The importance of aerodynamics and the role of aerodynamic measurements

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Your energy. Our passion.

The importance of aerodynamics and the role of aerodynamic measurements

Illustrated with results from the NASA-Ames experiment at yaw

Gerard Schepers (ECN) and Scott Schreck (NREL)
The science of Making Torque, Oldenburg

Content

- *Importance of wind turbine aerodynamics*
  - Aerodynamic design modelling
  - Aerodynamic measurements
- Aerodynamic wind turbine measurements
  - IEA projects on field and wind tunnel measurements
    (IEA Task 14, IEA Task 18, IEA Task 20 and IEA Task 29 (Mexnext-I))
    - Power at yawed conditions in NASA-Ames measurements
  - Current and future developments with regard to aerodynamic measurements

AERODYNAMICS OF WIND TURBINES

Important for:

- Energy production
- Loads (strength, costs!)
- Stability (failure, damage)
- Control
  - Stall
  - (Individual) pitch
  - Distributed aerodynamic control

And hence the overall success of a wind turbine design

AERODYNAMICS

- Aerodynamics of wind turbines is extremely difficult
  - Rotating
  - In lower part of atmosphere → extremely turbulent
  - Instationary
  - Stall(!)
  - Large variety in scales (Diameter can be twice span of Airbus A380!)
  - Constraints and interactions (e.g. costs, system dynamics)
  - Wind turbine aerodynamic calculations are extremely time consuming
    - Load calculations: Time domain, many long time series needed to get 'statistics right'
    - (~10^6 nr of time steps)→ Calculational time of a design spectrum can easily be longer than lifetime of the wind turbine
    - Generally calculations are done with simplified **Blade Element Momentum (BEM)** Theory with engineering add-ons to cover instationary effects, stall, 3D effects, yaw etc.

Aerodynamic modelling

- Former validation projects generally show 10-20% accuracy of blade loads calculated with **BEM** for **standard** conditions, (excluding stall) but still large uncertainties (i.e. 50%) in off-design conditions [1])
- What about uncertainties for modern wind turbines?
  - Wind turbine designs become **'unconventional'**, what about the modelling aspects?
  - Aerodynamic modelling of distributed control **devices**
  - For very **large** turbines BEM may not model correctly:
    - Incoherent structures over the rotor
    - Extreme shear, low level jets, 3D shear effects (wind farms!)
- Research needed to improve the accuracy, among others by other types of modelling, e.g **CFD**

1) Schepers, J.G.; Heijdra, J.J.; Thomsen, K.; Larsen, T.; Foussekis, D.; Rawlinson Smith, R.; Kraan, I.; Visser, B.; Øye, S.; Ganander, H.; Carlen, I.; Voutsinas, S.; Belessis, M.; Drost, L. Verification of European Wind turbine design codes, presented at European wind energy conference and exhibition, Copenhagen, Denmark, 2-6 july, 2001.

Aerodynamics

- **MEASUREMENTS , MEASUREMENTS, MEASUREMENTS**
- Detailed aerodynamic measurements along the blades are urgently needed at several conditions

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  - Current and future developments

IEA TASKS ON AERODYNAMIC MEASUREMENTS

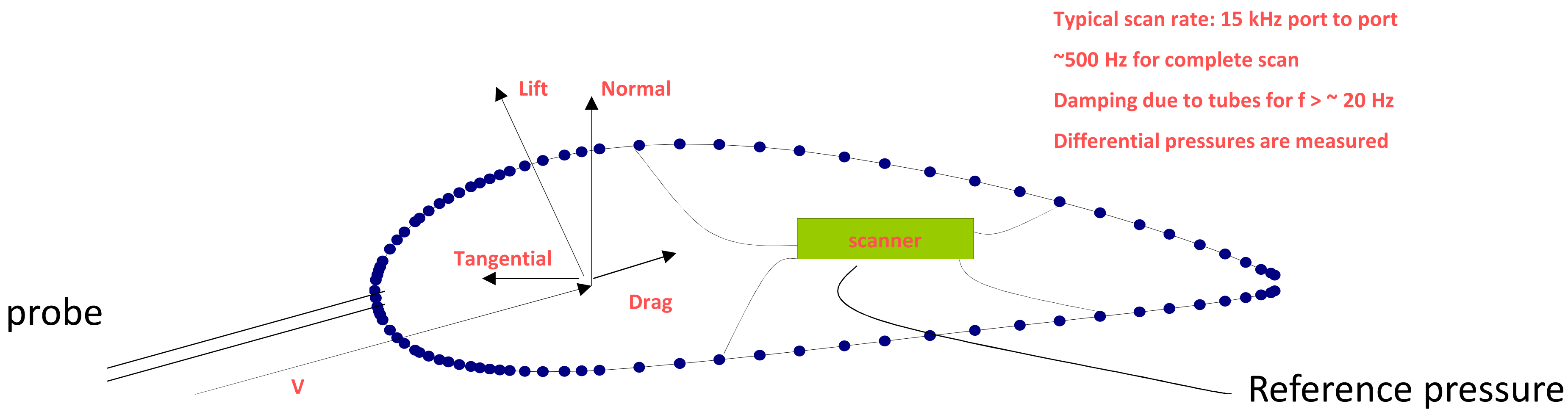
- 1991-1997: IEA Task 14 (Field Rotor Aerodynamics, Operating Agent: ECN)
- 1997-2001: IEA Task 18 (Field Rotor Aerodynamics, enhanced, Operating Agent: ECN))
- 2001-2007: IEA Task 20: (Analysis of NREL's NASA-Ames, measurements, Operating Agent: NREL)
- 2008-2011: IEA Task 29: Mexnext-I (Analysis of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

