Energy research Centre of the Netherlands

A short history of wind turbine aerodynamics, or: From Betz to Better

Herman Snel

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Herman Snel, ECN Wind Energy

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Albert Betz, Germany

Photograph from: E. Hau, Windkraftanlagen

From the start till 1973

Wind power (mechanical) has been in used at least since the **early middle ages** and perhaps already for two millennia

With start, we refer to the start of hydrodynamic or aerodynamic theory applicable to wind power. First steps were applied to ship propellers.

- First step is **W.J.M. Rankine**, who first described the momentum theory for an actuator disk (1865)
- Second **W. Froude**, who developed blade element theory (1898) and made the first combination (BEM was born)

Rankine:

Photograph from: Wikipedia

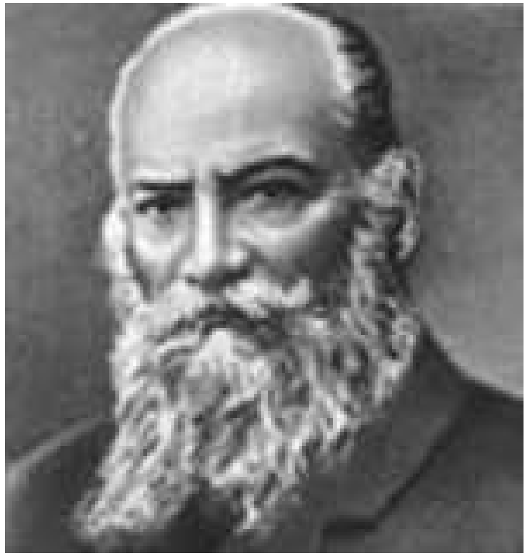
The so-called Betz maximum

The determination of the maximum amount of power that can be extracted from a free stream forms a definite application to wind energy. According to a recent article by **van Kuik**, three names are related to this:

Lanchester	1915
Betz	1920
Zhukovsky (**Joukowsky**)	1920

All based on actuator disk momentum theory (Rankine)

Lanchester's paper is primarily directed towards propellers, perhaps because of that not noticed by Betz



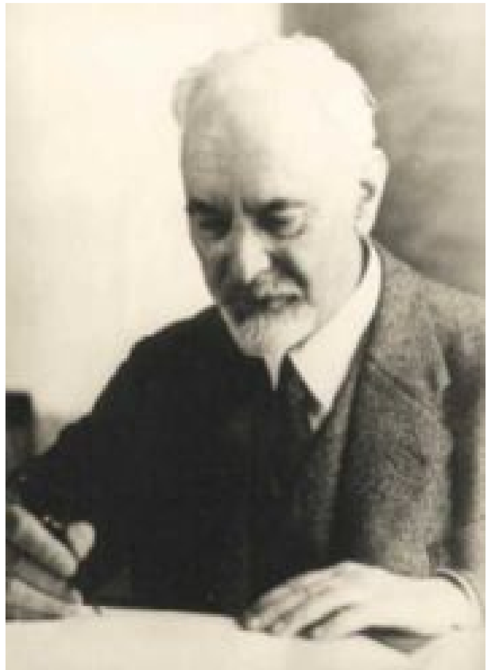
Joukowsky:

Photograph from: Wikipedia

Blade Element Momentum Theory

Hermann Glauert first described a full fledged Blade Element Momentum (BEM) Theory, in Durand (ed): Aerodynamic Theory div L, Ch. X, published in 1935, one year after his accidental death. This theory included some aspects of wake swirl, but not the effect on the radial pressure gradient

Ludwig Prandtl (1926) contributed the so-called tip correction, which in reality is a correction for the non-uniformity of the flow between blades.



Prandtl:

Photograph from: Wikipedia

ECN Early vortex theory, Goldstein

Already at an earlier stage, a vortex wake description for induction calculation had become available, from Sydney Goldstein (1929), but based on solely tip vortices of a fixed helical form.

Goldstein:

Photograph from: Wikipedia

First advances in the new wind age

The oil crisis of 1973 started the sustained modern development of wind energy, including a development of aerodynamic theory

The state of the art of around that time is present in the classic **Wilson and Lissaman** publication of 1974[1)] which introduced optimization, and in the (Agardograph) review by **Otto de Vries** of 1979[2)].

1) Applied Aerodynamics of Wind Power Machines

2) Fluid Dynamic Aspects of Wind Energy Conversion

State of affairs by the end of the 70’s

Assumptions in BEM, as described at the end of the ’70’s:	**Reality**
Steady flow	Unsteady flow: Turbulent wind, Control actions, system vibrations
Axially symmetric conditions	Always yawed flow, giving rise to unsteadiness and non uniform induction
Approximately 2D sectional flow because of slender blades, comparable to slender wings	Rotating blades cause large 3D effects especially in stall
No radial interdependence	Especially in yawed flow ridiculous

Developments in the 80’s and 90’s

The last two decades of the XX-th century showed an important number of European and National projects, leading to so-called ‘**Engineering Methods**’, to **remove part of** the limitations of BEM

and,

the development of so called **aero-elastic design codes** at the mayor European and American Research Centers, including **turbulent wind generators**.

