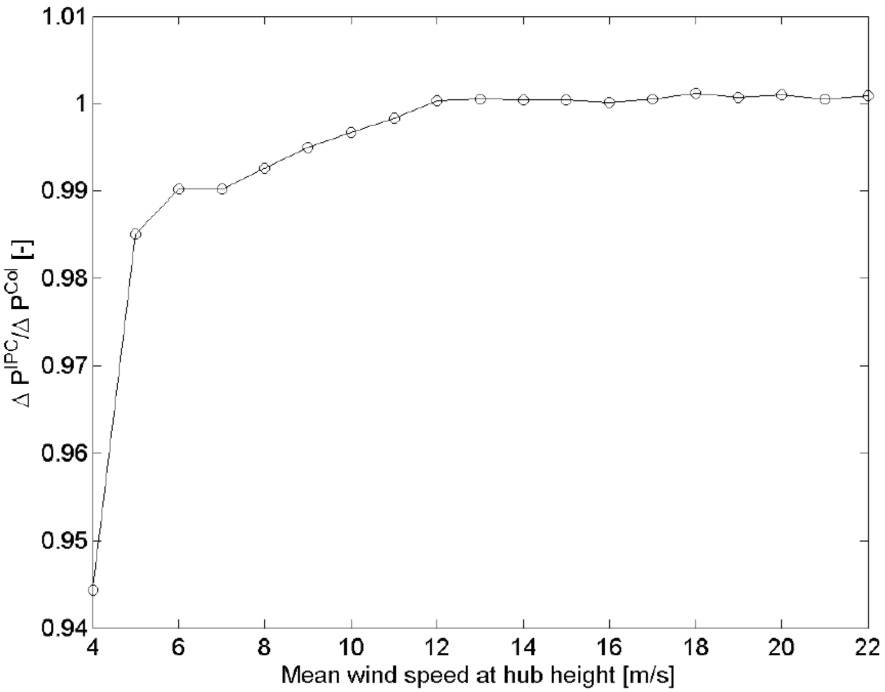




Mitigation - Decreasing angle of attack variations

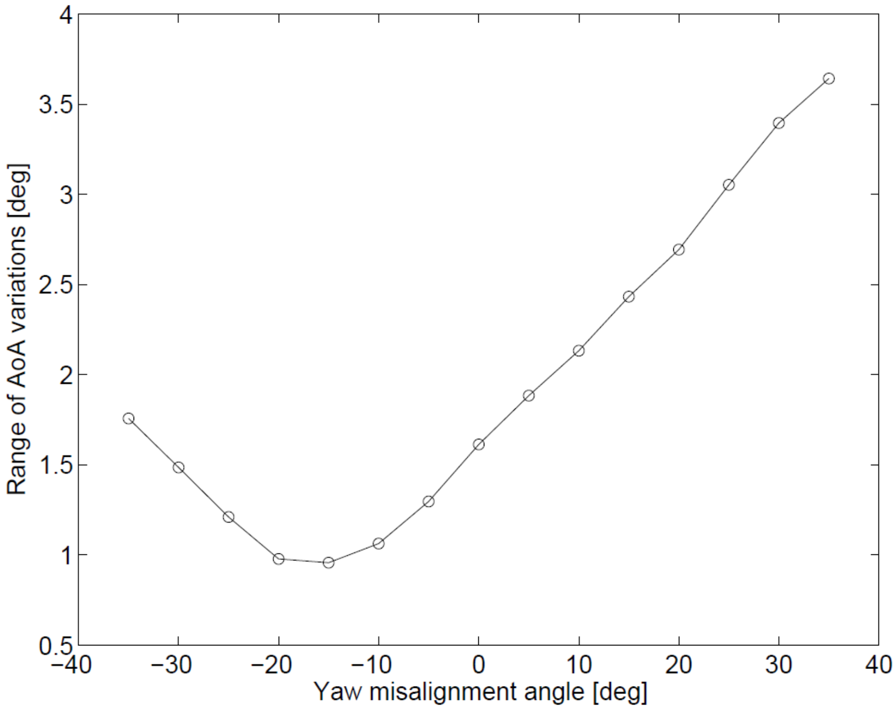
- HAWC2 simulations with individual pitch control, sheared inflow exp=0.5, no turbulence