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)

Aerodynamic measurements

– 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)



IEA Tasks 14/18: Facilities

ECN facility

NREL facility

IEA Task 14/18 some results

- Database on 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

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)

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    - *Power at yawed conditions in NASA-Ames measurements*
  - Current and future developments

Illustration of the value of aerodynamic measurements

A study of the power at yawed conditions in NASA-Ames

Most of the attention (also in the IEA tasks) was focussed on **loads** at yawed conditions

- What happens with the **power** in yaw?
- It is proposed to assume a cosinuidal behaviour (inspired by [1])
  - $P \sim P_0 \cos^x \phi_y$ with P_0 the power at zero yaw and x the exponent to be determined

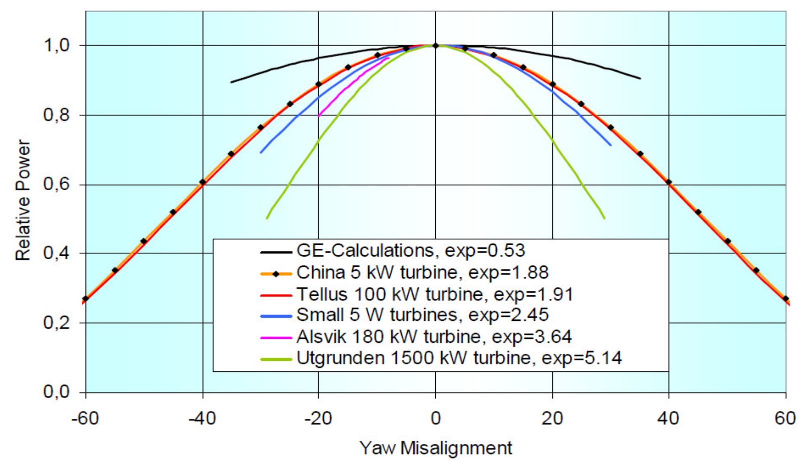
1) Dahlberg, J.A. and Montgomerie, B
Research program of the Utgrunden Demonstration Offshore Wind Farm, Final report Part 2, Wake effects and other loads
Swedish Defense Research Agency, FOI, FOI 2005-02-17 , 2005

$x = 3$?

- Some people think that $x = 3$: $P \sim P_0 \cos^3\phi_y$ based on the assumption that:
  - $P \sim V_{axial}^3$
  - $V_{axial} = V_w \cos(\phi_y)$
  - This (implicitly) assumes a constant *induction* with yaw angle
- However *induction* changes with yaw angle!

Research from Jan-Ake Dahlberg [1])

- Jan Ake Dahlberg (Vattenfall/FFA) finds on basis of field and wind tunnel measurements that:
  - $P \sim P_0 \cos^x \phi_y$ with x to vary between **1.88** and **5.15**
  - BEM **overpredicts** the power at yawed conditions