Apart from unsteady aerodynamic formulations, these programs include **time dependent structural deformations and deformation rates**, and their effect on aerodynamic forces

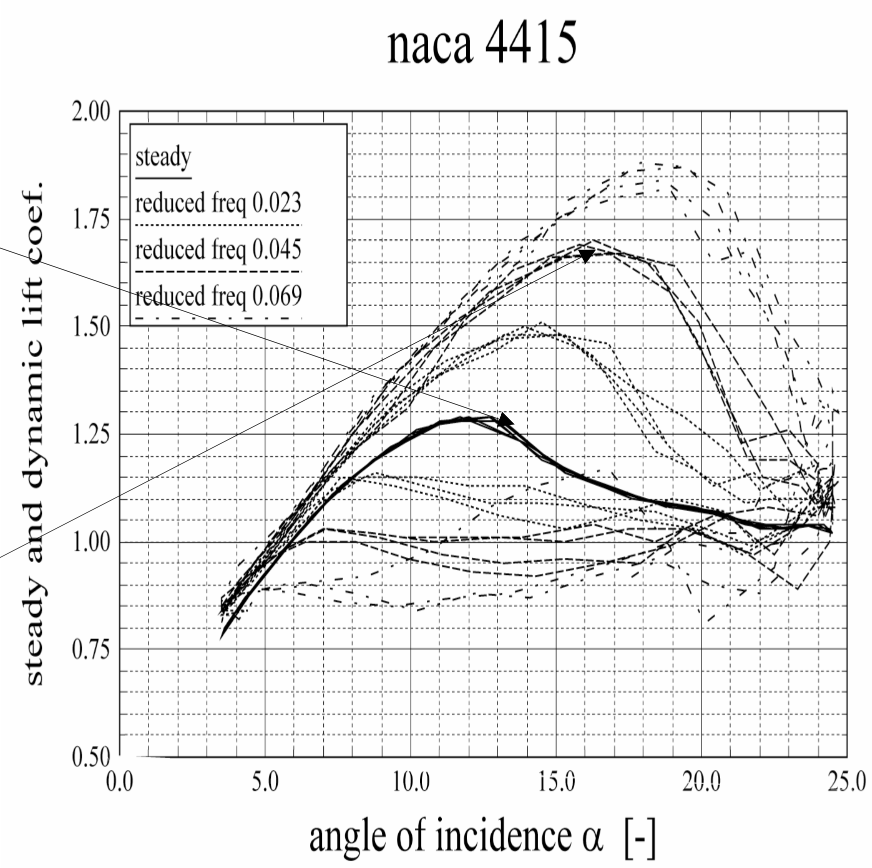
Dynamic profile characteristics

Steady profile characteristics depend on α only:

$$c_l(\alpha), c_d(\alpha), c_m(\alpha)$$

Dynamic profile characteristics, especially but not exclusively dynamic stall: Models describing hysteresis loops, in the form of first or second order ODE's in time:

$$A\frac{d^2c_l}{dt^2} + B\frac{dc_l}{dt} + f\left(c_l, \alpha, \frac{d\alpha}{dt}, \ldots\right) = 0$$



ECN Dynamic Inflow

Steady inflow equation:

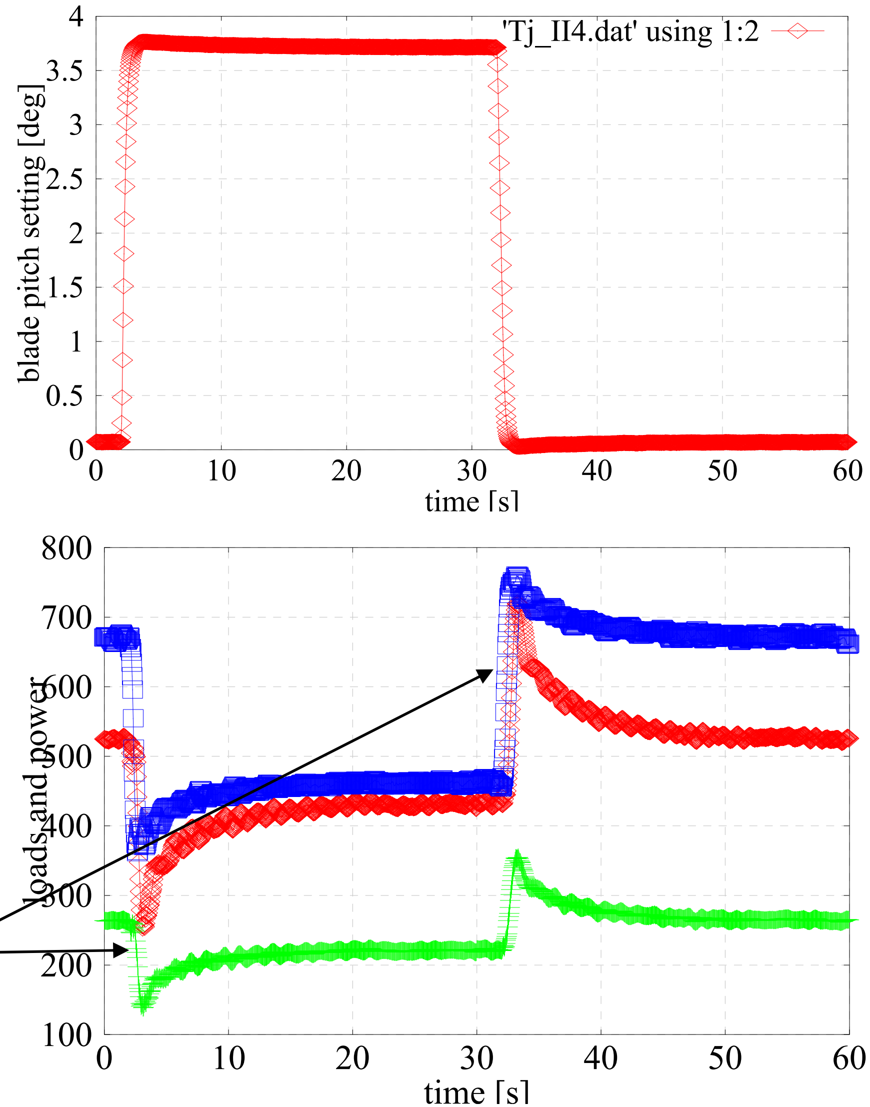
$$4u_i\left(U_\infty - u_i\right) = C_{D,ax}U_\infty^2$$

