Aerodynamic and acoustic international cooperation projects: How they (should) come together

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Contents

- *Aerodynamics, why is this an important subject?*
- International cooperation projects on aerodynamic measurements
- International cooperation projects on acoustics
- International cooperation project on aerodynamics **AND** acoustics
- Conclusions

AERODYNAMICS OF WIND TURBINES

Important for:

- Energy production
- Loads (strength, costs!)
- Stability (failure, damage)
- Control
  - Stall
  - (Individual) pitch
  - Distributed aerodynamic control
- Wind farm (wake) effects
- ***Noise production***!!!

And hence the overall success of a wind turbine and wind farm design and their social acceptance

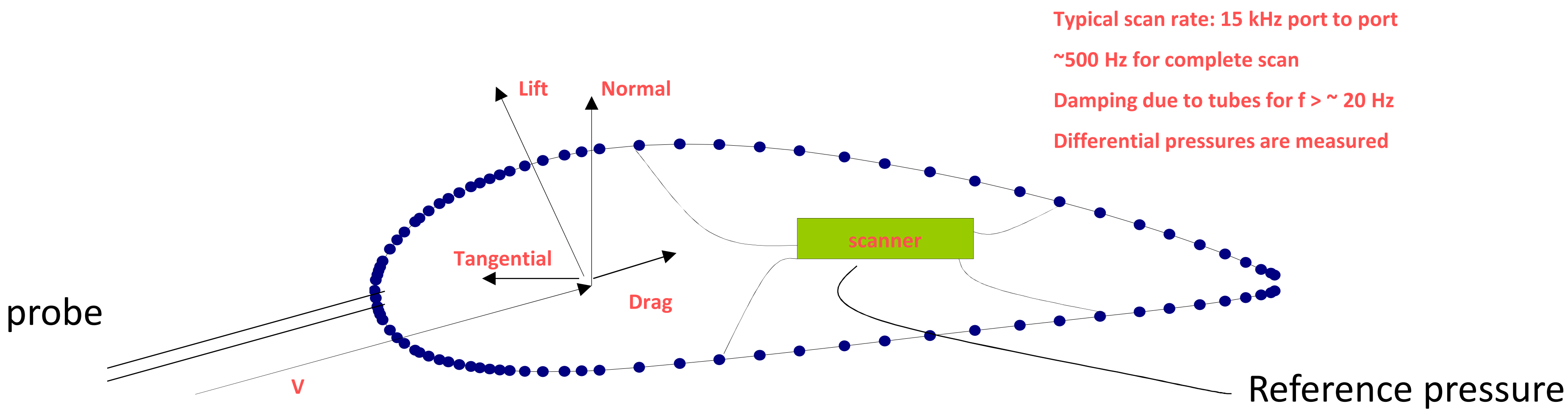
ECN

Aerodynamics: What we need most:

MEASUREMENTS , MEASUREMENTS, MEASUREMENTS!!

Aerodynamic measurements, Why?

– To develop, validate aerodynamic models
– Conventional measurement programs: Only indirect, global aerodynamic information
– Desired: Direct local aerodynamic properties (I.e. pressure distributions, inflow angles, inflow velocities)



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IEA *) TASKS ON AERODYNAMIC MEASUREMENTS

- 1991-1997: IEA Task 14 (Field Rotor Aerodynamics, Operating Agent: ECN)
- 1997-2001: IEA Task 18 (Field Rotor Aerodynamics, enhanced, Operating Agent: ECN))
- 2001-2007: IEA Task 20: (Analysis of NREL's NASA-Ames, measurements, Operating Agent: NREL)
- 2008-2011: IEA Task 29: Mexnext-I (Analysis of Mexico measurements, Operating Agent: ECN)
- 2011-2014: IEA Task 29: Mexnext-II (New Mexico measurements, including noise aspects, Operating Agent, ECN)

*) IEA = International Energy Agency

Rotor aerodynamic measurements: IEA Tasks 14/18

- Period: 1991-2001
- Aim: To coordinate aerodynamic test programs on **field** facilities
- Participants
  - Netherlands Energy Research Foundation, ECN (NL; Operating Agent)
  - Delft University of Technology, DUT (NL)
  - Imperial College/Rutherford Appleton Laboratory, IC/RAL (UK, Only Task 14)
  - National Renewable Energy Laboratory, NREL (USA)
  - RISØ, The Test Station for Wind Turbines (DK)
  - Mie University (JP, Only Task 18)
  - Centre for Renewable Energy Sources, CRES (Gr, Only Task 18)