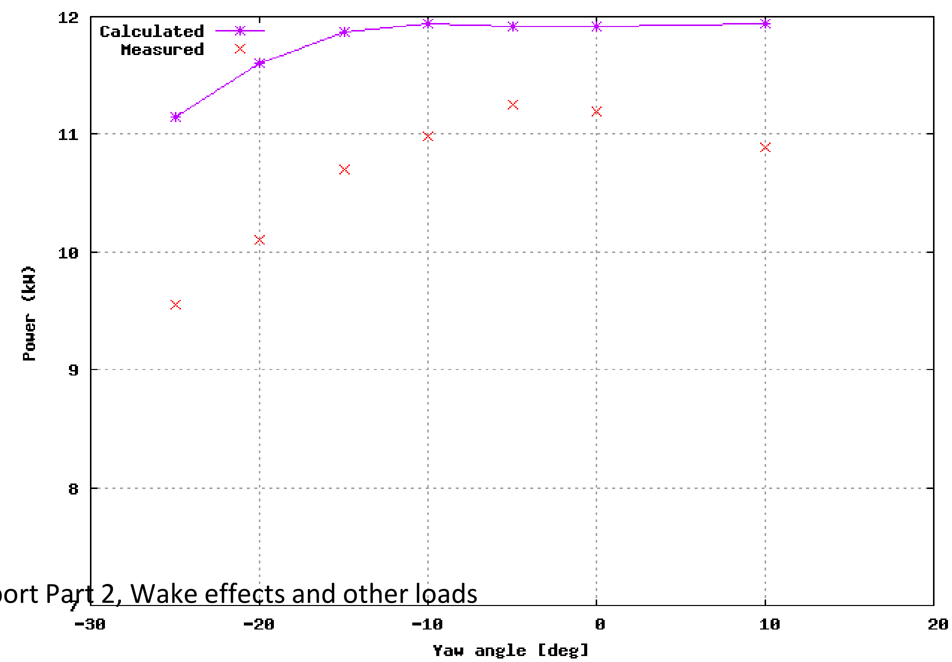


[1]) Dahlberg, J.A. and Montgomerie, B
Research program of the Utgrunden Demonstration Offshore Wind Farm,
Final report Part 2, Wake effects and other loads
Swedish Defense Research Agency, FOI, FOI 2005-02-17 , 2005

DATA measurements on rotor with D=4.5 m in German Dutch Wind Tunnel DNW at design conditions [1])

- $P \sim P_0 \cos^x \phi_y$ with **x ~ 1.8**
- BEM **overpredicts** the power at yawed conditions

→Generally consistent with findings from [2])

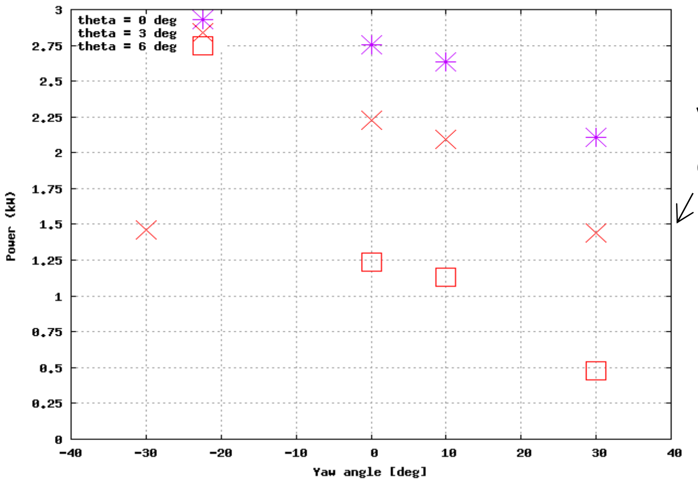


[1]) J.G. Schepers EU project in German Dutch Wind Tunnel ECN-RX--01-006, 2001

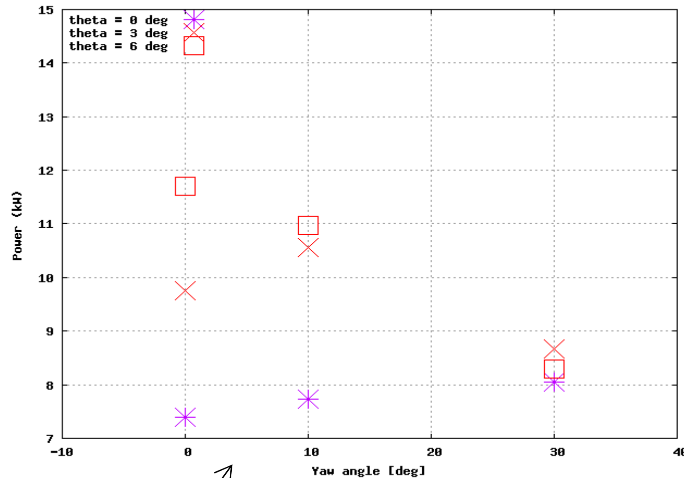
[2]) Dahlberg, J.A. and Montgomerie, B
Research program of the Utgrunden Demonstration Offshore Wind Farm, Final report Part 2, Wake effects and other loads
Swedish Defense Research Agency, FOI, FOI 2005-02-17 , 2005