Unsteady (dynamic) inflow

$$C(r)R\frac{du_i}{dt} = C_{D,ax}U_\infty^2 - 4u_i\left(U_\infty - u_i\right)$$

Based on simple vortex cylinder analysis and measurements on the ‘old’ Tjaereborg 2MW turbine

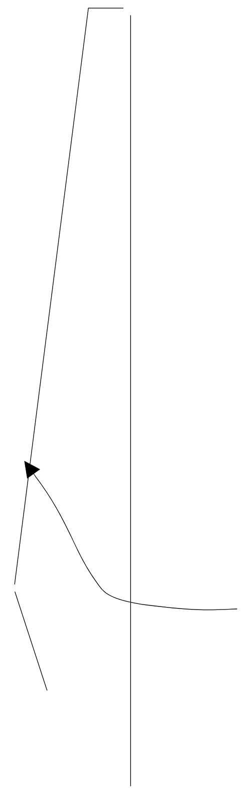
Effect of a step in pitch angle on loads

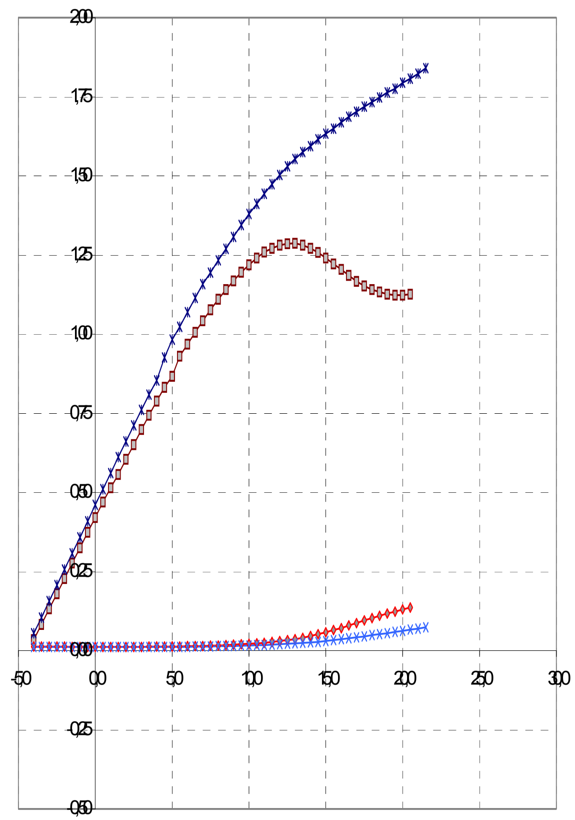


3D rotational augmentation

Outward Radial flow caused by radial pressure gradient and ‘centrifugal’ forces, when ‘residence time’ of fluid is long enough (stall)

Radial flow together with rotation gives virtual Coriolis forces which act as a chord wise, favorable pressure gradient and change the character of stall (less decambering)



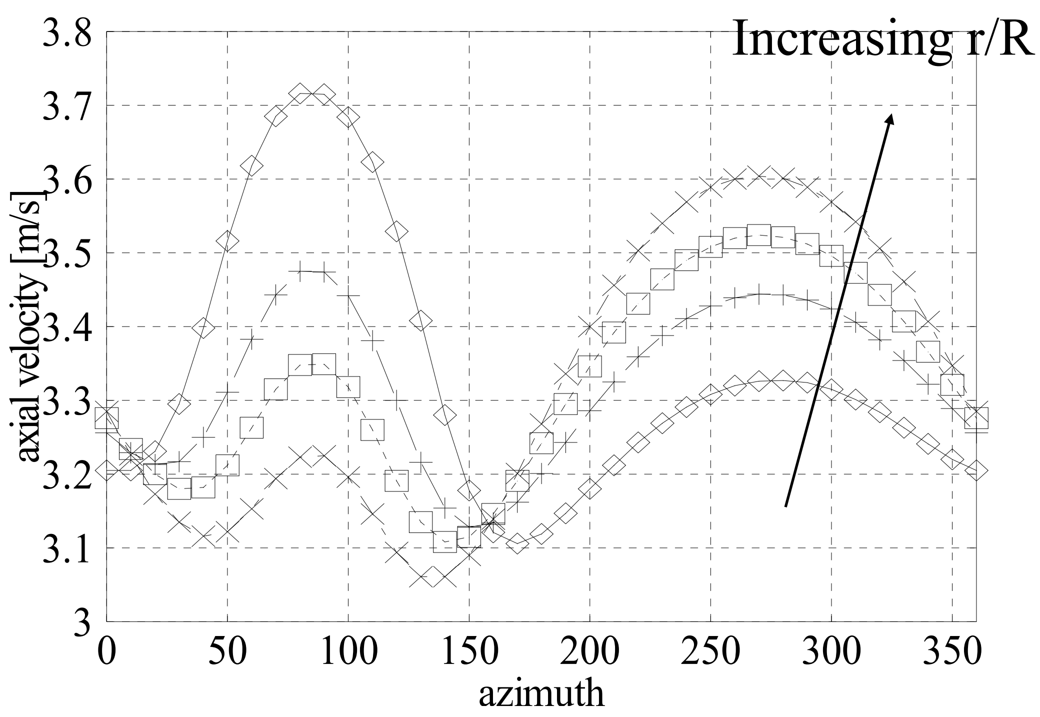


Results from RFOIL calculations

ECN

Yawed flow induction models

For yawed flow, the induction distribution is far from uniform, giving unsteady flow conditions for the blades and contributing to fatigue loads. Because of turbulence, a certain amount of misalignment is always present.