IEA Tasks 14/18: Facilities

ECN facility

NREL facility

Validation measurements, status at end of 90's

1990:

Measurements of power and loads showed differences but they were too global to form a basis for improvement of aerodynamic models

Desired:

- Local aerodynamic loads (pressure distribution) in field conditions (IEA Tasks 14/18)
- But also: Constant, uniform and controlled conditions (→Windtunnel)

Measurements in NASA-Ames wind tunnel

- Carried out by NREL (National Renewable Energy Laboratory), USA
- Spring 2000
- 24m x 36m NASA-Ames wind tunnel.
- 10 m rotor
- Measurement of pressure distributions at 5 locations along rotor blade
- Analysed in IEA Task 20 (Operating Agent: NREL)
- Participants:
  - ETS (Canada)
  - RISO/DTU (Denmark)
  - CRES/NTUA (Greece)
  - ECN/TUDelft (Holland)
  - IFE (Norway)
  - CENER (Spain)
  - HGO (Sweden)

Validation measurements, status at ~2005

1990:

Measurements of power and loads showed differences but they were too global to form a basis for improvement of aerodynamic models

Desired:

- Local aerodynamic loads (pressure distribution) in field conditions (IEA Tasks 14/18)
- Constant, uniform and controlled conditions (→NASA-Ames windtunnel measurements from IEA Task 20)
- But also: Induced velocities and wake velocities (→ Detailed flow field measurements from Mexico project)

Rotor aerodynamic measurements: EU project Mexico
Model rotor EXperiments In COntrolled conditions [1])

- Coordinated by ECN
- 2001-2006
- Measurements in German Dutch Wind tunnel, DNW
  - North East Polder (Netherlands)
  - Open test section: 9.5 x 9.5 m^2
  - Diameter of rotor:4.5 m
    - Fast pressure measurements at 5 positions (25%, 35%, 60%, 82% and 92% span) along the blade
    - Particle Image Velocimetry (PIV): Quantitative flow visualisation

[1]) Participants: see http://www.ecn.nl/nl/units/wind/rd-programma/aerodynamica/projects/mexico/

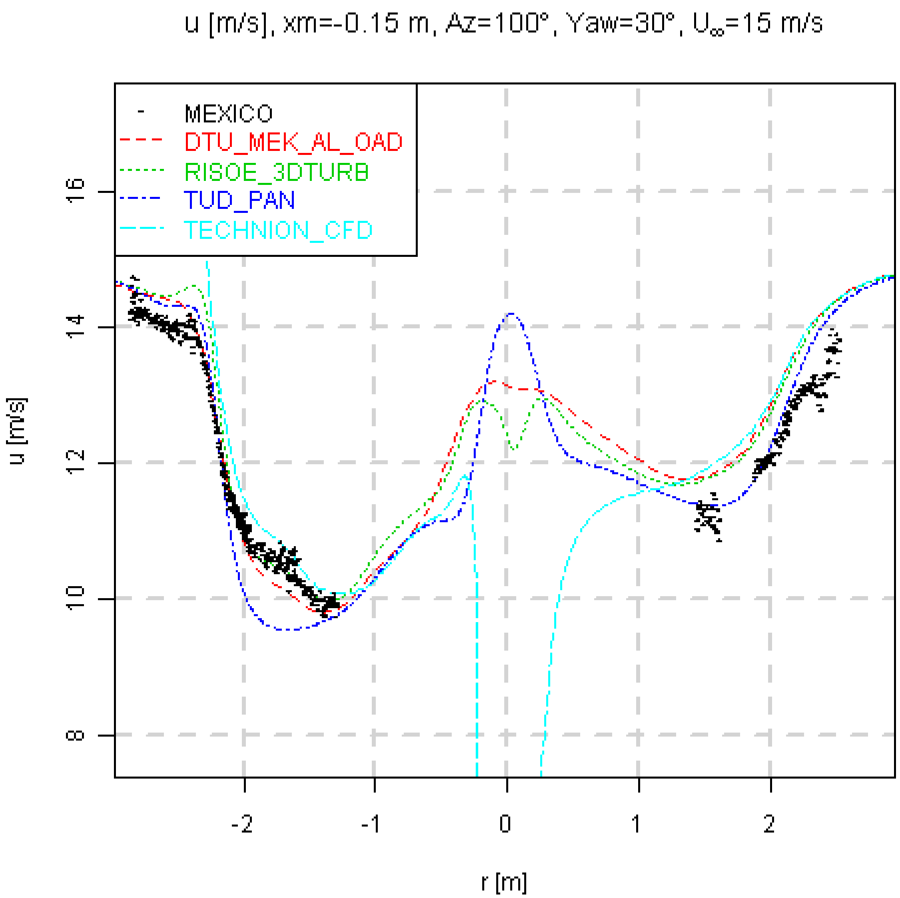
Rotor aerodynamic measurements: IEA Task 29 MexNext-I: Goals and Participants