Analysis on NREL Phase VI(NASA-Ames) $P(\phi_y)$ measurements

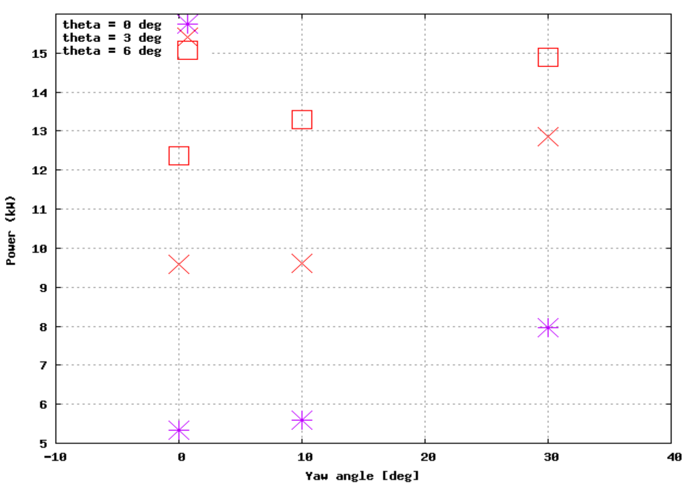
Results analyzed at V_{tun} = 5, 10 and 15 m/s and θ = 0, 3 and 6 degrees



V_{tun}=5m/s: Power decreases with yaw



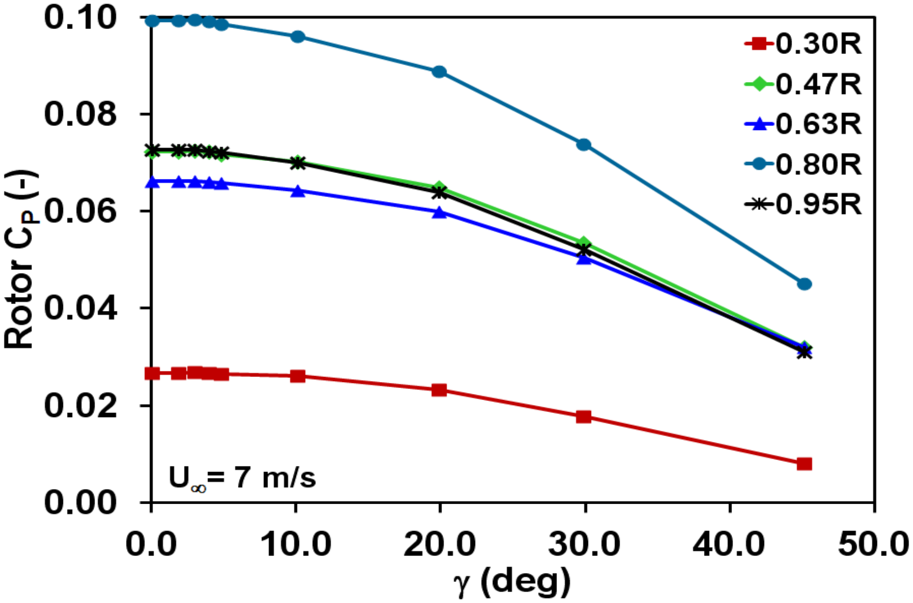
V_{tun}=10m/s: Power decreases with yaw for θ =6 deg
increases with yaw for θ = 0 deg

