Aerodynamic Optimisation of Airfoils and Winglets for Wind Turbine Application

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Outline

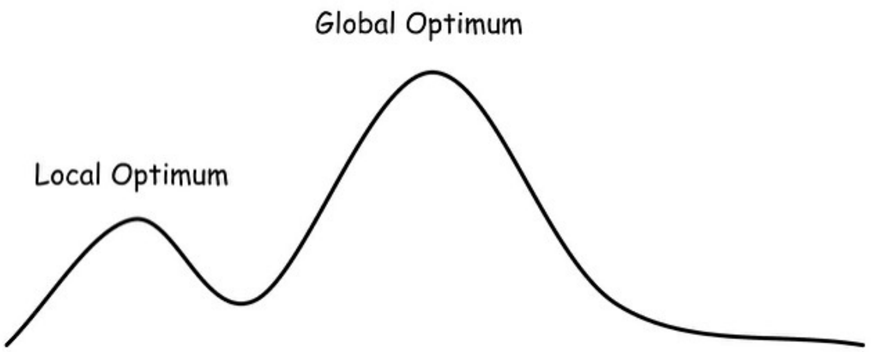
- **Numerical optimisation**
  - Evolutionary algorithms
  - Application to wind energy
- **Thesis projects**
  - Airfoil optimisation
  - Winglet optimisation

What is numerical optimisation?

- The science of minimising or maximising a mathematical model by applying search algorithms

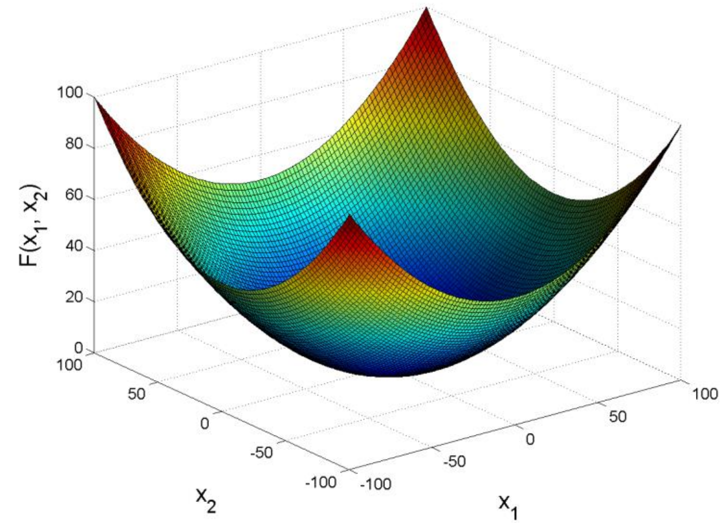
- ***Local solvers*** normally use gradient information to quickly find the local optimum

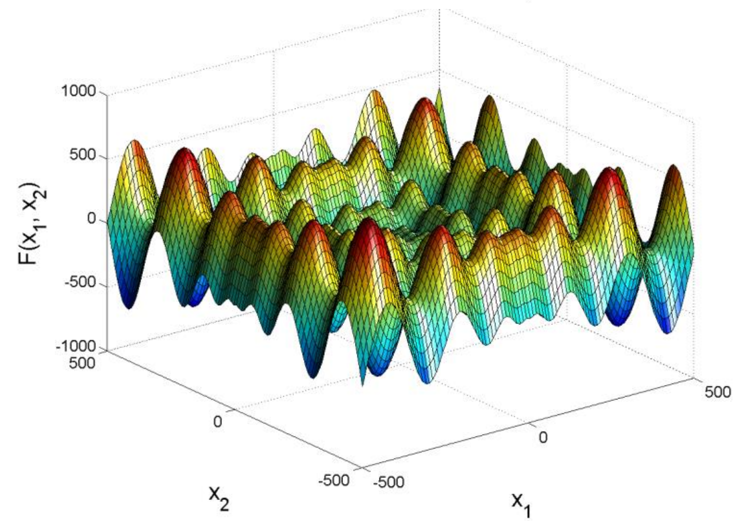
- ***Global solvers*** are gradient free but require many iterations → can potentially find the global optimum



Do we need numerical optimisation?

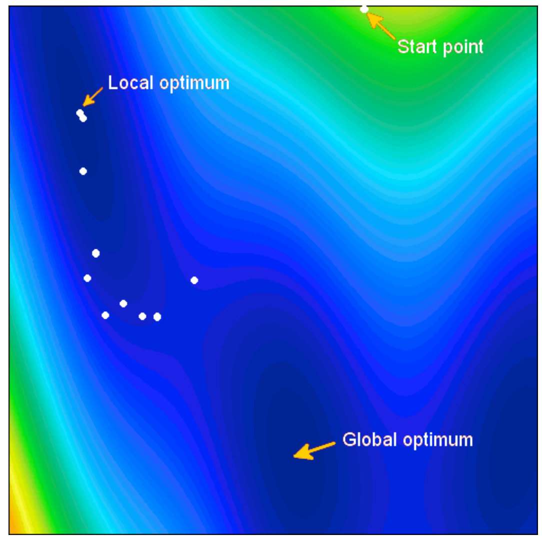
- When solving a design problem we tend to visualise the response in the solution-space as convex
- If the problem is not convex it will take us a long time to find the best solution
- When the problem has more than 2 DOFs we can not visualise the solution space, not even in our minds
- Our brain is simply not designed to solve such complex problems



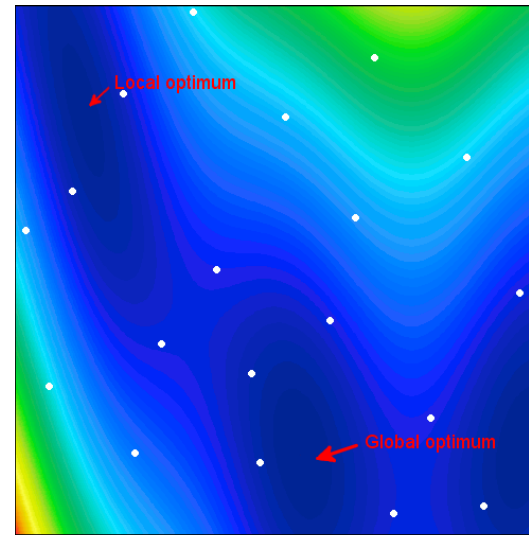


Evolutionary optimisation

- EO mimics Darwin's natural selection by only allowing the fittest members of a generation to produce offspring
- EO requires a more lengthy and expensive search compared to local gradient methods
- However, EO has the potential to find the global optimum solution in the design space