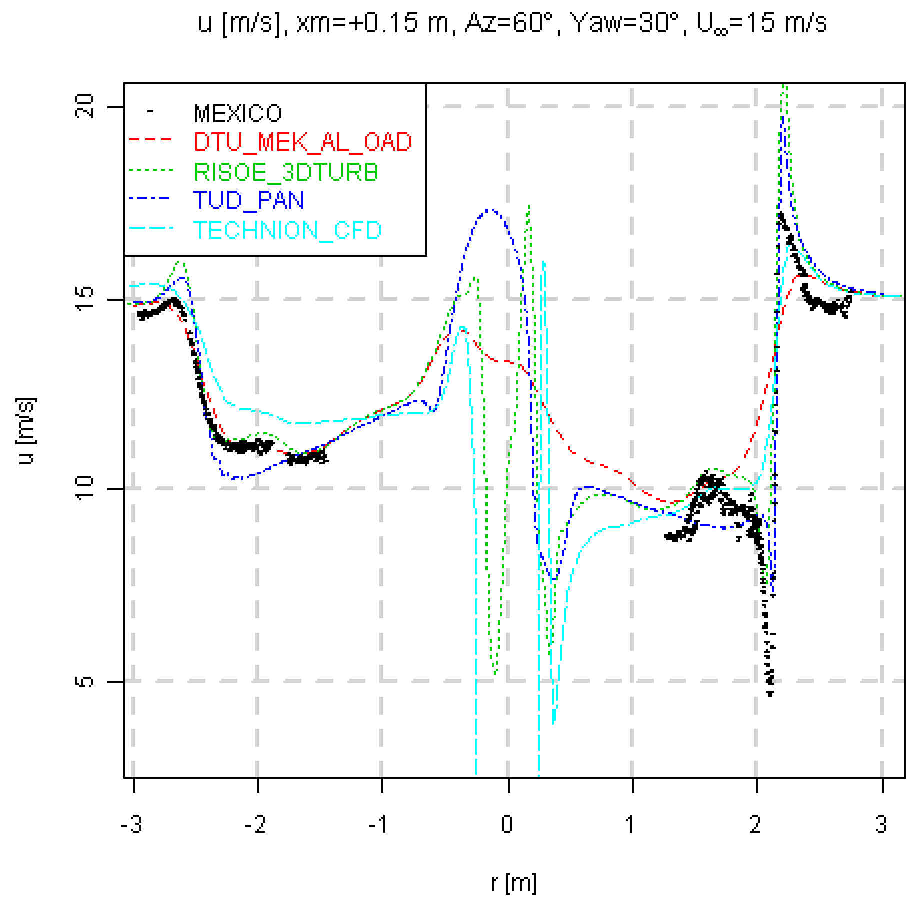
- Goal: Analysis of Mexico measurements
- Coordinated by ECN with participation from the following institutes:
  - Canada (École de technologie supérieur, Montreal (ETS), University of Victoria (UVic))
  - Denmark(DTU-RISO/DTU(Mek))
  - Germany(University of Stuttgart (IAG), University of Applied Sciences, Kiel, Forwind)
  - Israel (Israel Institute of Technology (Technion))
  - Japan (Mie University/National Institute of Advanced Industrial Science)
  - Korea((Korea Institute of Energy Research (Kier) and Korea Aerospace Research Institute (Kari))
  - Netherlands(Energy Research Center of the Netherlands (ECN), University of Delft (TUDelft), Technical University of Twente, Suzlon Blade Technology)
  - Norway (Institute for Energy Technology/Norwegian University of Science and Technology (IFE/NTNU))
  - Spain(Renewable Energy National Centre of Spain (CENER) and National Institute for Aerospace Technology, INTA)
  - Sweden(Royal Institute of Technology/University of Gotland (KTH/HGO))
  - USA (National Renewable Energy Laboratory (NREL))

