The History and Future of CFD in Wind Energy

Or Why We need Large Computers

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Department of Wind Energy · DTU

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Acknowledgement

The presentation is based on the work of several colleagues in the following sections

FLU, MET, AED

Thanks to all the involved persons for providing me with the necessary input for the presentation, and for the amount of work spent over the years bringing us to were we are today.

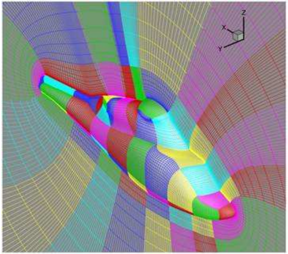
Special thoughts goes to Jess A. Michelsen, who made the Basis for it all.

Also a special thanks to the staff in AIT for always being helpful irrespectively of the amount of work and difficulties generate from my side.

Definition

By Computational Fluid Dynamics (CFD) we will today understand the solution of the Navier-Stokes equations by a spatial and temporal discritization of the flow equations.

- Typically, we we will partition the fluid volume into a series of control volumes



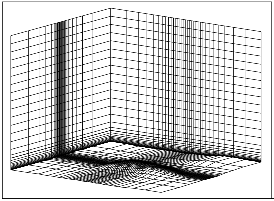
- And we will solve the equations at a series of distinct time instances in space

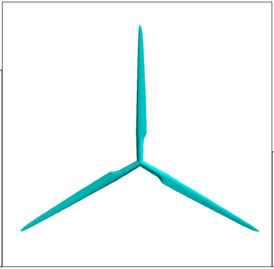
$$t(n) = t(0) + n \times \Delta t$$

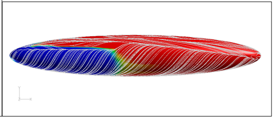
CFD in the Risø Wind Energy Department

- Flow Over Terrain, Anne de Baas (1991)
- General Purpose Flow Solver Applied to Flow over Terrain(1995)
- Rotor and Airfoil Aerodynamics (1996-Today)
- WAsP CFD (2012)

Today several other CFD based programs as the WRF, Open Foam and SCADIS are used in the department.



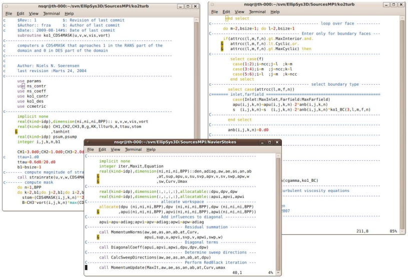




The EllipSys Code

The code has been developed with wind energy application in mind over the last 20 years, by the former MEK at DTU and here at the former Risø

- Accurate
- Consistent and convergent
- Stable
- Conservative
- Versatile
- Fast and Scalable



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From GIER to JESS

Before my time there was the the GIER and a series of Burroughs and VAX machines

- 1989: Apollo DN 10000
- 1991: HP 9000/750 and a CONVEX C220 2 processor vector machine
- 1994 SGI ORIGIN (8 Procc 1.8 GFlops)
- (2000-2003) IBM RS-6000 SP POWER-2 (from 8 to 24 x 2CPU's)
- 2002 DCSC ÅRHUS Fenris maskinen
- 2004 DCSC YGGDRASIL (210 x 1 CPU) Gigabit Ethernet
- 2004 MARY (240 x 1 CPU) Gigabit Ethernet
- 2007 THYRA (128 x 4 CPU's) + ALFHEIM(130x4 CPU'S) DCSC
- 2011 GORM (80 x 12 CPU's)
- 2014 JESS (320 x 20 CPU's) (143 TFlops)

Applications

Highlights

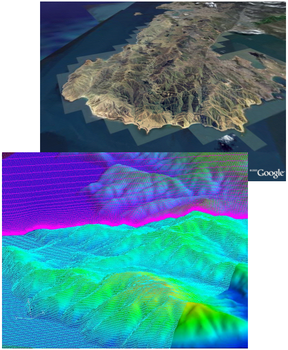
The following slides show a series of applications. Hopefully they will help illustrates the large spectrum of applications that have been addressed over the years.