Models based on helicopter practice, on prescribed wake results and/or on wind tunnel measurements: first and second harmonic distributions:

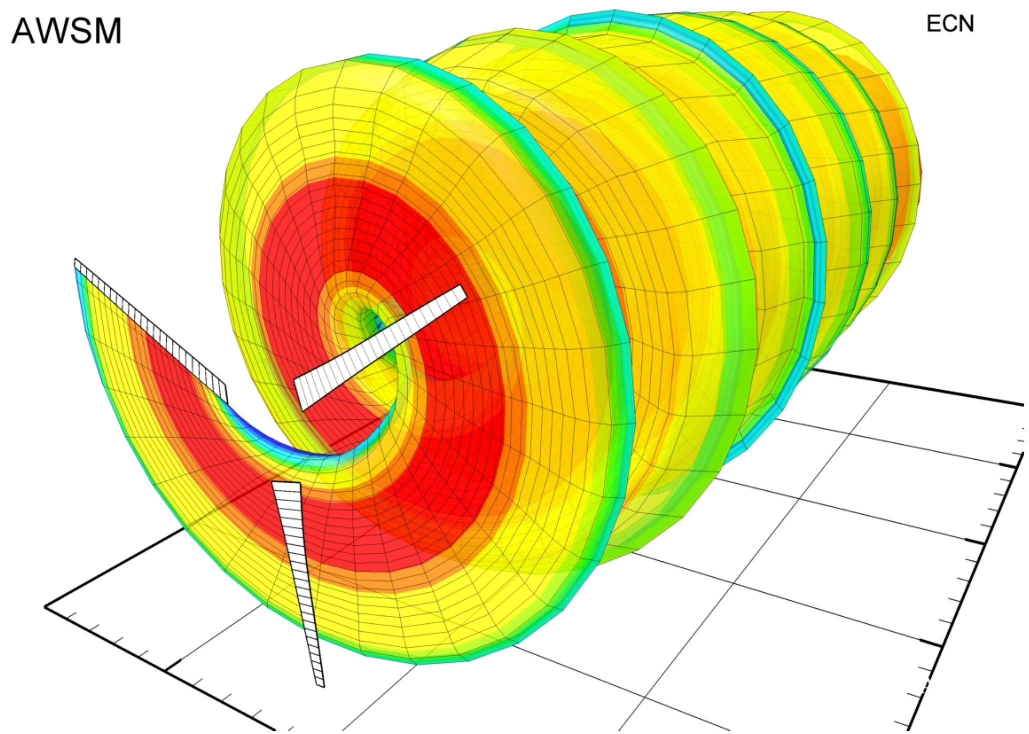
$$u_i = f\{A_i(r, \Psi_{yaw})\sin(i\Phi_{az} + \Xi_i(r))\} \quad i = 1,2$$

Free vortex wake models

Another development for induction determination was free vortex wake modelling (e.g. NTUA, UniStuttgart, ECN).

Rotor plane induction is calculated on basis of all trailed and shed vorticity present in the wake. Vorticity is transported with the total local convection velocity in the wake, partly induced by wake vorticity itself.

This model can handle yawed inflow and unsteadiness in an acceptable way, but much more time consuming than BEM



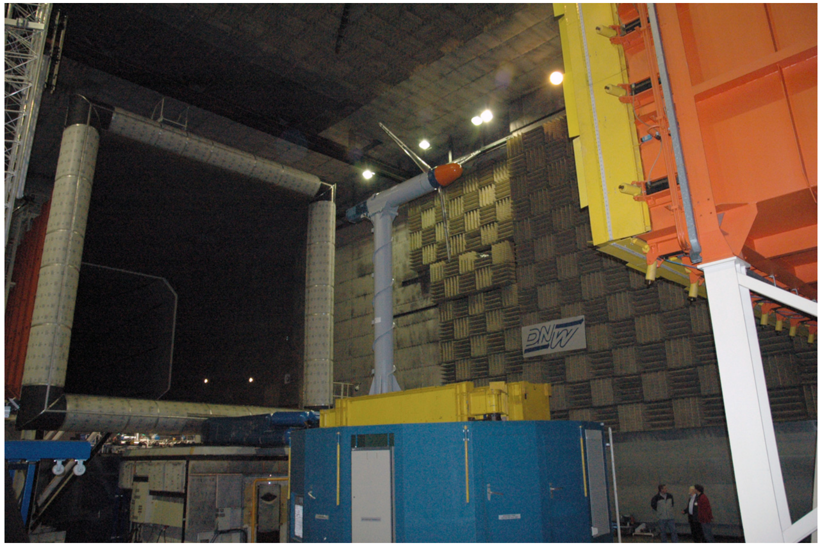
The big experiments

NREL NASA Ames and MEXICO

Two large scale aerodynamic experiments were held in the first decade of the XXI-st century