IEA Tasks: some highlights

- Databases of measurements made available, eg.
  http://www.ecn.nl/nl/units/wind/projecten/field-rotor-aerodynamics-database/
- 'Discovery' of
  - Stall delay on wind turbines (underprediction of loads at inner part of the blade at large angles of attack when using 2D airfoil coefficients)
  - Overprediction of tip loads when using 2D airfoil coefficients
  - 'Compensating' errors when using global measurements
  - Power increases with yaw angle at large angles of attack!
  - Very detailed validation of codes leading to several improvements showing e.g. an excellent prediction of velocities at yaw by CFD
  - Some non-understood phenomena….., see [1]

Mexico rotor at yaw: PIV velocity traverse along radial coordinate from '9 to 3 'o clock position'; just upstream (left) and downstream (right) of the rotor plane; measured and calculated





Conclusion: Extremely good agreement!

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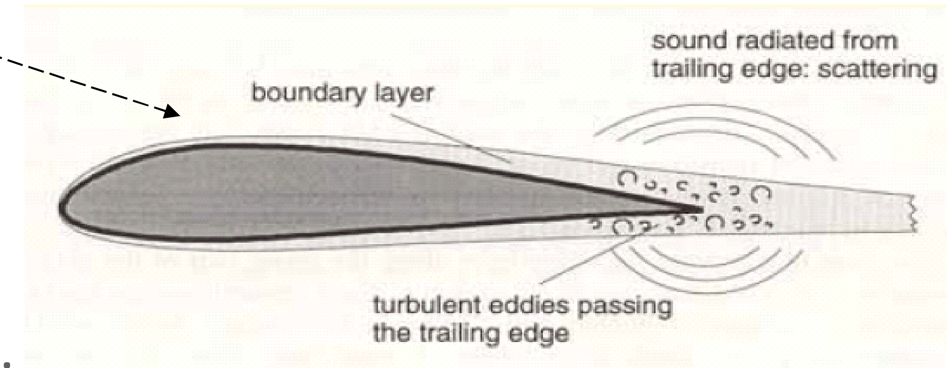
SIROCCO, SIlent ROtors by aCoustiC Optimisation

- 2004-2007
- Participants:
  - Energy Research Centre of the Netherlands, **ECN** (Coordinator)
  - National Aerospace Laboratory, **NLR**
  - University of Stuttgart, **Ustutt**
  - Gamesa Aeólica, **Gamesa**
    GE Wind Energy/Global Research, **GE**

- Funded by:
  - EU 5th Framework

SIROCCO, OBJECTIVE

- To develop 'tip'-**airfoils** (r/R >0.75) by which aerodynamic noise of wind turbines can be reduced significantly **without loss in aerodynamic performance**;

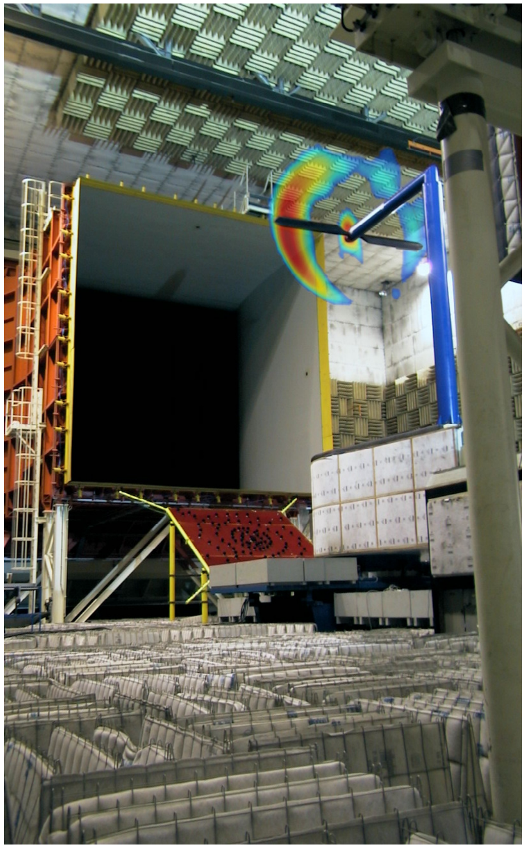


- Focus is on reduction of **trailing edge noise** (> inflow noise)!
  - Noise scattered from turbulent eddies at the trailing edge
  - So this is is very **AERODYNAMIC** subject