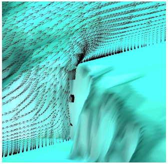
Applications *Terrain Flow*

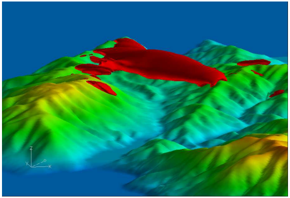
CFD Siting Simulations

CFD studies in connection with siting are typically used to look for sever flow conditions. The cases are typically ones where the linear models are insufficient.

- High levels of turbulence
- High velocity gradients
- High values of directional shear
- High flow inclination
- Recirculating flow

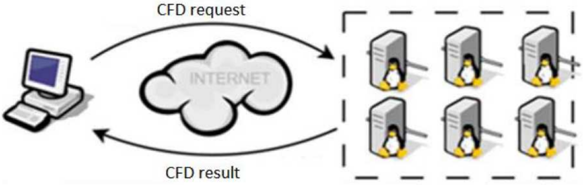




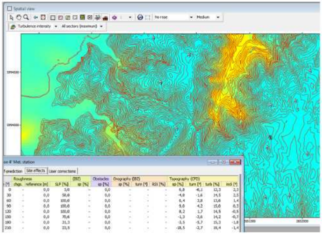


Applications *Terrain Flow*

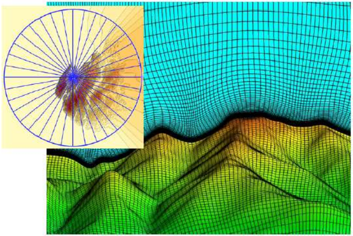
WAsP CFD



WAsP

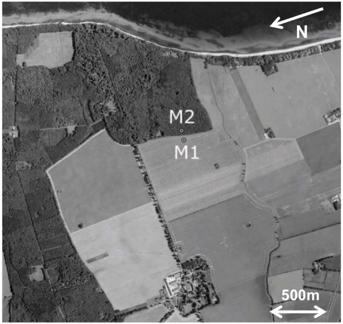


EllipSys

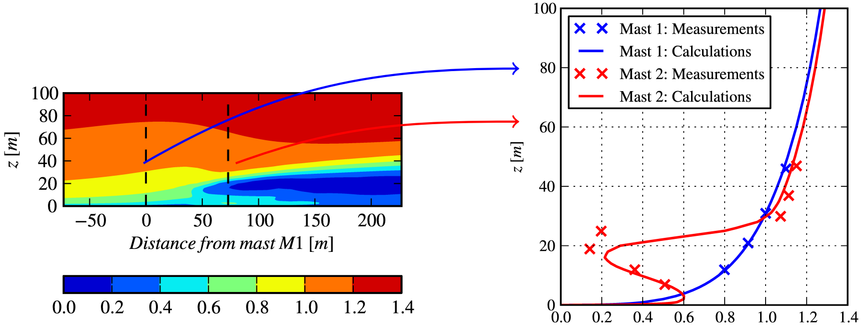


The Falster forest edge experiment

- Located in Denmark in a mixed agricultural-forested area,
- Two masts instrumented (mostly) with sonic anemometers,
- Populated with tall European beech trees,
- Measurement campaign conducted from March-September 2008,
- Wind direction considered : $\theta = 285^\circ$.



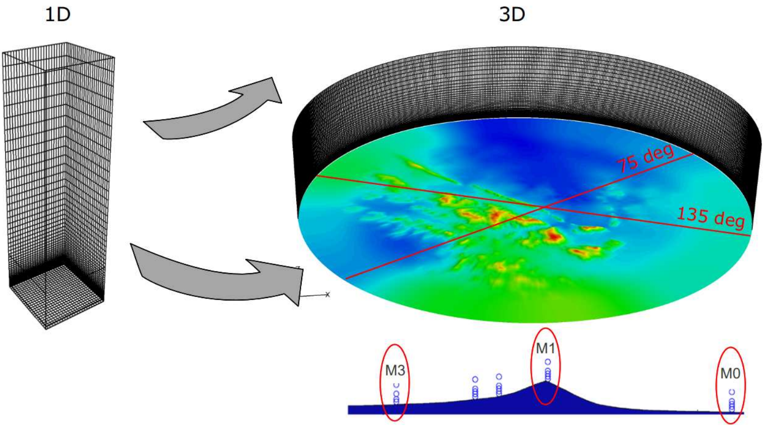
Validation / Falster



- Velocity contours (left) and velocity profiles (right) of u_{285°/u_{ref}
- **Good general agreement** but under prediction of drag/velocity in the top part of the canopy