Local, gradient optimisation



Global, evolutionary optimisation

Application to wind energy

- The wind turbines in use today have been evolved for more than 25 years
- Modern turbines are much better than they were 25 years ago, they produce more power, are more reliable and more silent
- **But**, wind turbines still need to be improved further in order to be cost competitive to oil and gas
- Evolutionary optimisation can help speed up the design process

Airfoil Optimisation for Wind Turbine Application

Motivation

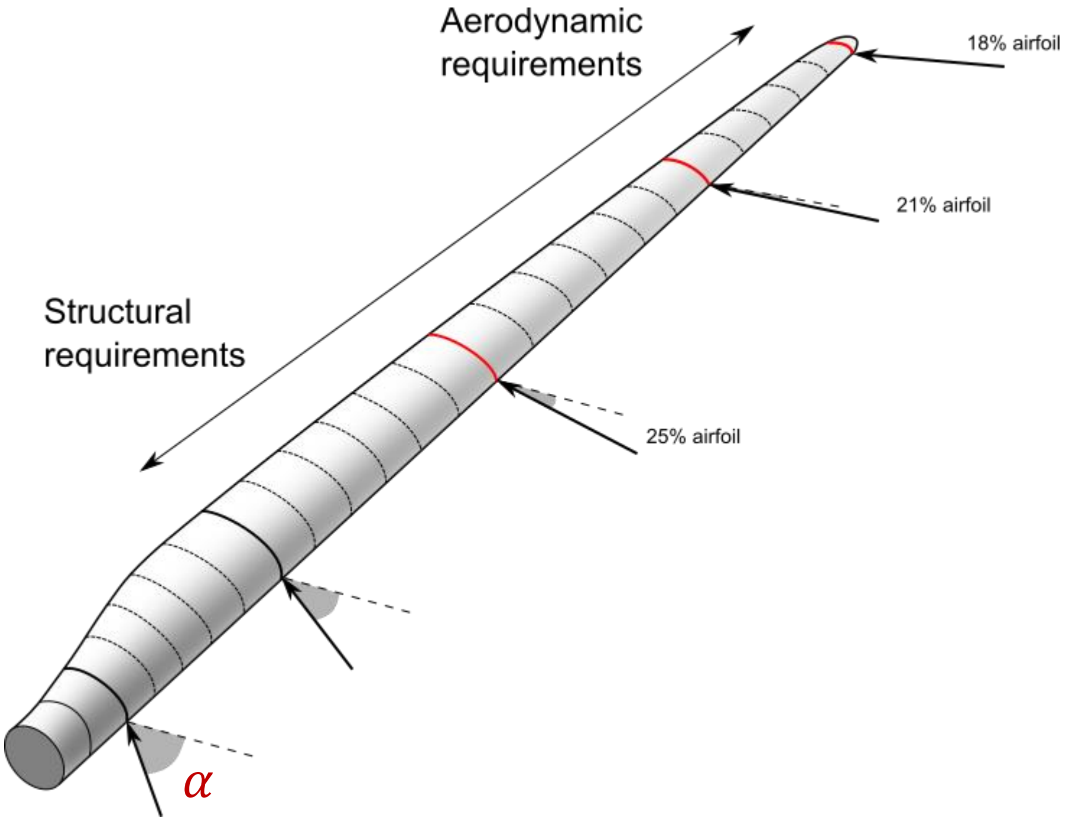
- Wind farm operators report loss in power production over time of about 10-15%
- The loss is caused by increased surface roughness due to leading edge contamination
- The contamination comes from insects, sand, salt, and hail hitting the turbine over time
- Will eventually lead to blade erosion and require repair

Operation > days/weeks

Operation > 3 years

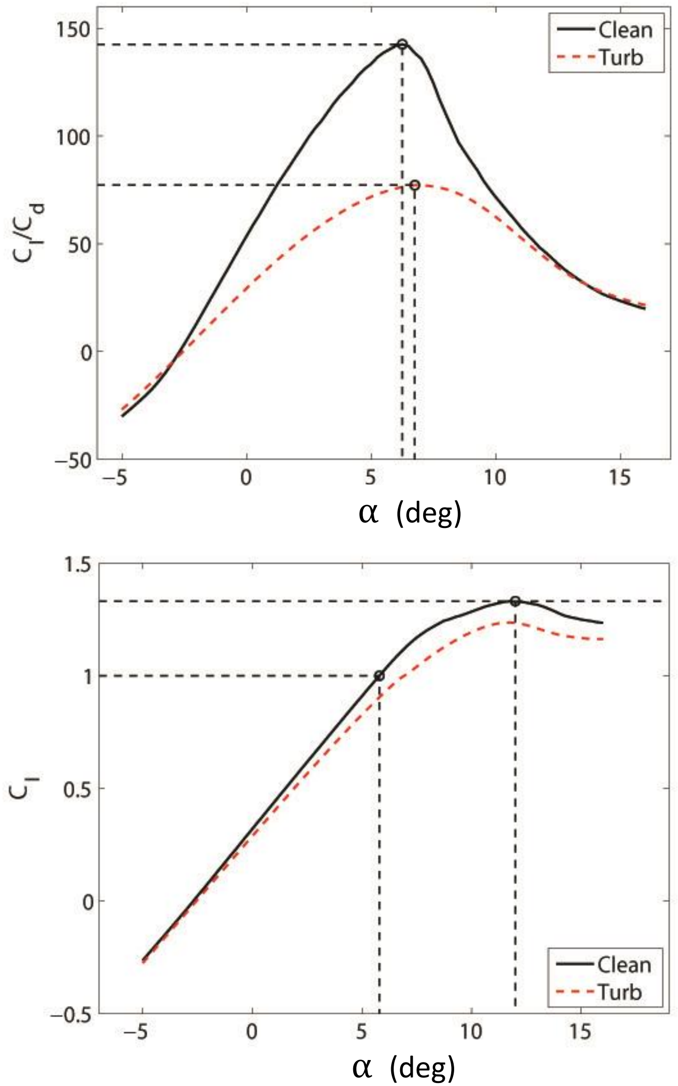
Airfoil optimisation project

- Optimisation tool that automatically optimises airfoils is developed
- Method controls the loss in performance due to leading edge contamination
- Tested for the design of airfoils at the outer part of MW-class wind turbines