SIROCCO, Background

EU project 'DATA':

- 1998-2001
- Coordinated by University of Stuttgart
  - Participants: NLR, ECN, TNO, LM Glassfibre
- Acoustic measurements on a 4.5 meter model rotor in DNW
- Rotor with baseline airfoils and acoustic airfoils
  - Noise reduction of 3-6dB(A) on rotor with acoustic airfoils!
  - Trailing edge noise dominant
- Will this also be found in the field? → Sirocco!



SIROCCO BASELINE TURBINES

Two 'baseline' turbines:

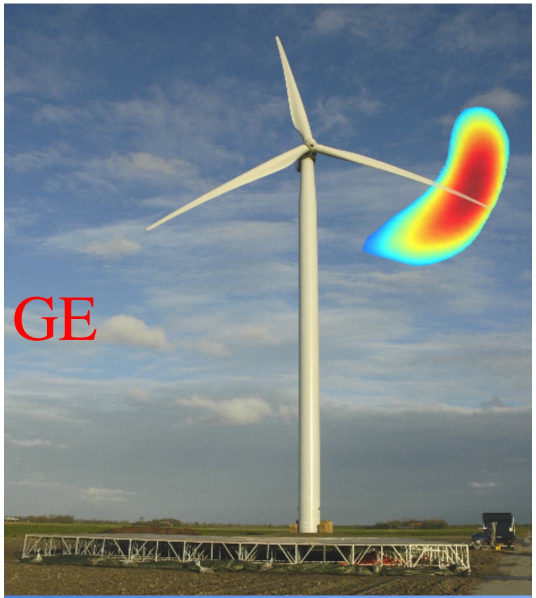
- Gamesa (G58, D=58 m, 850 kW, at Zaragoza)
- GE (2.3 MW, D=94 m, at ECN test field)

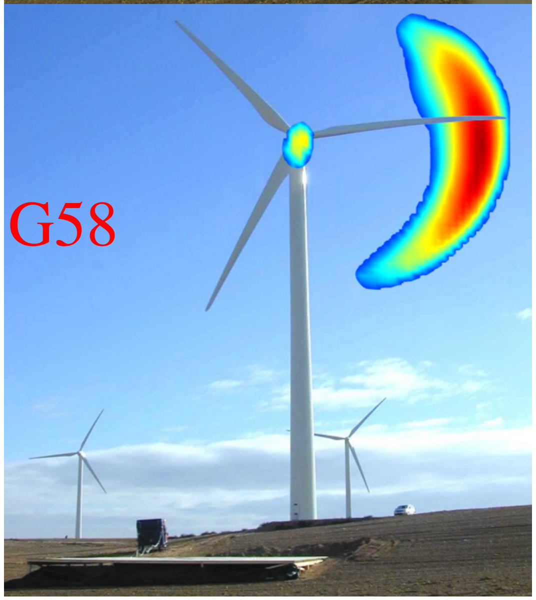
Replace airfoils at outer part of the blades by silent Sirocco airfoils

Acoustic array measurements: Some observations

- Turbine noise dominated by rotor blades
  - **Aerodynamic** noise is dominant!
- Noise radiated from outer part of blades (but not the very tip)
- Practically all blade noise (emitted to ground) produced during downward movement.
  Explained by combination of:
  - Convective amplification
  - **Trailing edge noise** directivity
- Gamesa blade has been tripped: Tripped blade noisier
- Noise proportional to 5th power of velocity at blades
- Comparison of measurements with acoustic design code SILANT from ECN shows very good agreement