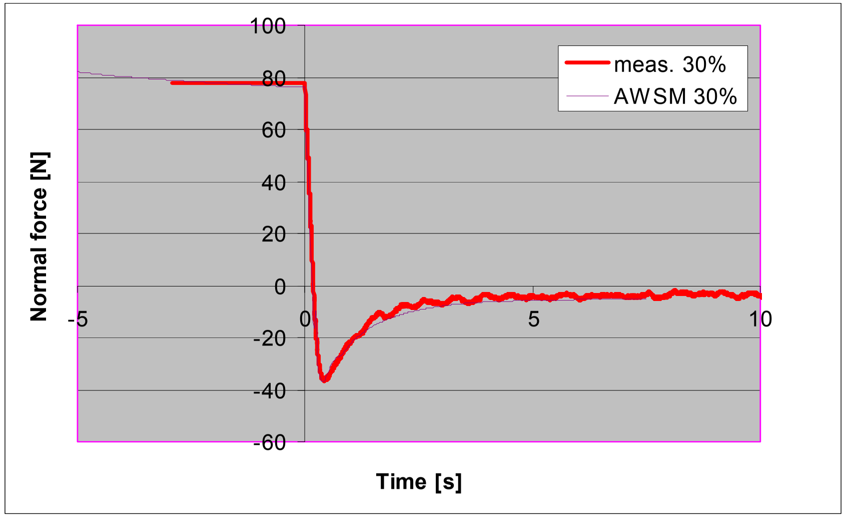
- 2000: **NREL NASA Ames**, 10 m diameter, 2 bladed model: Surface pressure distributions blade loads and total loads. Much analysis already done
- 2006: European '**MEXICO**' project. 4.5 m diameter, 3 bladed model: Surface pressure distributions, blade loads, total loads, flow field by PIV. Analysis just starting

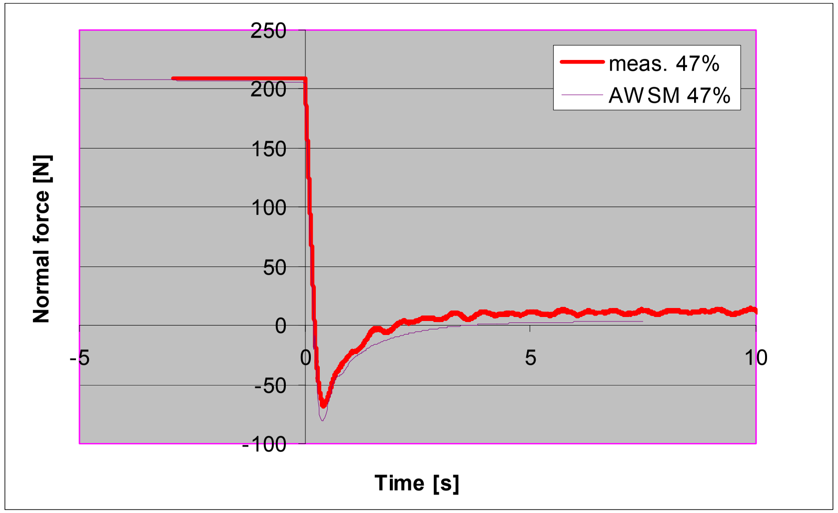
The experiments make real validation and improvements possible for both BEM and CFD

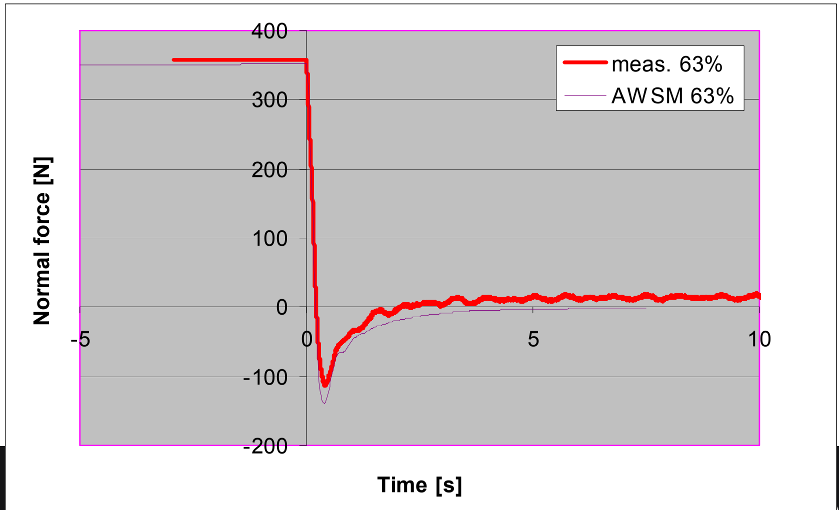


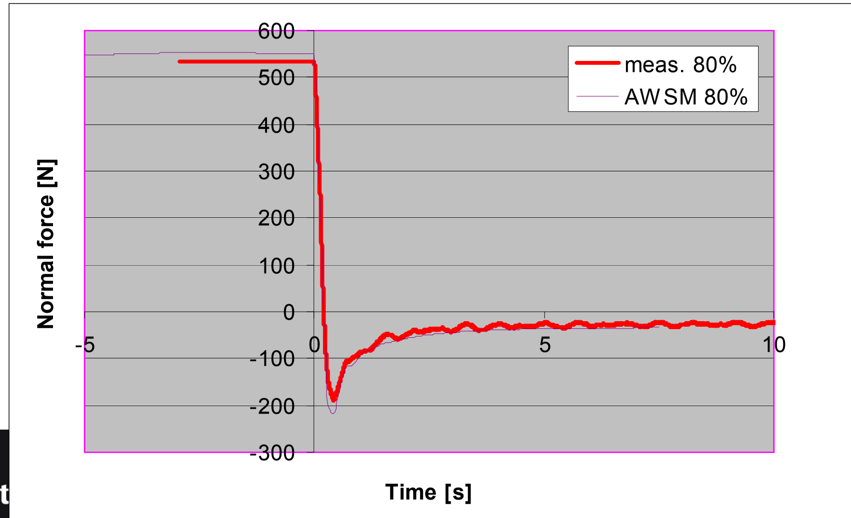
ECN Examples of validation efforts

Free wake program AWSM compared to NREL NASA Ames measurements for pitch steps, at 4 radial stations