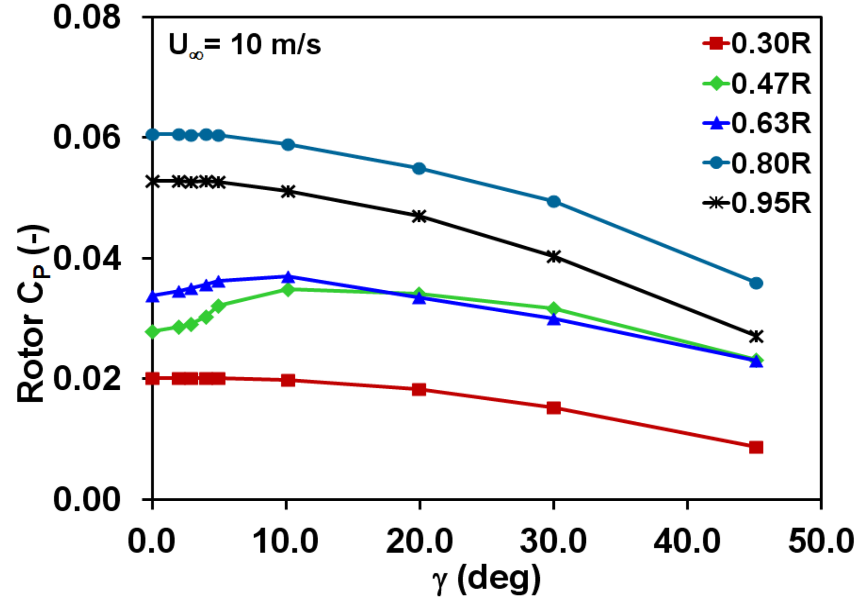


V_{tun}=15m/s: Power **increases** with yaw

- Trend: Power decrease with yaw seems less apparent for **larger angles of attack** (high wind speed and low pitch angle) and eventually the power even **increases** with yaw!

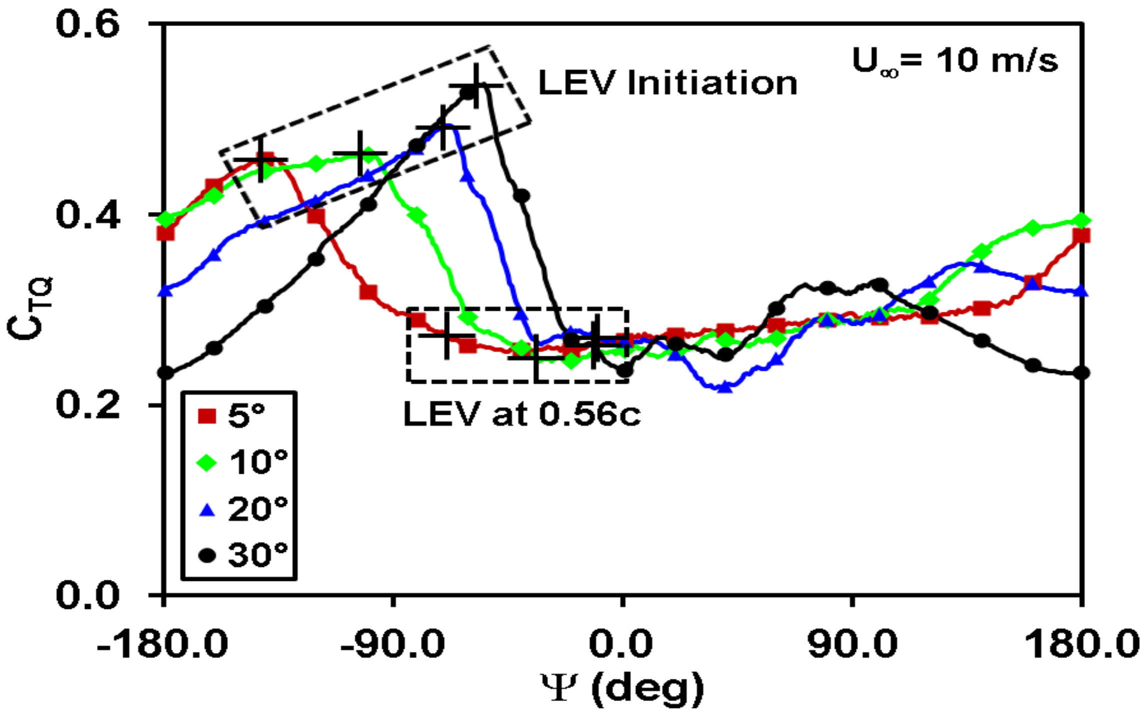
Analysis on NREL Phase VI(NASA-Ames) $C_P(\phi_y)$ measurements





- Sectional C_P as function of yaw angle at 7 m/s and 10 m/s
- Conclusion:
  - 7 m/s: Monotonic decrease
  - 10 m/s: Initial increase at 47% and 63% span

Analysis on NREL Phase VI(NASA-Ames) measurements at yaw



Sectional torque coefficient as function of azimuth angle at different yaw angles

Conclusion:

- Strong unsteady aerodynamic effects dependant on yaw angle
- Non-linear unsteady aerodynamic effects determine the rotor averaged torque (i.e. power)