Picture: nlr/ecn



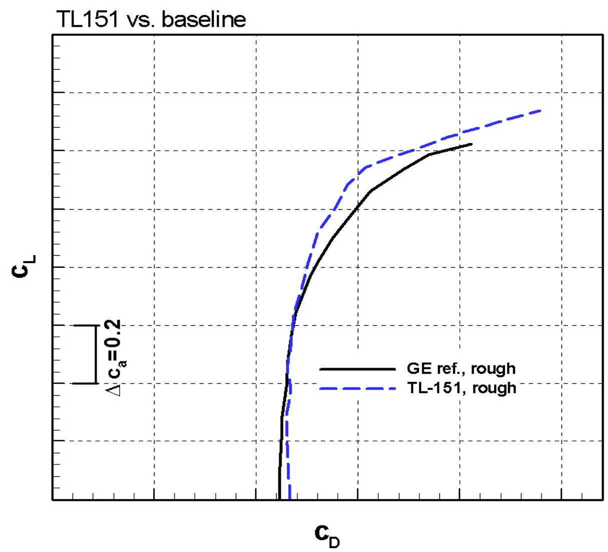


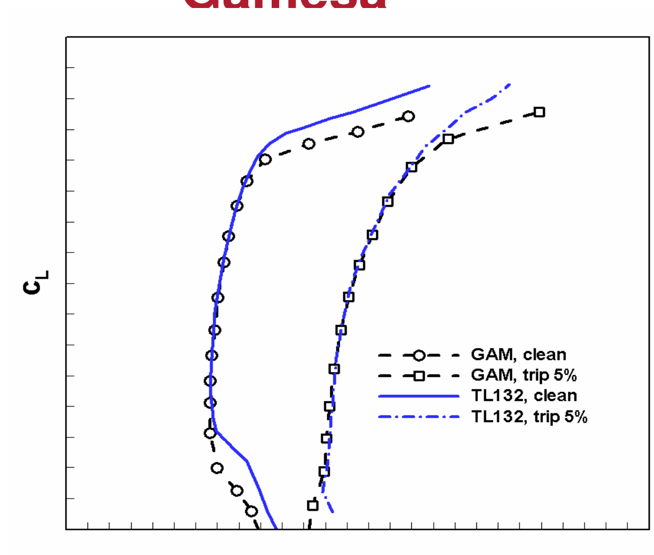
Validation of new silent airfoils designed by University of Stuttgart (TL-airfoils) by means of 2D wind tunnel measurements