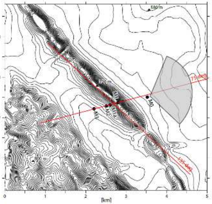
Simulating Benakanahalli

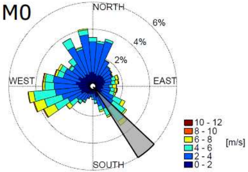
Running the terrain with inflow bc's from the precursor simulation:

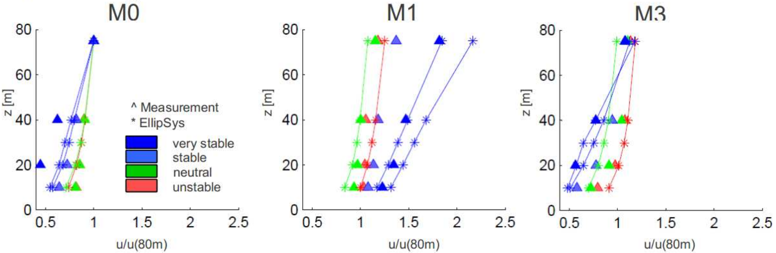


Simulating Benakanahalli

Wind speed and direction, comparison of modeled and all observed data for a given sector

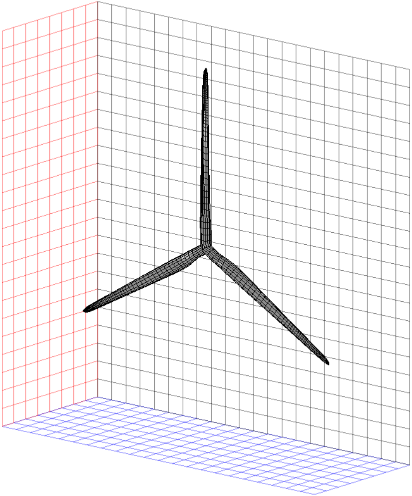






Actuator Disc/Lines

The Actuator Line/Disc technique was pioneered by Nørkær and Shen



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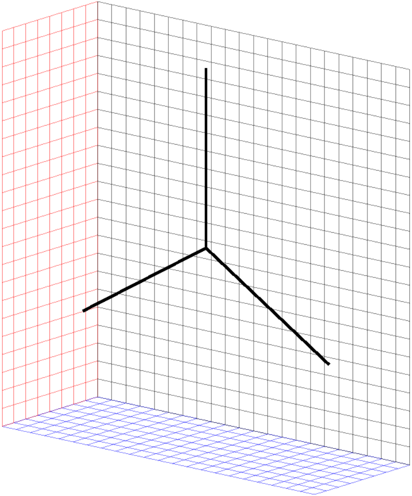

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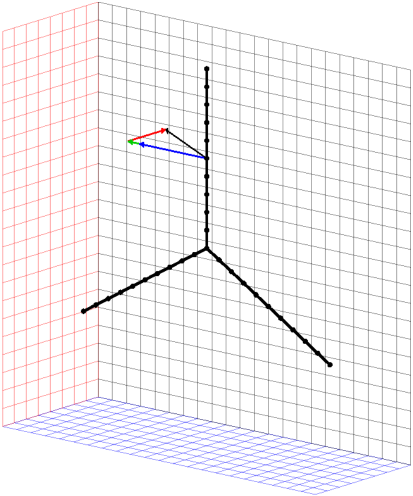