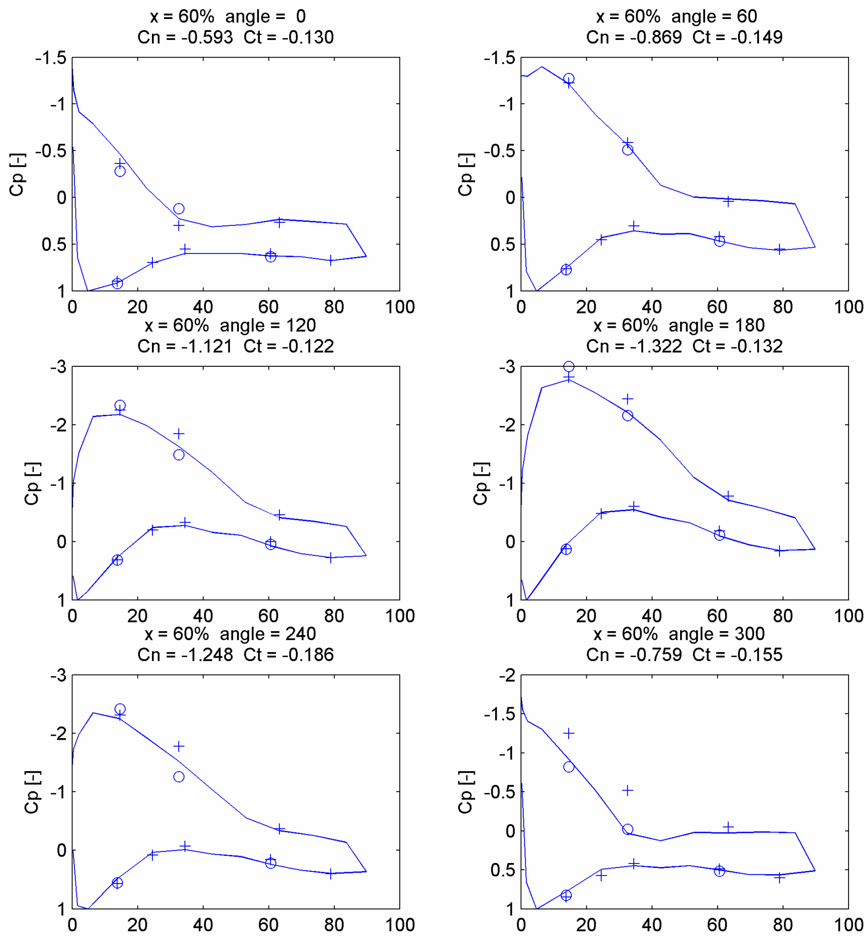




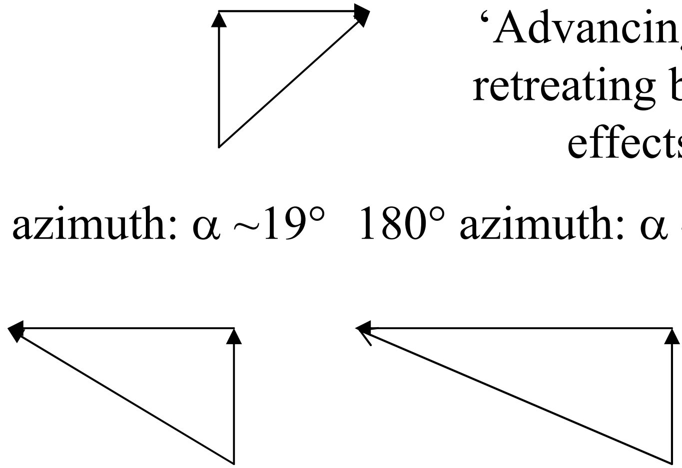




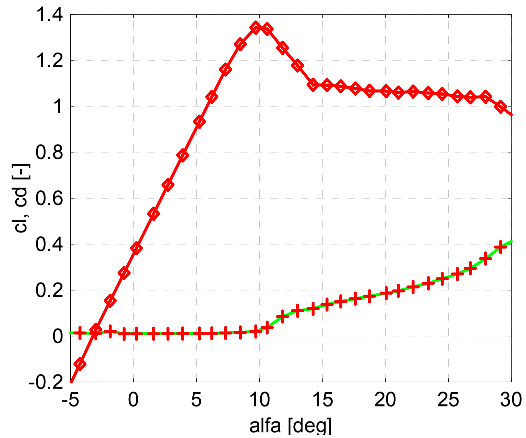
ECN Example of MEXICO Results



'Advancing and retreating blade' effects



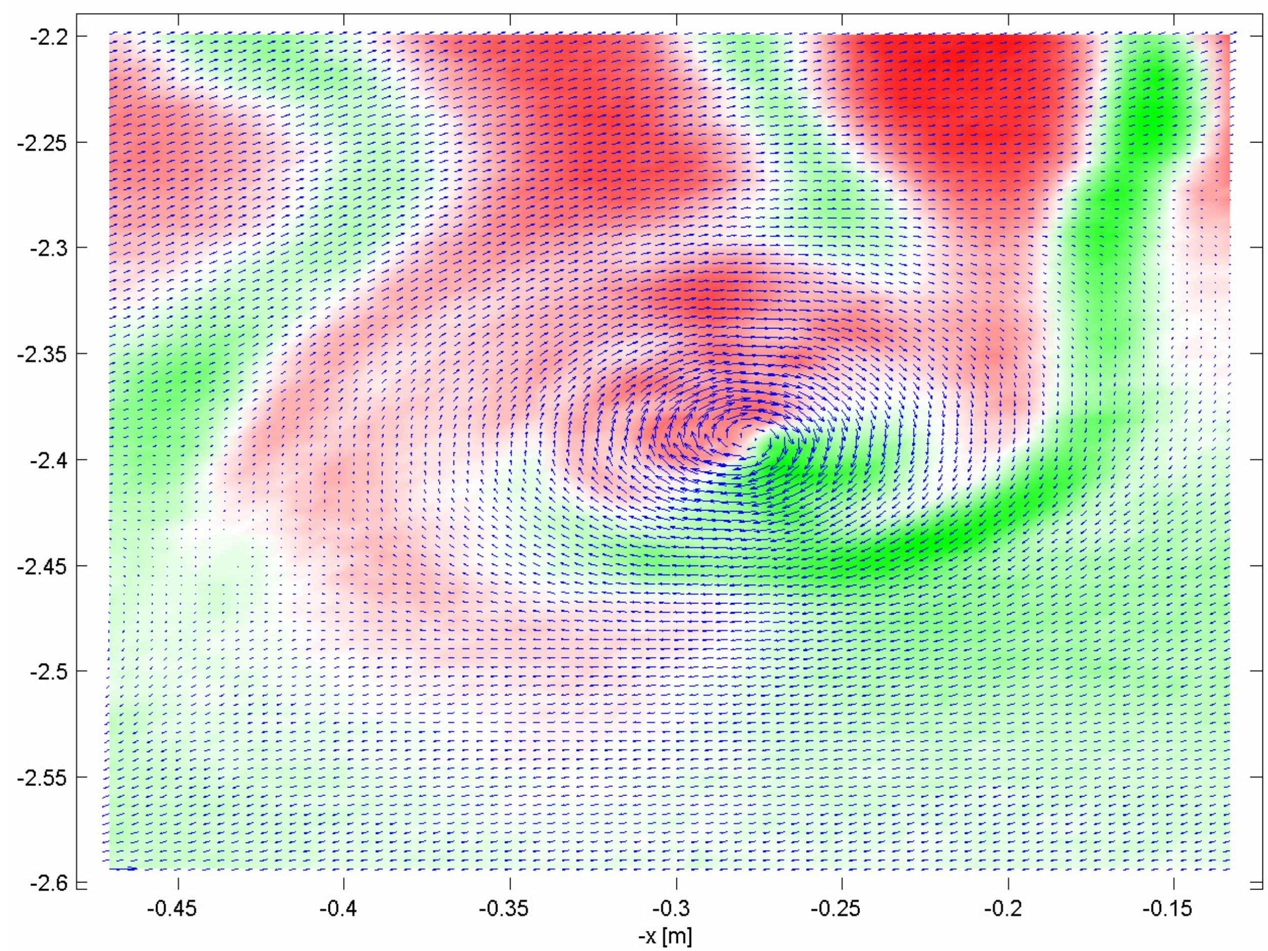