GE

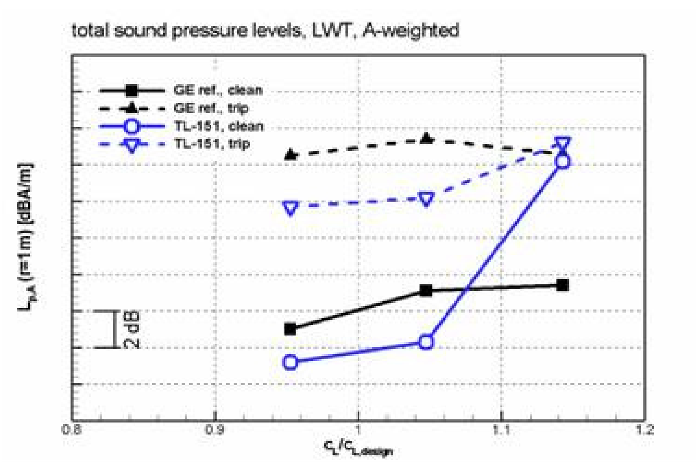
Gamesa

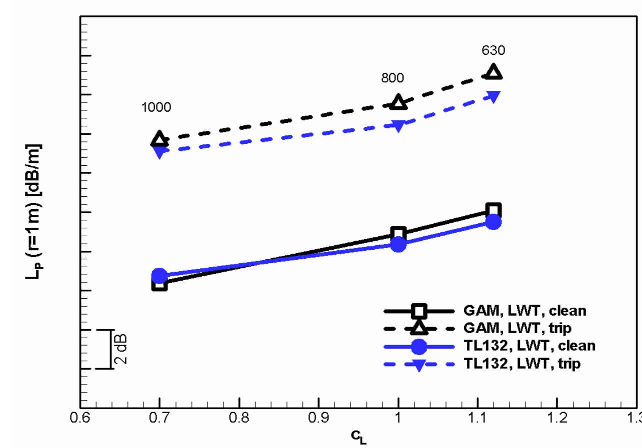
Drag polars



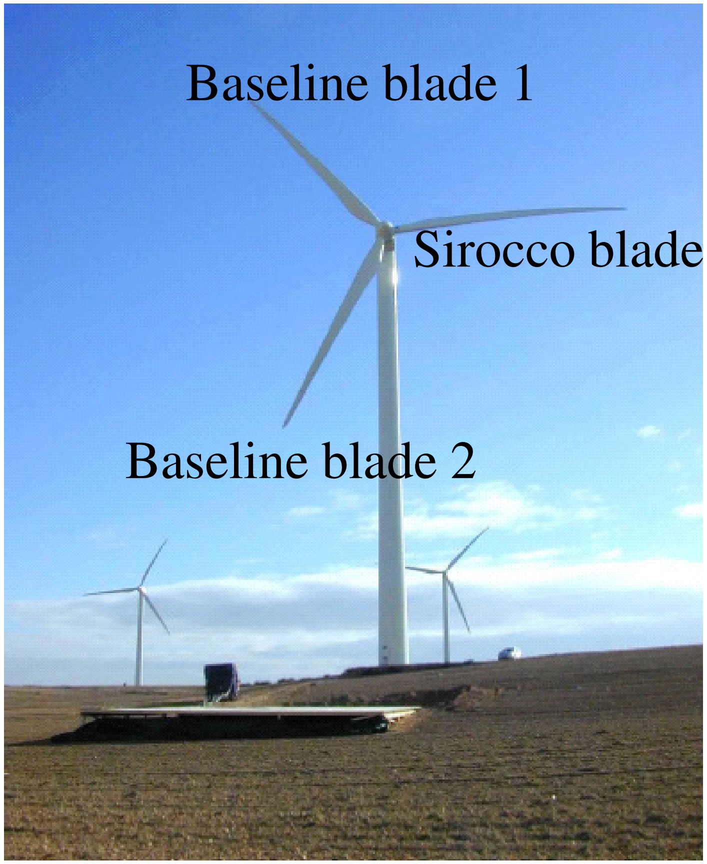


Noise polars





Final validation on a hybrid rotor



- 1 Sirocco blade with silent airfoils and 2 baseline blades
- Behavior of Sirocco blade can directly be compared with behavior of the baseline blades (same atmospheric conditions)

Validation: Acoustic field measurements on hybrid GE rotor

Blade: State nr	Sir	GE_2	GE_1
State 1	clean with trip	clean with trip + serrations	clean with trip
State 2	untreated	serrations	untreated

GE measurements: Different states

Blade: State nr	Sir	GE_2	GE_1
State 1			
State 2	-0.5	-3.2	0

Differences in apparent sound power level as measured by array, relative to blade 1

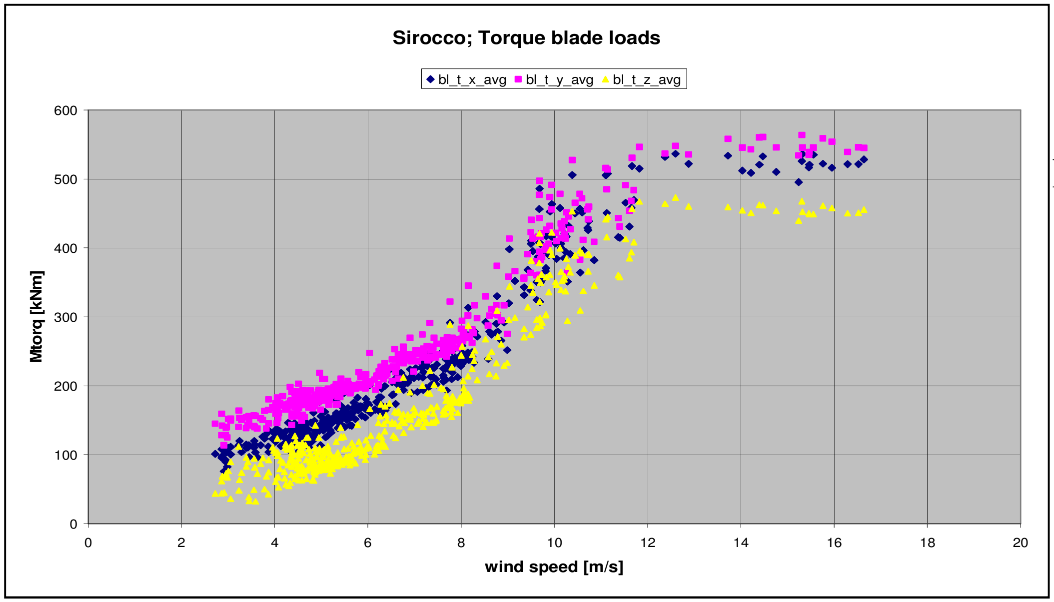
Observations on GE measurements:

- State 1 (tripped) measurements: Too little data available (no proper weather conditions in measurement window (April 2007 turned out to be a hot Dutch summer month!))
- State 2 (untreated/untripped) measurements: Sirocco blade shows reduction of 0.5 dB(A)
- Serrations: Noise reduction of 3.2 dB(A) (can work additively to the reduction from the acoustic airfoils)

Picture: Steno project (University of Stuttgart)

Validation: Field measurements on hybrid GE rotor, blade loads carried out by ECN

ECN



In plane blade root moments (torque contribution)

Indications for increase of performance from Sirocco/serrations blade:

- Increase found from the in-plane torque of the Sirocco blade and the blade with serrations
- Power curve measurements indicate increase in annual energy production of ~ 2.8% from Sirocco blade.
- Acoustic measurements at **same** aerodynamic performance would have given us a larger noise reduction

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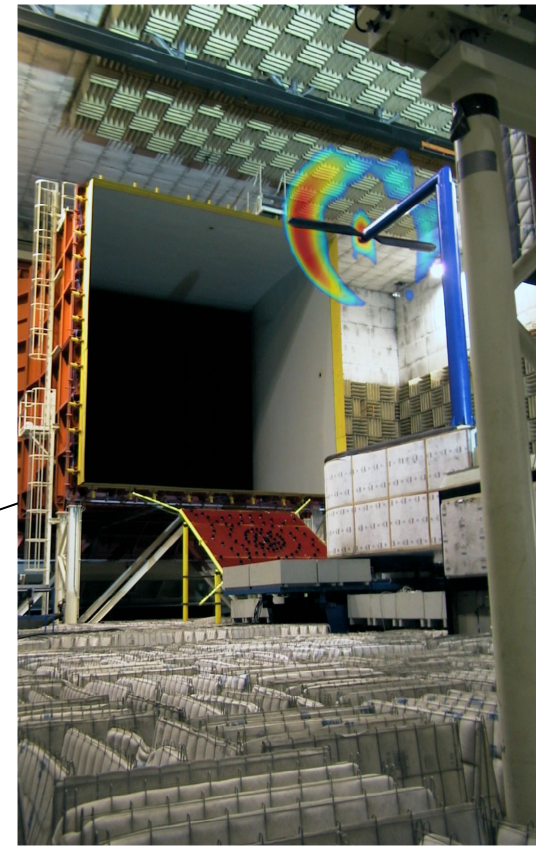
‘New Mexico’ experiment

- The Mexico model is still in a good shape, so additional wind tunnel measurements can be performed to fill the missing gaps from the Mexico project, taking into account the lessons learnt [1]), and:
  - Combine detailed **aerodynamic** measurements with detailed **acoustic** measurements to establish the acoustic/aerodynamic link
  - Detailed pressure and flow measurement (Mexico-techniques) combined with mic array and possibly far field mic measurements (DATA-techniques). Note: no boundary layer data

[1]) Note: The measurements were originally supposed to be done in 2 slots, to include the lessons learnt from the first slot in the second slot but this was abandoned due to financial constraints



Acoustic measurements in DNW tunnel on a different model made in the EU project DATA gave detailed information on the acoustic behaviour of a wind turbine rotor but no information on the aerodynamics

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Conclusions

- Several international cooperation projects have been carried out in which the understanding of wind turbine aerodynamics and acoustics has increased enormously
- Generally speaking aerodynamic noise is found to be the dominant noise source:
  - Aerodynamics can be seen independant from acoustics but not vice versa!
- Within the New Mexico project aerodynamic (pressure and flow-field) measurements are combined with acoustic array measurements
- The link between acoustics and aerodynamics mainly lies on the field of inflow, pressure distributions and **boundary layer** properties.
- Until now measurement and modelling of detailed **boundary layer** properties on a rotating wind turbine blade got (too) little attention