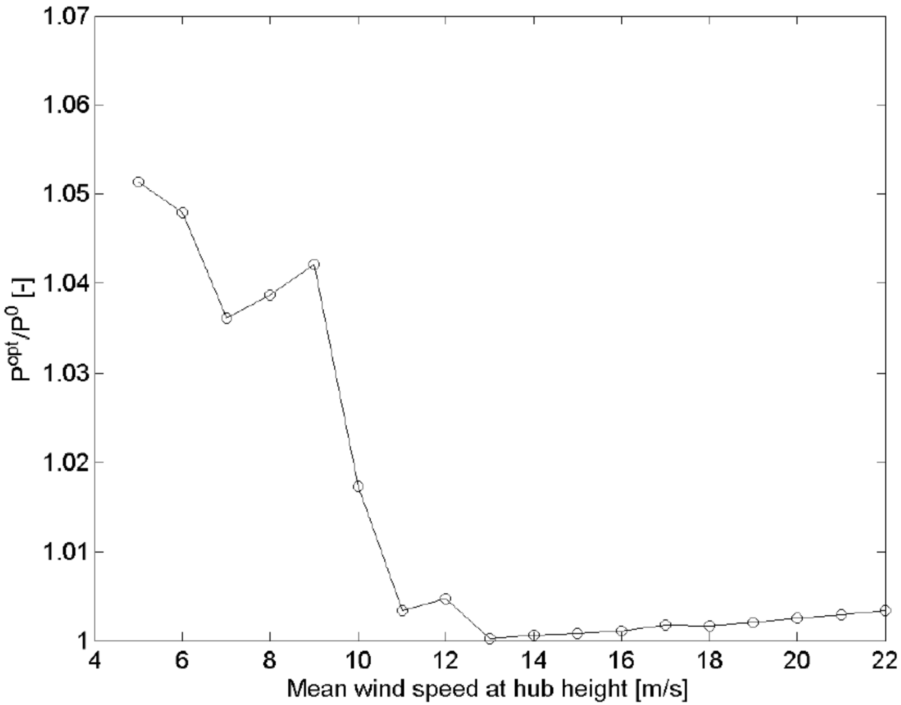




Mitigation - Decreasing angle of attack variations

- Yaw misalignment





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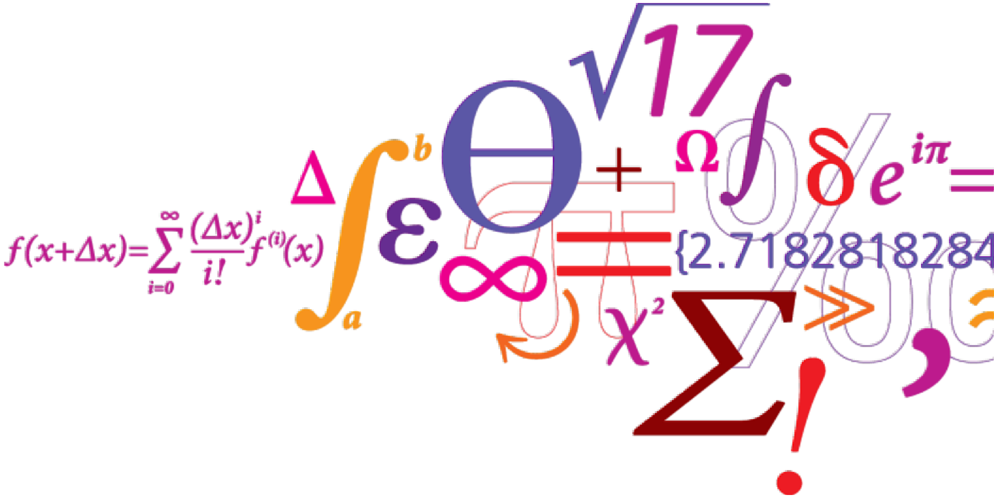
Conclusions

- Variation of the angle of attack during a revolution causes changes in the spectral energy of the noise sources on the blade
- Under normal conditions the variations of spectral energy are too small to lead to amplitude modulation far away from the turbine (NAM)
- If the blade undergoes transient stall the spectral energy in the low frequency range is significantly increased and it can lead to OAM
- Wind conditions leading to transient stall: high shear in combination with a mean wind speed close to rated wind speed
- Control strategies to mitigate OAM:
  - reducing the mean angle of attack (collective pitch)
  - reducing the angle of attack variations (individual pitch or yaw control)

References

1) Oerlemans S. An explanation for enhanced amplitude modulation of wind turbine noise. In: Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effect. RenewableUK, Dec. 2013.
2) Brooks TF, Pope DS, Marcolini MA. Airfoil Self-Noise and Prediction. NASA Reference Publication 1218, 1989.
3) S. Moreau and M. Roger. Back-scattering correction and further extensions of Amiet’s trailing-edge noise model. Part II: Application. J. of Sound and Vib. 323 (2009) 397–425
4) H. A. Madsen et al. The DAN-AERO MW Experiments: Final report. Tech. Rep. Risoe-R-1726(EN), Risoe-DTU, Roskilde, Denmark, September 2010.
5) Roger M, Moreau S. Back-scattering correction and further extensions of Amiet’s trailing-edge noise model. Part 1: theory. J. Sound Vib. 2005; 286:477–506.

Thank you!



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