Value of aerodynamic wind tunnel measurements because:

- The $P(\phi_y)$ behaviour could be deteremined at well defined conditions
- The sectional $P(\phi_y)$ behaviour could be determined
- The unsteady airfoil aerodynamics could be determined at yaw
- The conclusion can be drawns that high wind speeds, low pitch angles, and the inner part of the blad makes a a power increases with yaw angle more likely
  → large angles of attack lead to a power increases due to unsteady airfoil aerodynamics
- Remaining question: Why does BEM overpredicts the power at yawed conditions
  - Possibly related to the generally accepted calculation of disc averaged induction according to Glauert:

$$F_{ax} = \rho\, A_r \,|\, \vec{V}_w + \vec{u}_{i0} \,|\, .\, 2\, \vec{u}_{i0}$$

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  - Current and future developments

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
- Participation from the following institutes from 11 different countries:
  - 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))

Results from Mexnext-I

- Has already been presented where it is mainly the combination of flow field measurements and detailed aerodynamic measurements on the blade which made the Mexico experiment unique

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Current and planned developments on the field of aerodynamic measurements

- IEA Task 29, Mexnext-II:
  - Unexplored aerodynamic data from several facilities (both wind tunnel and field) to be discussed at
  - New Mexico measurements in DNW wind tunnel [1]) based on the existing measurement set-up to complement the database
- UAE Phase VII: New measurements in NASA-Ames wind tunnel
- TUDelft wind tunnel measurements
- Mie wind tunnel measurements ----- and some more wind tunnel measurements
- Dan-Aero: Danish field aerodynamic measurements
- EERA (European Energy Research Alliance) : New field facility

[1])Acknowledgment to ESWIRP and Inwind

DU Windtunnels for aerodynamic research on wind turbines (Courtesy Gerard van Bussel)