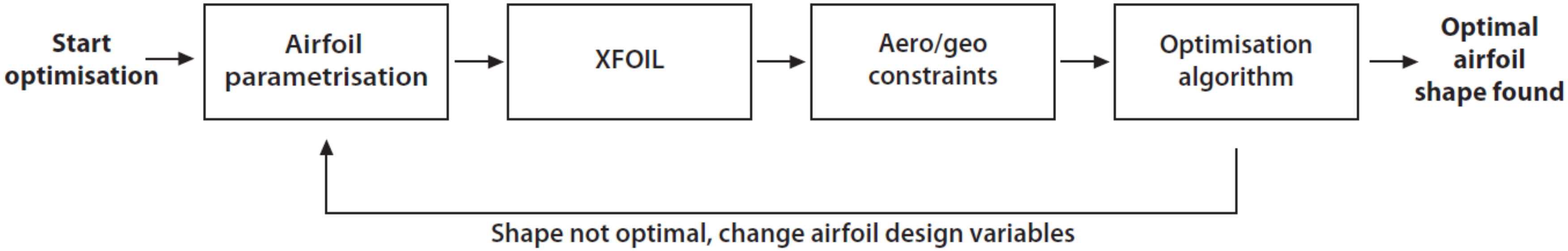
Optimisation and constraints

- Airfoil design philosophy: maximise performance for the full life-span of the rotor blade
- 8 aerodynamic and geometric constraints are required to control the airfoil performance
- Adaptive penalty function created to ensure that the algorithm finds the best possible solutions



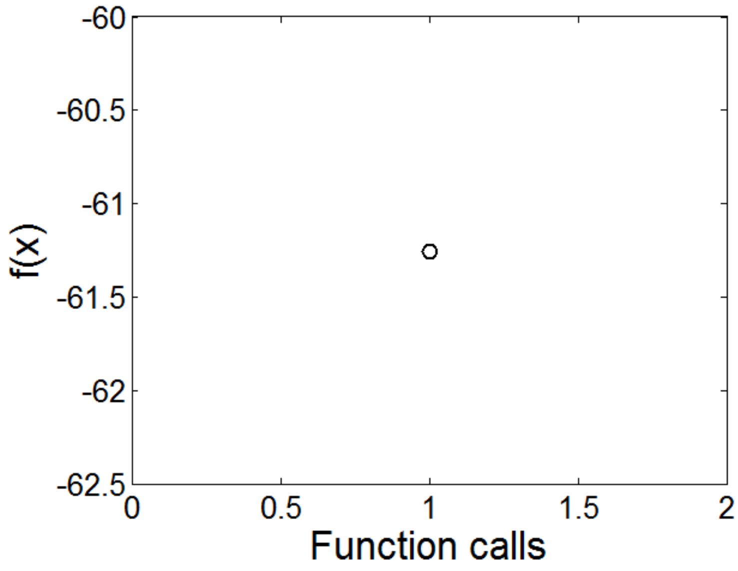
Airfoil design tool

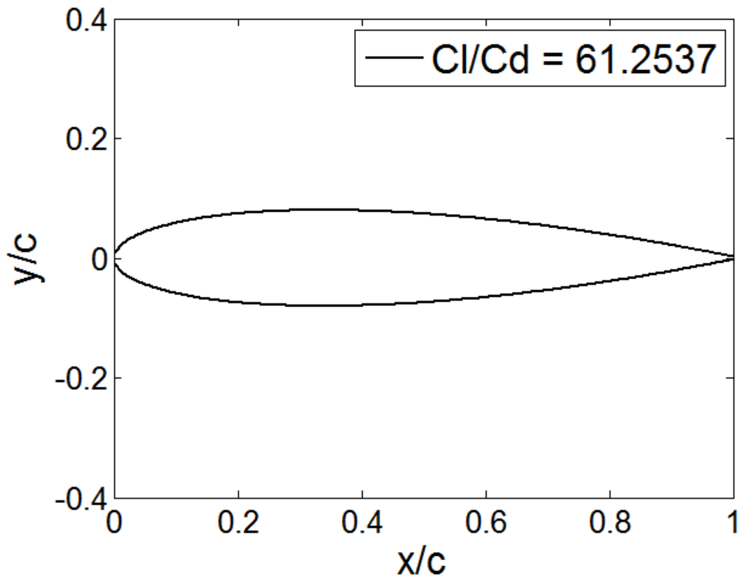
- Airfoil shapes are created using the Class-Shape Transformation (CST) technique
- The airfoil performance is computed using the panel code XFOIL
- Adaptive penalty function is used to constrain the airfoil properties
- Optimisation is performed using the gradient free CMA-ES algorithm



Example of airfoil optimisation

- Maximise C_l/C_d at $\alpha = 6$, Re = 1 million
- CST = 4/4
- Simplified example, only thickness constraint (16%) applied