0° azimuth: $\alpha \sim 19°$ 180° azimuth: $\alpha \sim 10°$



Dynamic Stall in 45 degrees yaw measurements

Mexico PIV results

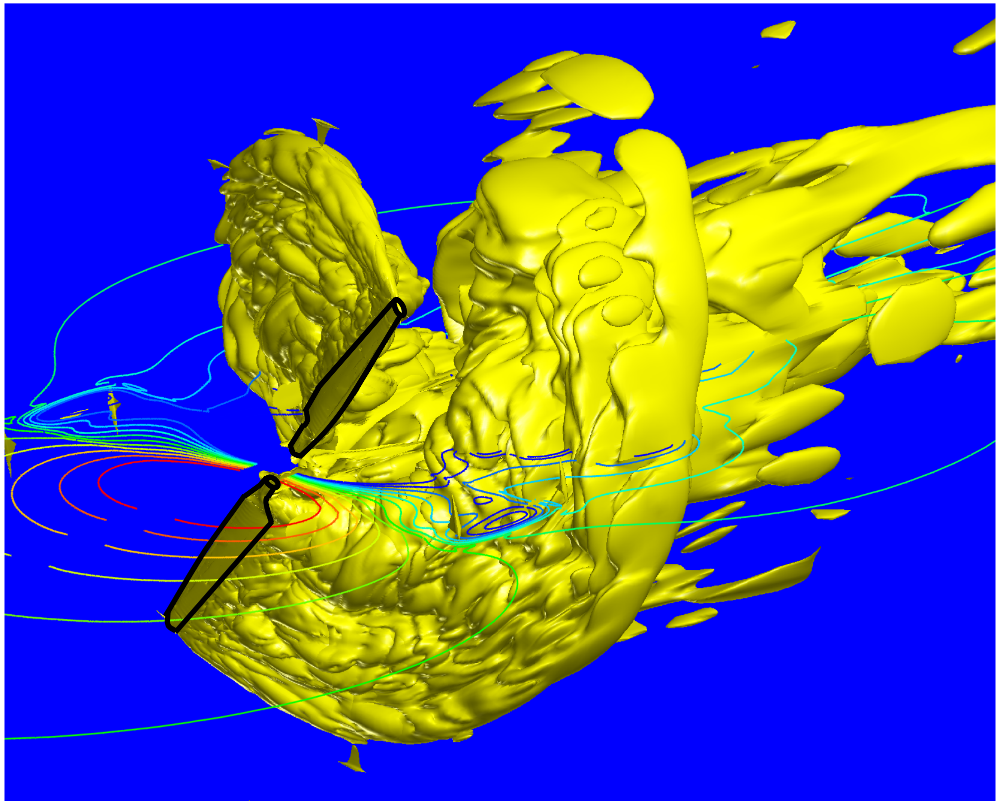
The PIV results permit a validation of vortex paths and trajectories