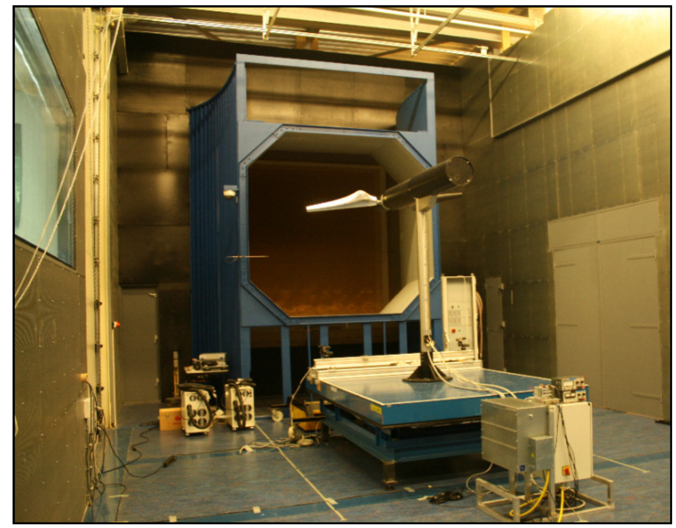
ECN

LSTL tunnel
V_{max} =110 m/s

test section 1.2 x 1.85 m
mainly for airfoil development

Open Jet tunnel
V_{max} =15 m/s

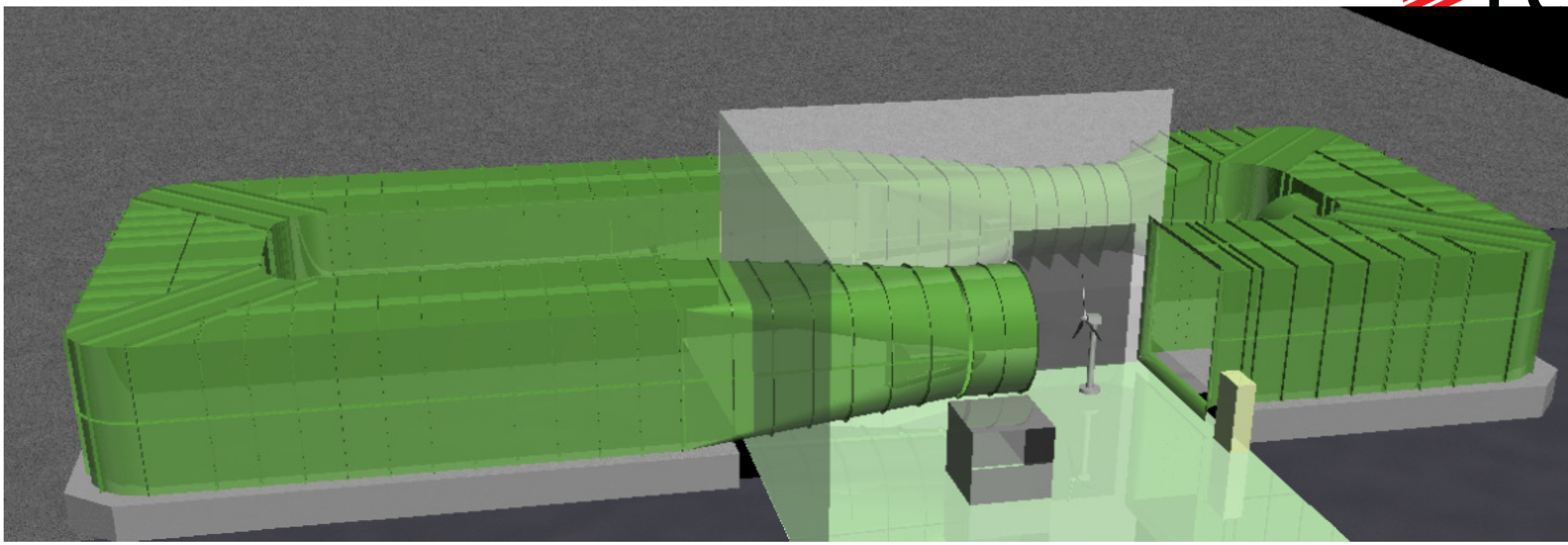
test section 2.2 m Ø
mainly for rotor flow analysis



Open Jet Facility (2009)
V_{max} =35 m/s

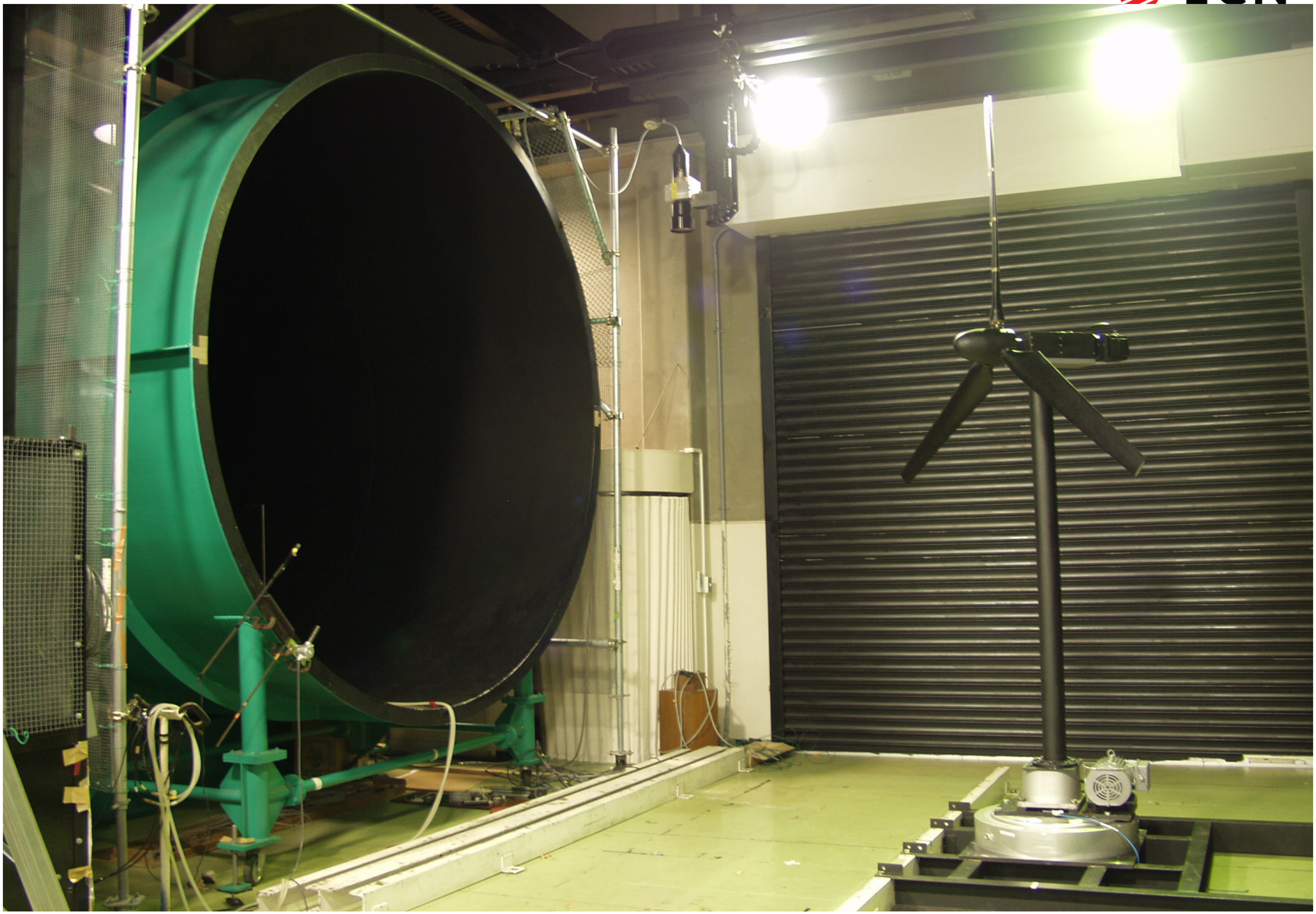
test section 3.0 m Ø 13 m long
rotor- and unsteady flow analysis