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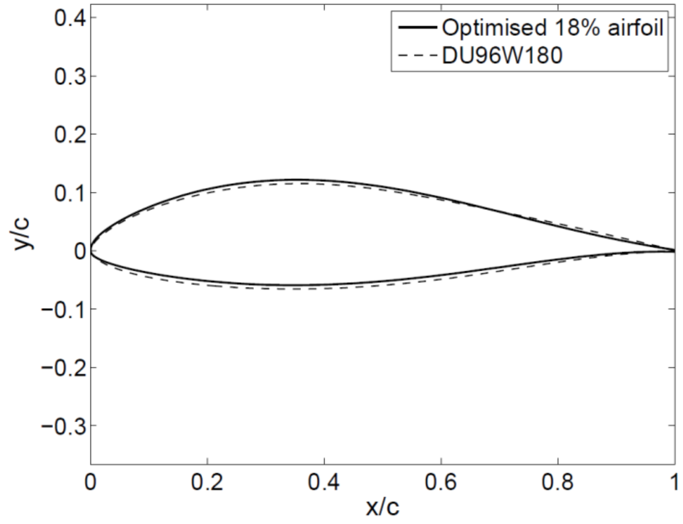
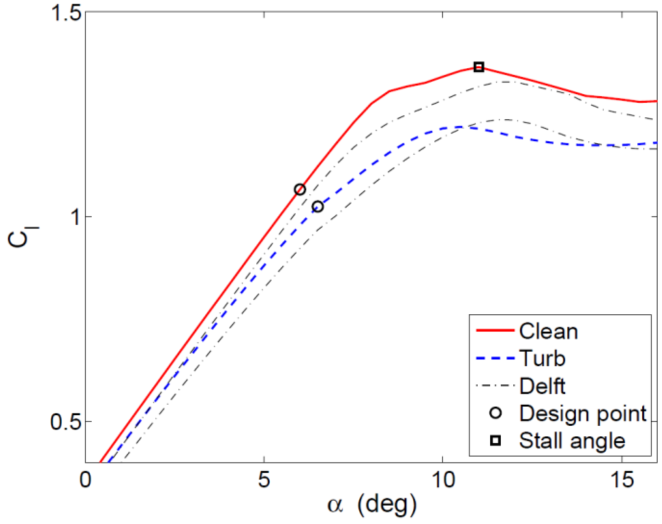
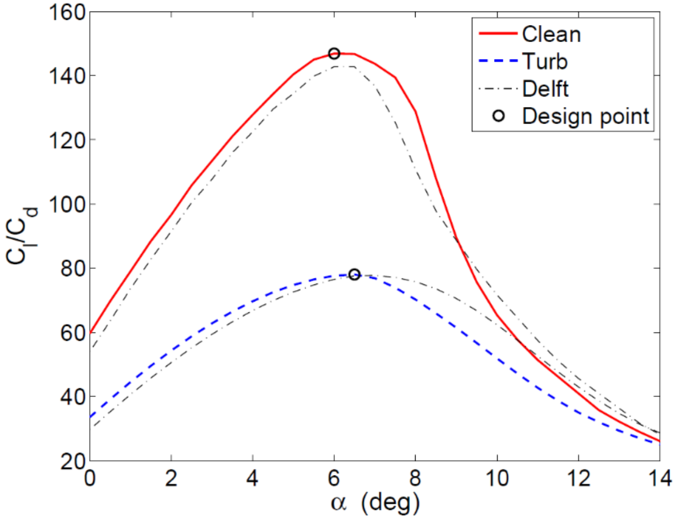
Optimised 18% airfoil

- Similar or improved performance compared to equally thick Delft airfoil, optimised at Re = 3 million

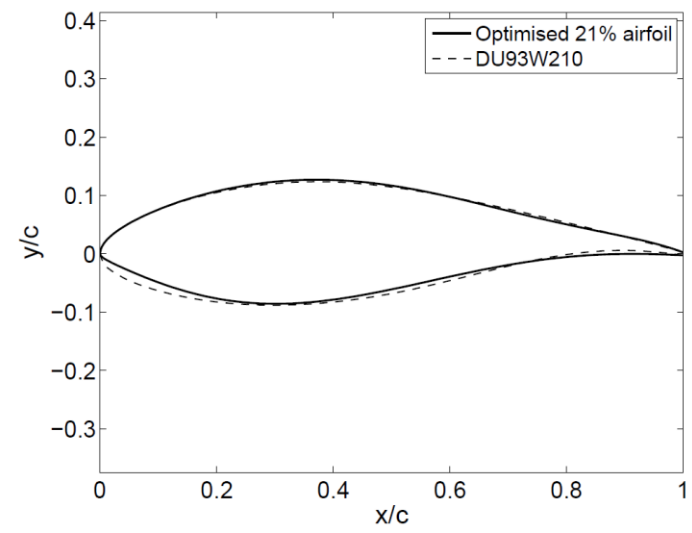


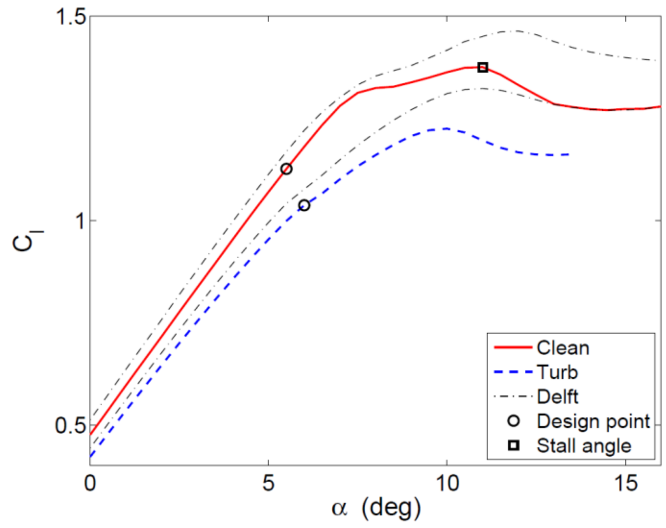


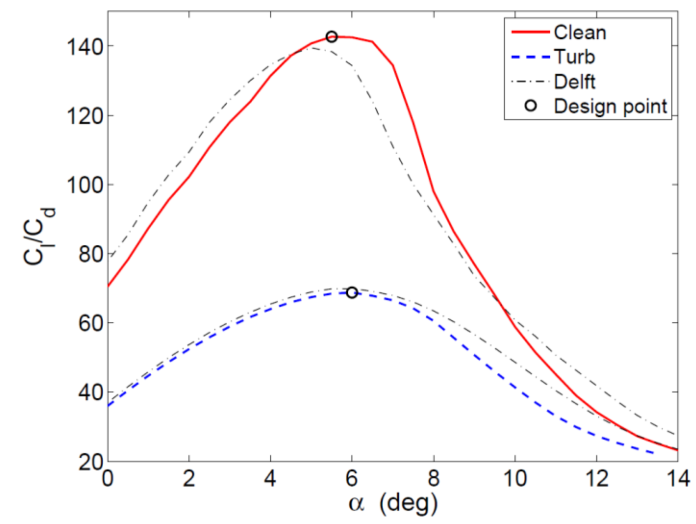


Optimised 21% airfoil

- Similar or improved performance compared to equally thick Delft airfoil, optimised at Re = 3 million