ECN The dawn of CFD

CFD in the form of the numerical solution of the Reynolds Averaged Navier Stokes equation, or LES/DES type of solutions, hold a large promise. For much time to come this will not be the solution for design or certification calculations (except special cases) but to **improve**:

- Aero-elastic codes based on ‘improved’ BEM
- Free or prescribed wake type codes
- **Most important: an improved fundamental understanding of the aerodynamics of wind turbines and farm interaction**



Example of DES calculations for the NREL NASA-Ames turbine in stall by EllipSys 3D (DTU/RISOE)

The dawn of CFD -2-

Main actors:

CRES/NTUA

DTU/RISOE (Ellypsis 3D, including DES possibilities)

Present limiting factors for CFD

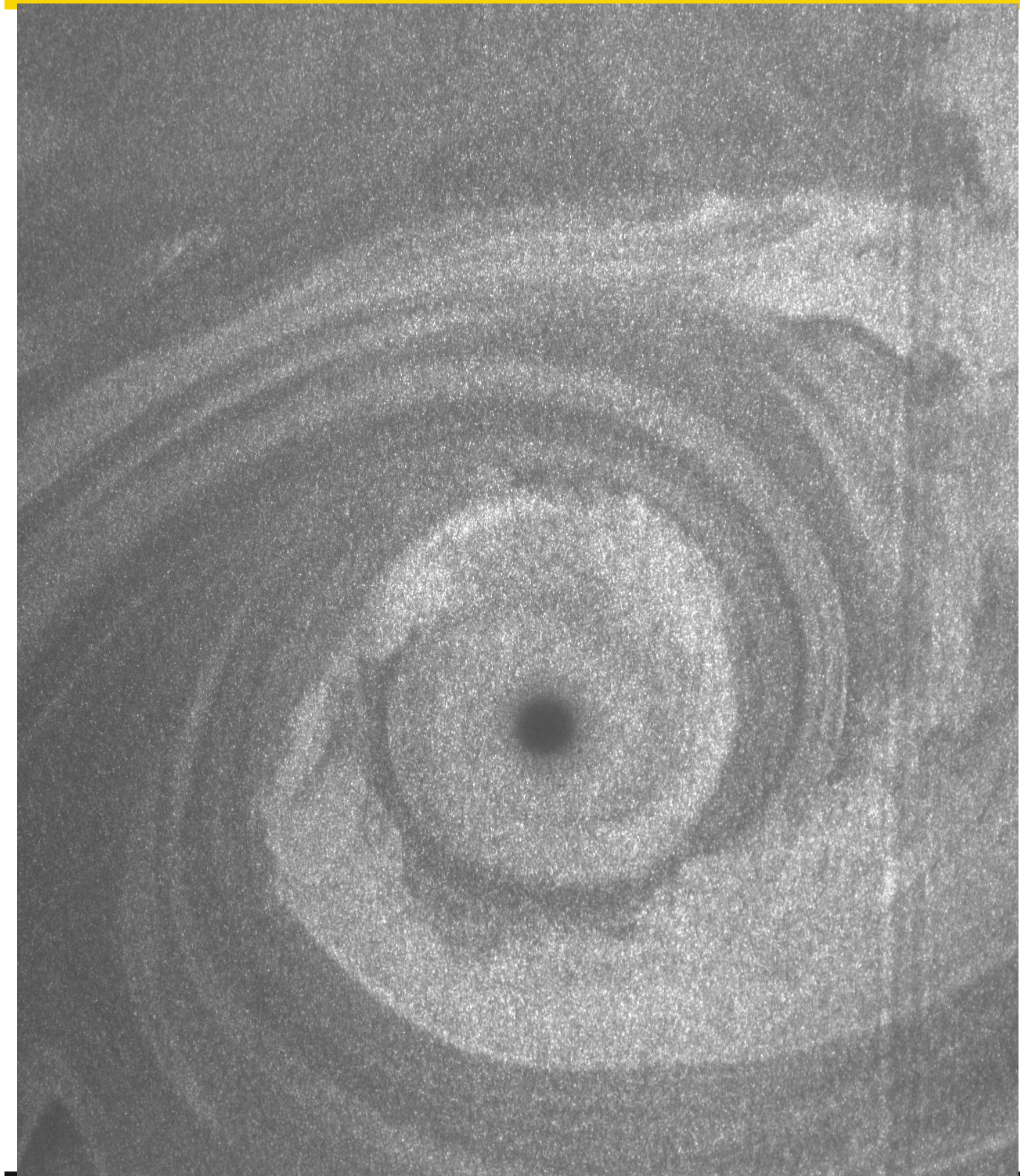
- Computer time needed, because of large Re numbers and associated grid requirements near the blade surfaces
- Laminar-turbulent transition issues, including roughness effects and by pass transition due to free flow turbulence
- In general turbulence modelling, specifically for RANS
- Compressibility effects for higher tip speed off-shore turbines?

From Betz to Better to Bezt ?

Possible roads to more reliable design tools, needed to limit risks and optimize multi MW wind turbines:

- Faster, much faster CFD
- Temporary use of ‘intermediate’ methods, potential flow + boundary layer combined with free vortex wake.
- **Validation** using the big experiments.
- Better free wind description is important for loads, especially strong gusts
- CFD for wake interaction problems
- Etc, etc, many years of work

Conclusion and questions



- Whom or what did I forget?
- We have come a long way, but there is still a longer way to go

Tipvortex from MEXICO measurements