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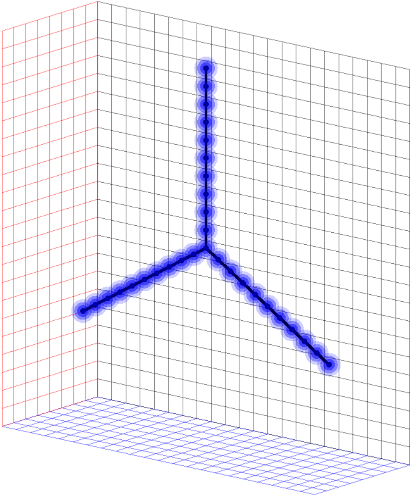
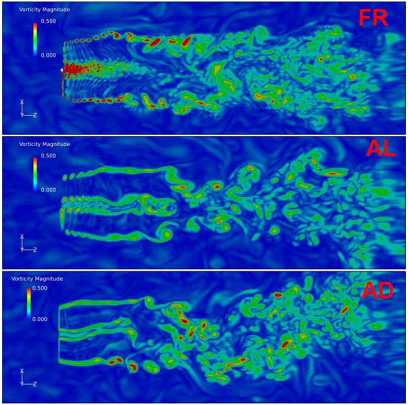
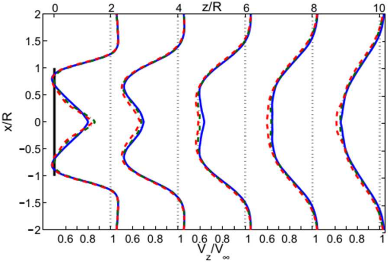


Applications *Wake Flow*

Actuator Disc/Lines

When including inflow turbulence the models give similar wake behavior





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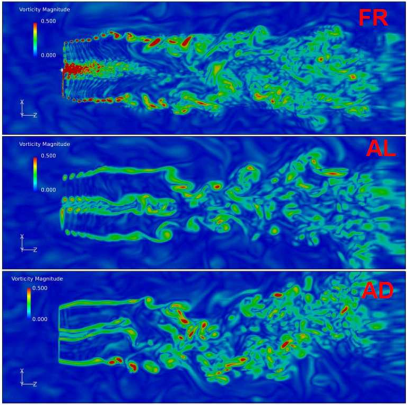

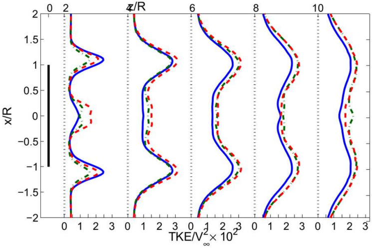

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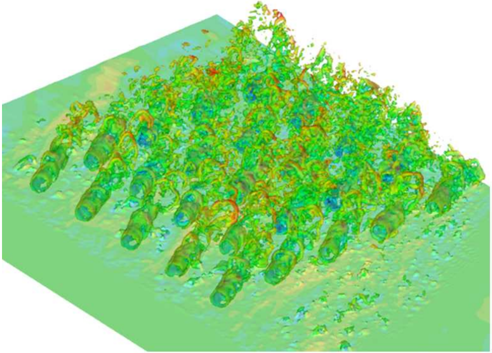
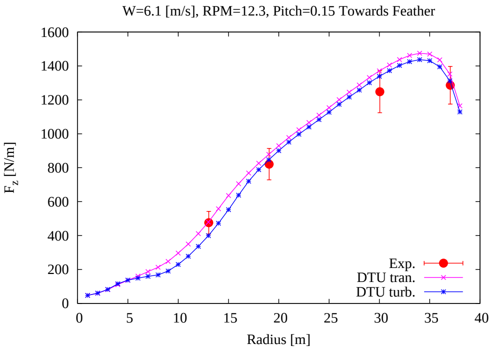


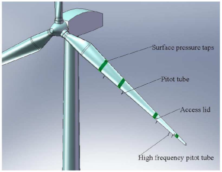
Applications *Rotor Aerodynamics*

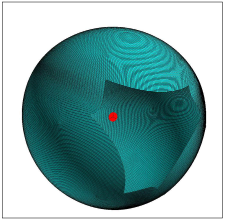
NM80 Turbine, DanAero

Rotor computations

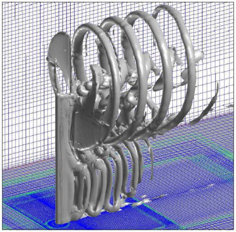
- Evaluations of power and forces on new rotors
- Extraction of profile data for engineering models
- Improved understanding of physical processes