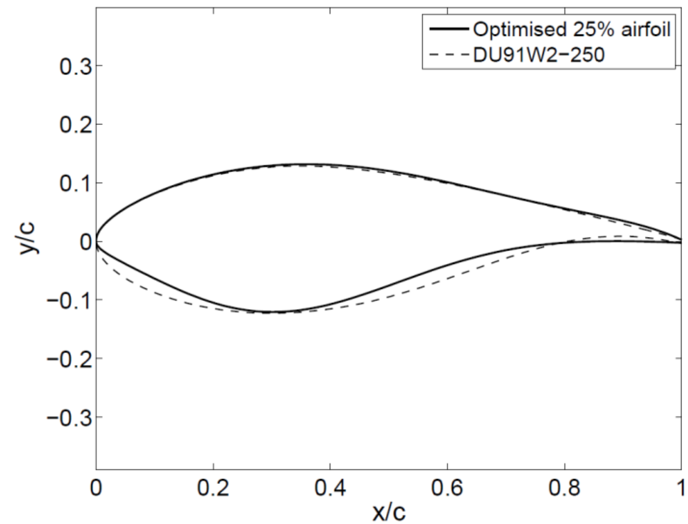


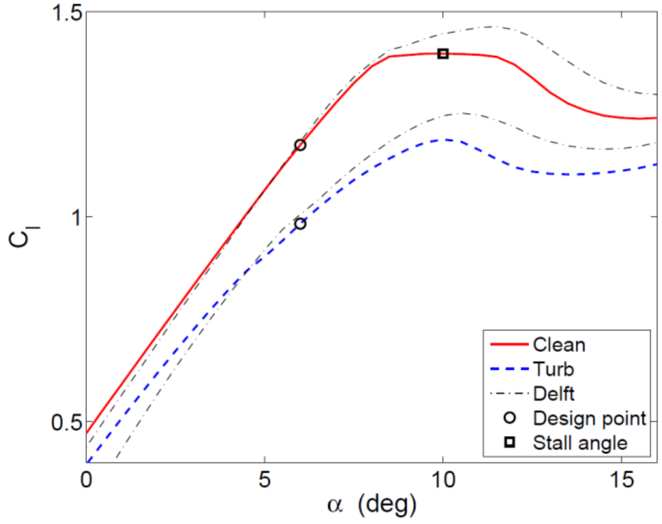


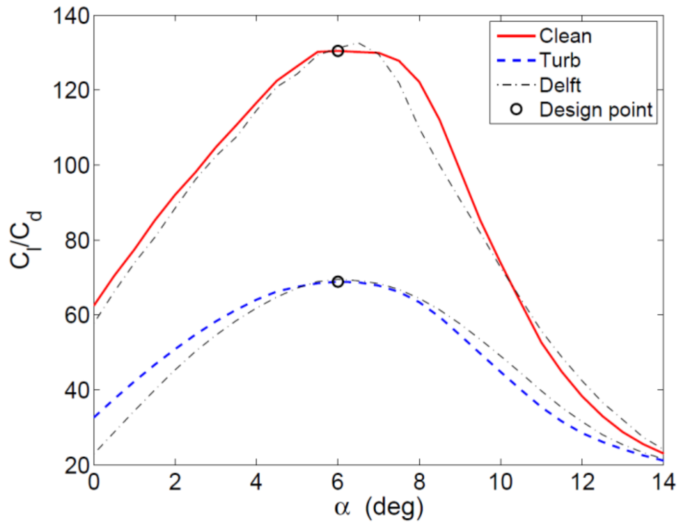


Optimised 25% airfoil

- Similar or improved performance compared to equally thick Delft airfoil, optimised at Re = 3 million







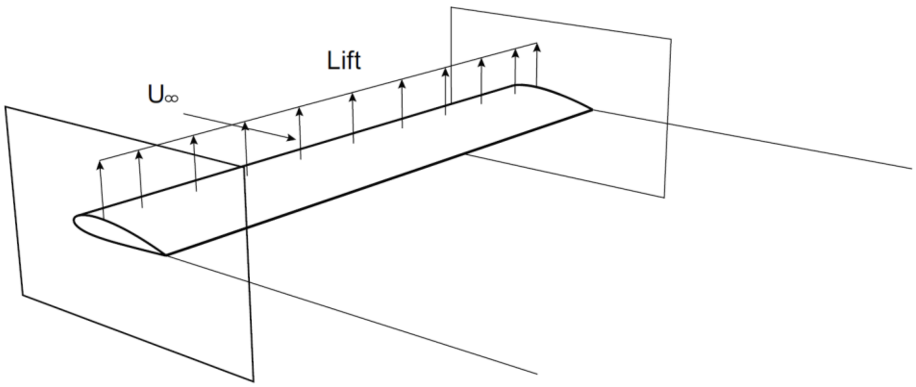
Winglet Optimisation for a Model-Scale Wind Turbine

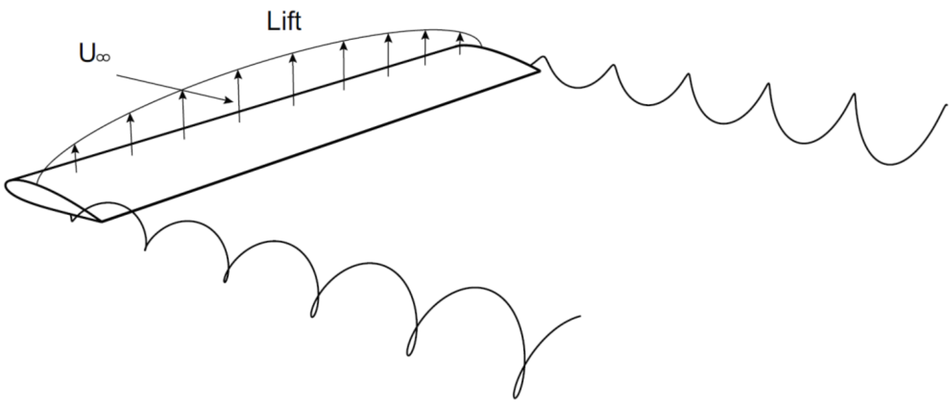
Winglets

- In the early 1980’s winglets where tested on gliders
- Now all gliders use winglets
- Today most transport aircraft use winglet