Mie University Wind Tunnel



Single return wind tunnel with open test section	
Outlet diameter	3.6m
	or 3.0m using high contraction nozzle
Suction section	4.5m x 4.5m rectangular cross-section
Length of test section	4.5m
Wind speed	0 - 30m/s for 3.6m nozzle
Uniformity	< 1.5% (7m/s)
Turbulence level	< 0.5% (7m/s)
Measurements	e.g. pressure measurements along blade, LDA

Rotor with diameter of 3.4 meter



EERA Field experiment, background

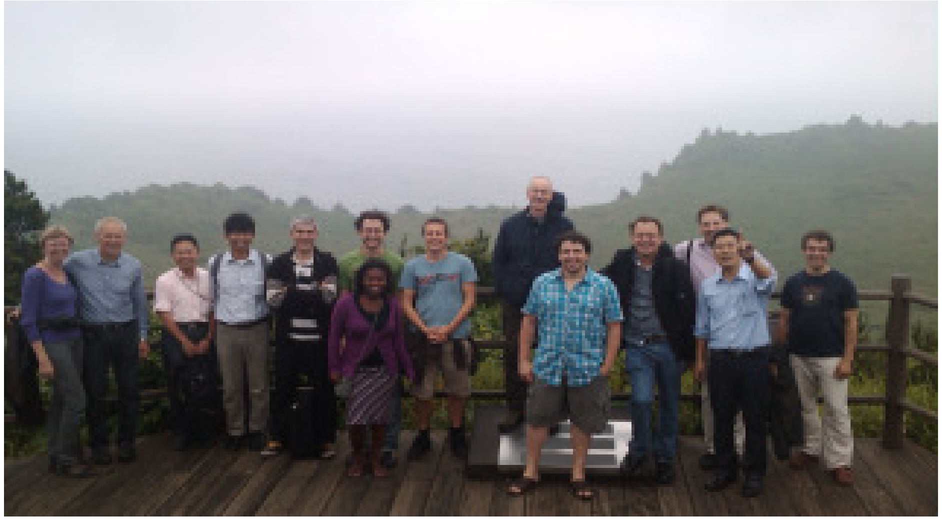
- **Wind tunnel** measurements and **field** measurements should be seen as COMPLEMENTARY
  - Wind tunnel measurements are done at well known (but less representative) conditions
    - This facilitates the interpretation of data and enables the determination of e.g. the $P(\phi_y)$ behaviour
  - Field measurements are done at representative (but less known) conditions
- We see initiatives on wind tunnel measurements (e.g. *New Mexico/NASA-Ames/TUDelft*) but not on field measurements:
- **The time is ripe for a PUBLIC aerodynamic field experiment on a wind turbine representative for the current and future generation of wind turbines based on:**
  - Most innovative measurement techniques
  - Carried out under auspices of EERA (European Energy Research Alliance)

Conclusions

- Since the end of the 80's/beginning of the 90's dedicated aerodynamic measurements have been performed on wind turbines both in the field and the wind tunnel.
- The level of maturity of these measurements has been improved enormously over the years.
- The measurements have delivered a huge amount of data and knowledge by which design codes could be improved and validated which led to more reliable and efficient wind turbine designs.

Questions?

ECN



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