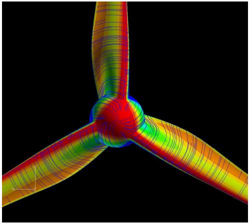


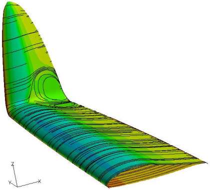


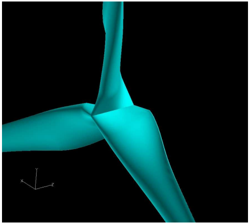


Design of rotor details





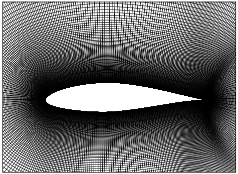


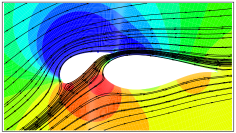


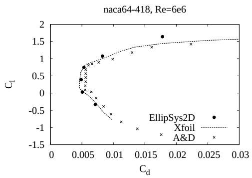
RANS

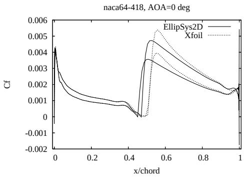
CFD computations of airfoil aerodynamics is a backbone activity:

- Design and analyzing new airfoils
- Providing input for engineering methods
- Preparation of wind tunnel experiments
- Studying laminar/turbulent transition
- Special configurations (Multi element, flat-backs)



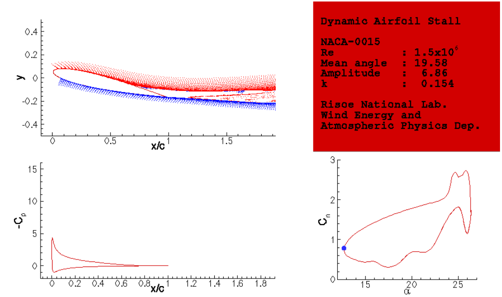


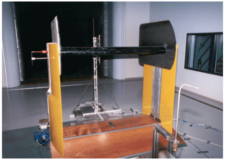




Dynamic stall

- Dynamic stall is important in connection with vibration analysis of turbines
- Dynamic stall computations can be performed for prescribed motion or coupled to an aeroelastic model
- The present example is prescribed motion according to an experiment of Galbraith et. al.
- The present computation is performed fully turbulent in an moving frame

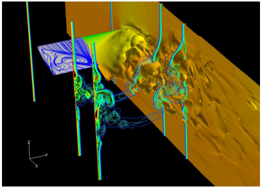


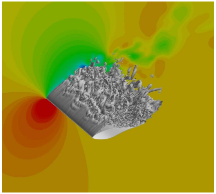


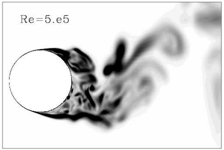
DES Airfoil Simulations

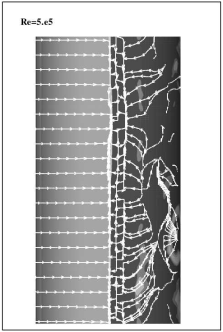
For some configuration with severe 3D effects the RANS is replaced by DES