Induced drag

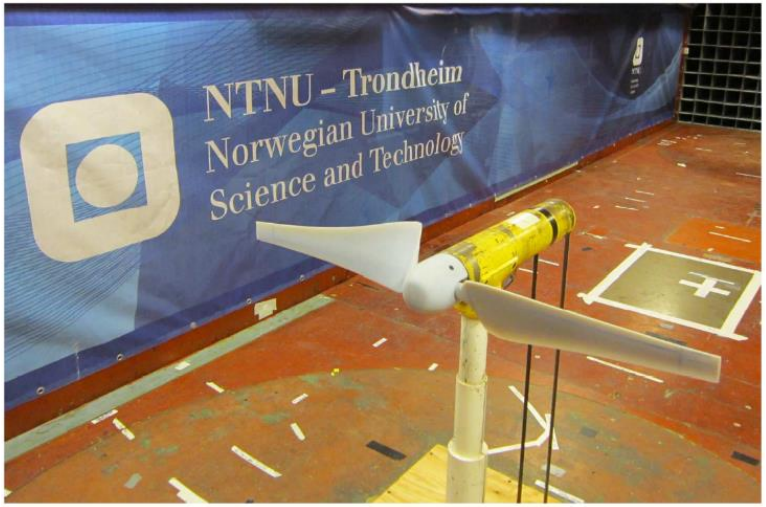
- Winglets reduce the induced drag of a wing
- The induces drag phenomenon both reduces the lift and increases the drag
- The local pressure difference at the tips of the wing creates a vortex system

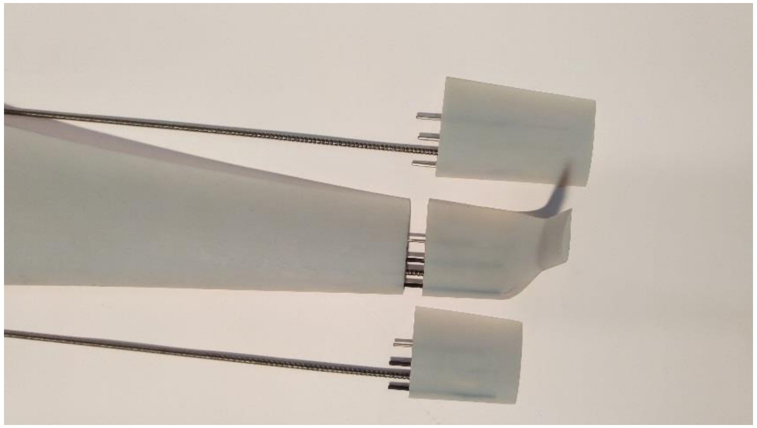




2-bladed rotor

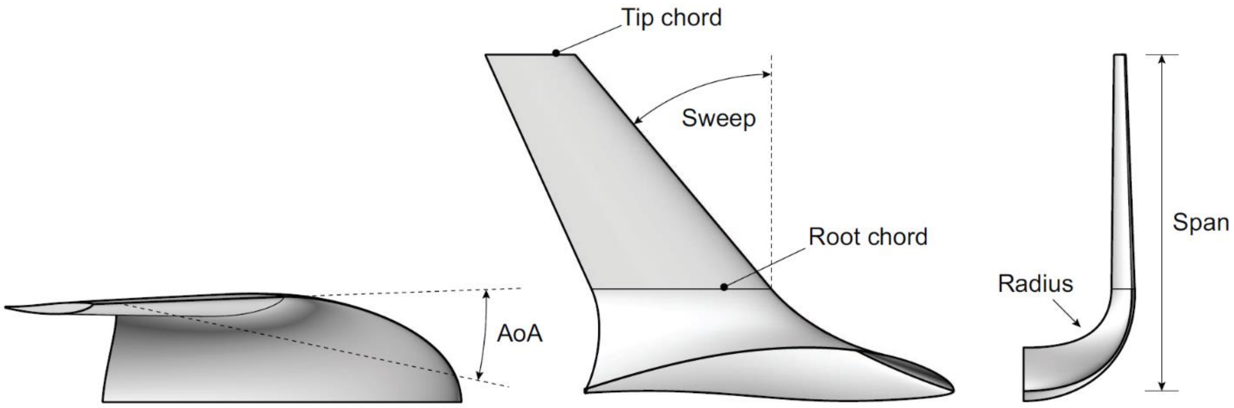
- New rotor with removable tips developed for the winglet project
- Rotor and winglet 3D printed in acrylic plastic
- Two bladed turbine chosen to increase chord size and Reynolds number on the winglets
- Optimum chord and twist distribution computed using BEM theory

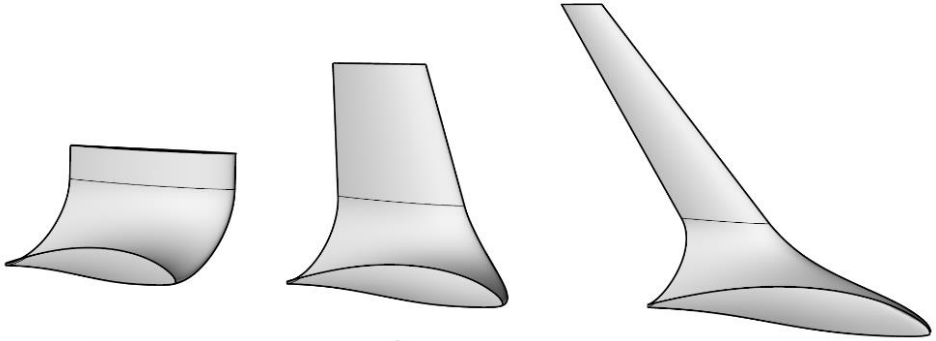




Winglet parametrisation

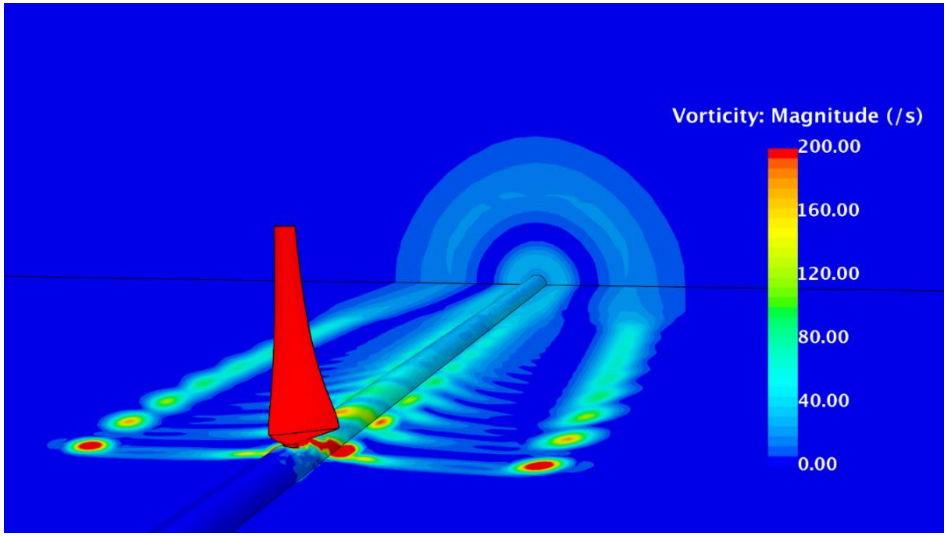
- Winglet is parametrised using 6 DOFs
- Span on rotor equal both with and without winglet
- Large design space of feasible winglet shapes





CFD simulations

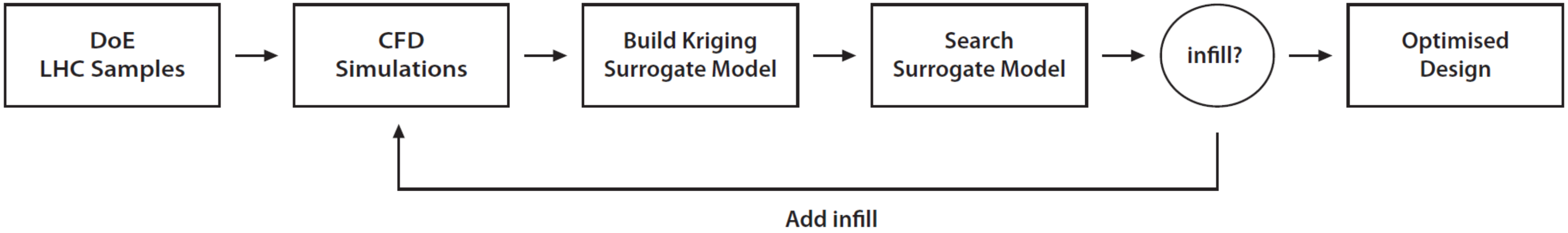
- The wind turbine performance is simulated using RANS CFD
- Turbulent flow predicted with the Spalart Allmaras turbulence model
- Simulation time is approximately 3-4h



TSR = 6

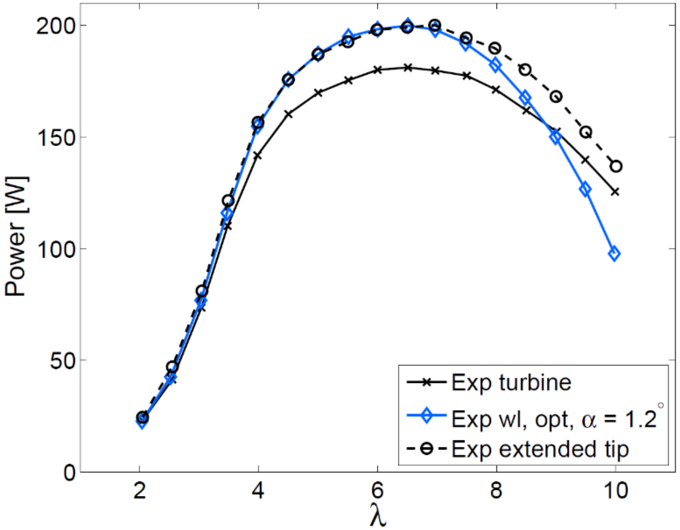
$$\text{Tip speed ratio} = \lambda = \frac{\omega R}{U_\infty}$$