- Predictions of heavily stalled configurations
- Tunnel wall interference

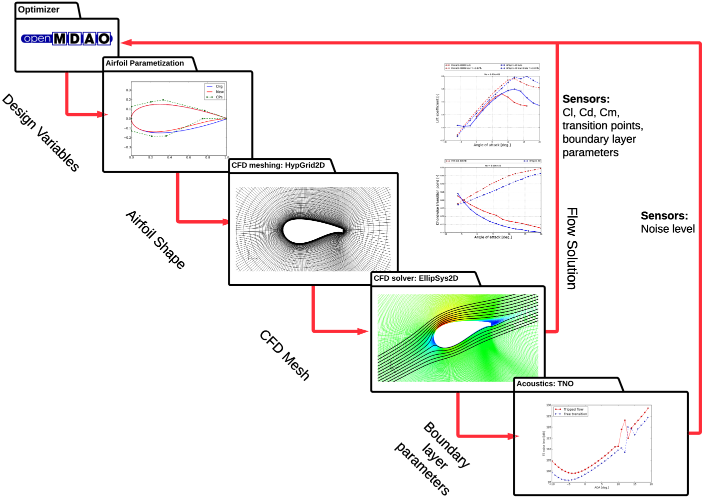




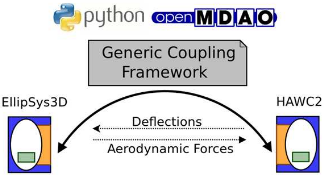




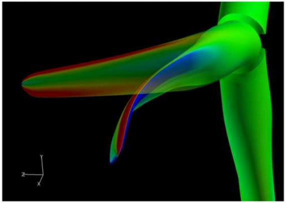
Airfoil Aero-Acoustic Optimization Using 2D CFD



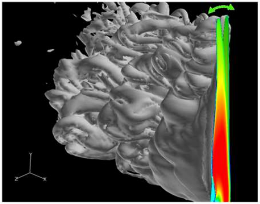
Turbine aeroelasticity using 3D CFD

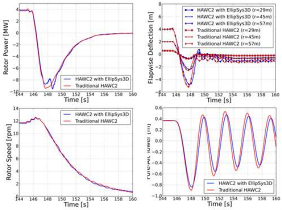


Emergency Shutdown (NREL-5MW-RWT)



Standstill Vibrations (DTU-10MW-RWT)

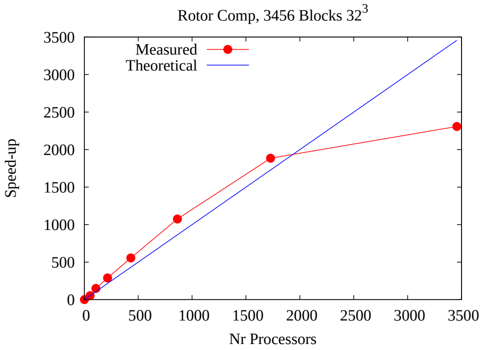


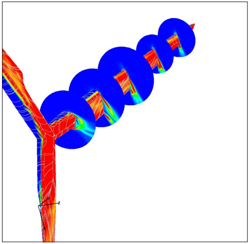


Parallel Speedup

The flow solver need to be capable of exploiting the massive parallel architecture:

- Rotor case with 3456 blocks of 32^3 (113 mill. points)
- Rotor comp. is 67 percent efficient on 3456 processors.
- The speedup is 2300 times the single processor performance.





Performance of the new cluster

Rotor Computations

What is the time consumption for a single 3D steady state rotor computation?

Performance of the new cluster

Rotor Computations

What is the time consumption for a single 3D steady state rotor computation?

- Year 2000, Rotor comp., 3.10 mill points, RISSP2, 4 Proc., 1800 min.
- Year 2011, Rotor comp., 14.1 mill points, GORM, 108 Proc., 32.6 min.

Performance of the new cluster

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- Year 2014, Rotor comp., 14.1 mill points, JESS, 108 Proc., 23.7 min.

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- Year 2014, Rotor comp., 14.1 mill points, JESS, 216 Proc., 11.4 min.

Performance of the new cluster

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- Year 2014, Rotor comp., 14.1 mill points, JESS, 432 Proc., 6.2 min.

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- Year 2014, Rotor comp., 14.1 mill points, JESS, 432 Proc., 6.2 min.

Using only 7 percent of the new machine, we can compute a point on a power curve using 3D CFD in less than 10 minutes

DTU

Future Plans

The ultimate goal is of course to be able to compute the loads on a full aeroelastic wind turbine, including the ABL, complex terrain effects and eventual wakes from other turbines.

But less can do !

- Airfoils at high Reynolds number of 10-15 Millions using RANS.
- DES/LES airfoil simulations
- RANS rotor performance, airfoil data etc.
- CFD based optimization of rotors and airfoils
- Aeroelastic simulations of complex situations
- Large scale stratified simulations over forested terrain
- Rotors in stratified flow

This is not the END

The new machine has been awaited for a long time, and we have great plans for it!

- The new machine will allow us to do new things
- The new machine will allow us to do more of the same
- The new machine will allows us to keep a high quality of our research
- The new machine will be hopefully be replaced in the future with a even large machine

THANKS FOR LISTENING !