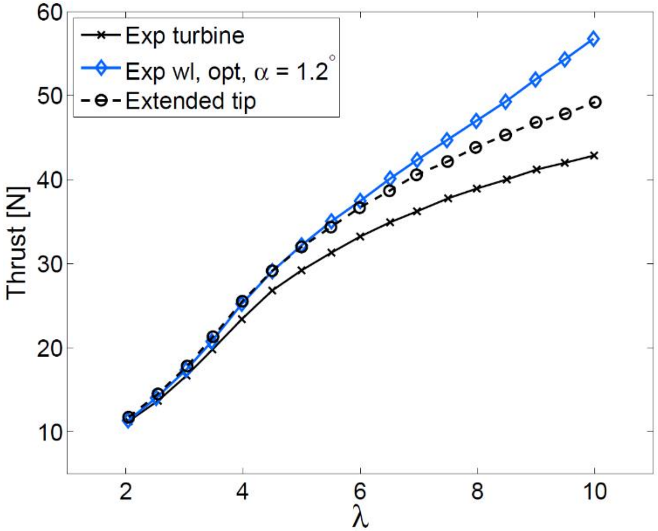
Winglet optimisation loop



Optimised winglet

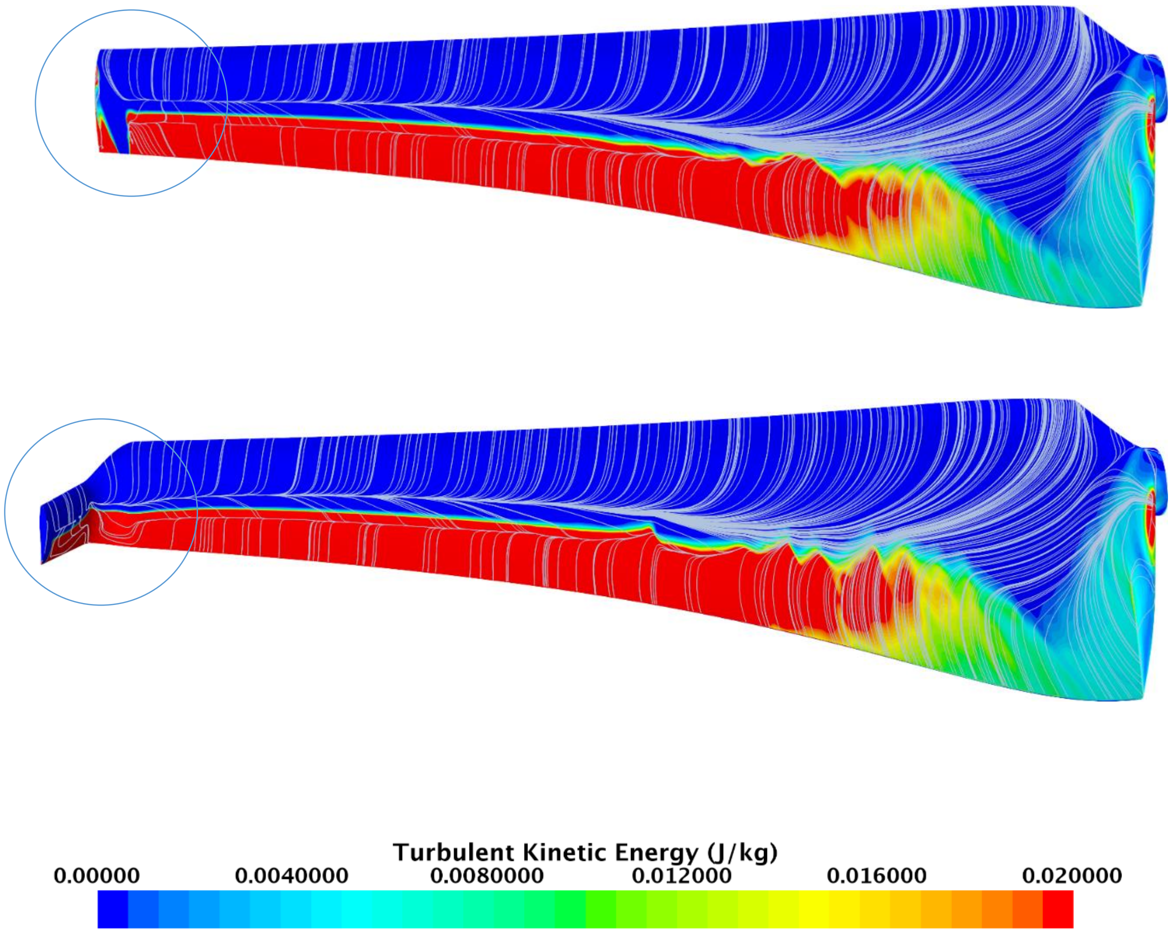
- Power increase with winglet:
- CFD = 7.8%
- Exp = 10.3%
- Winglet also compared to extended tip
- Performance at TSR > 6 is worse due to bending of the 3d printed plastic winglets





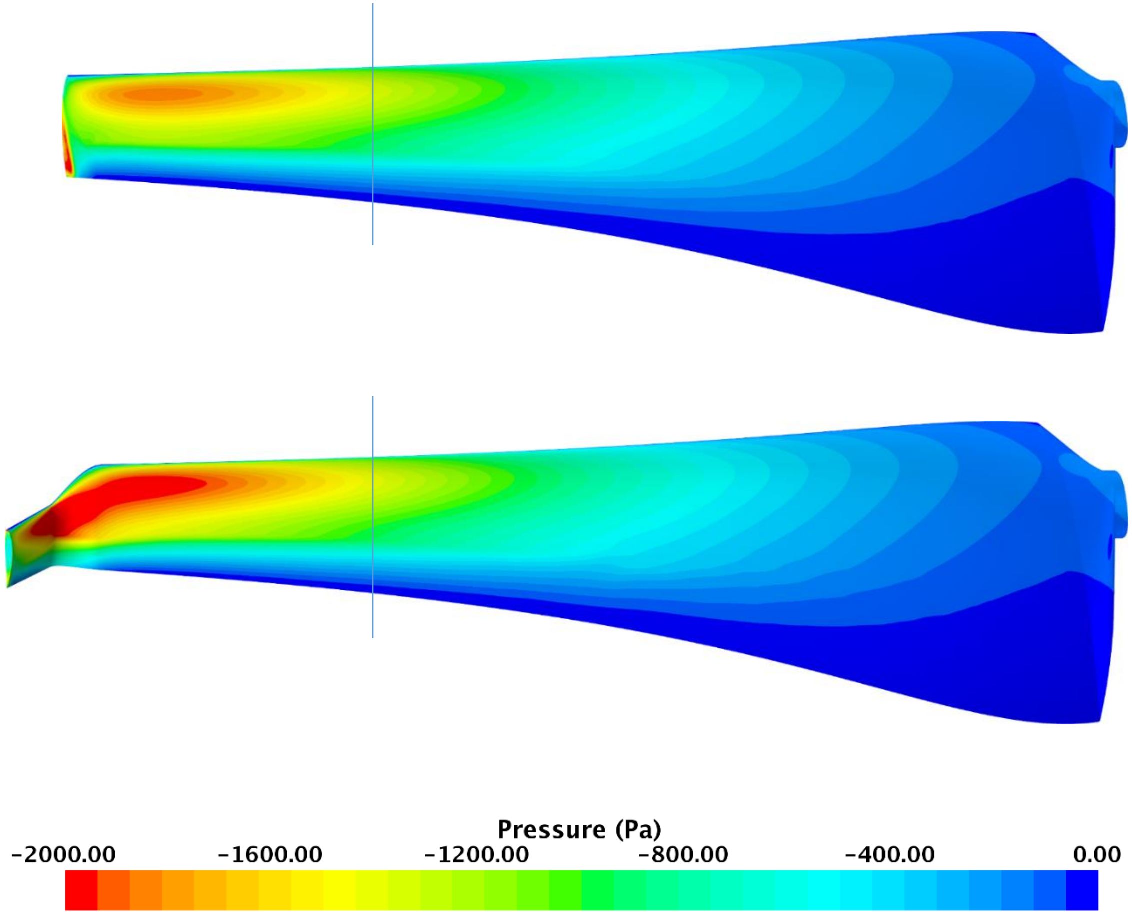
Flow on rotor blade

- TKE and streamlines of rotor at TSR = 6
- Simulations performed using the Reynolds-Stress Model
- Strong 3D flow at root of rotor blade
- Winglet improves flow condition locally at the tip



Pressure on rotor blades

- Pressure represents the production of lift
- More lift is generated locally at the tip for the rotor with winglet →induced drag is reduced
- Pressure on the inboard part is equal
- Winglet improves lift only in the tip region



Questions?