Integrated airfoil and blade design

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Outline

- Some previous work on airfoil and blade optimization
- The integrated design method
- Airfoil and blade design
- Numerical simulations
- Conclusions

Some previous work / airfoil design

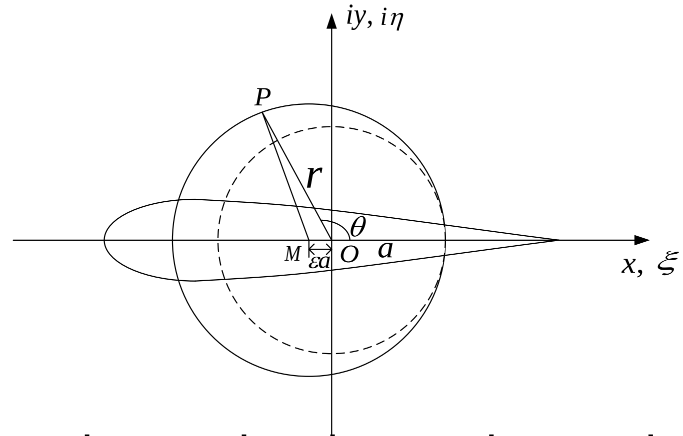
- Airfoils are mapped to a near circle by Joukowski transformation

$$\varsigma = f(z) = z + a^2 / z$$

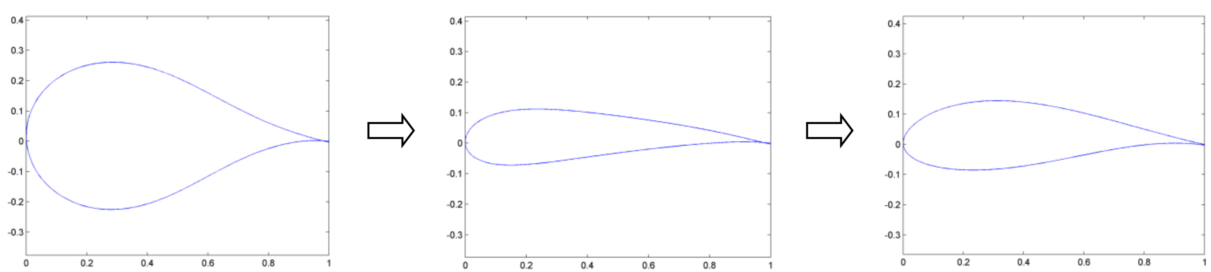
$$a = c/4$$

$$z = a\exp(\varphi + i\theta)$$

$$\varphi(\theta) = \sum_{k=1}^{n} (a_k (1-\cos\theta)^k + b_k \sin^k \theta)$$



- a_k *and* b_k are the coefficients to be determined, we choose k=3 in the present optimization, x=[a_1, b_1, a_2, b_2, a_3, b_3]

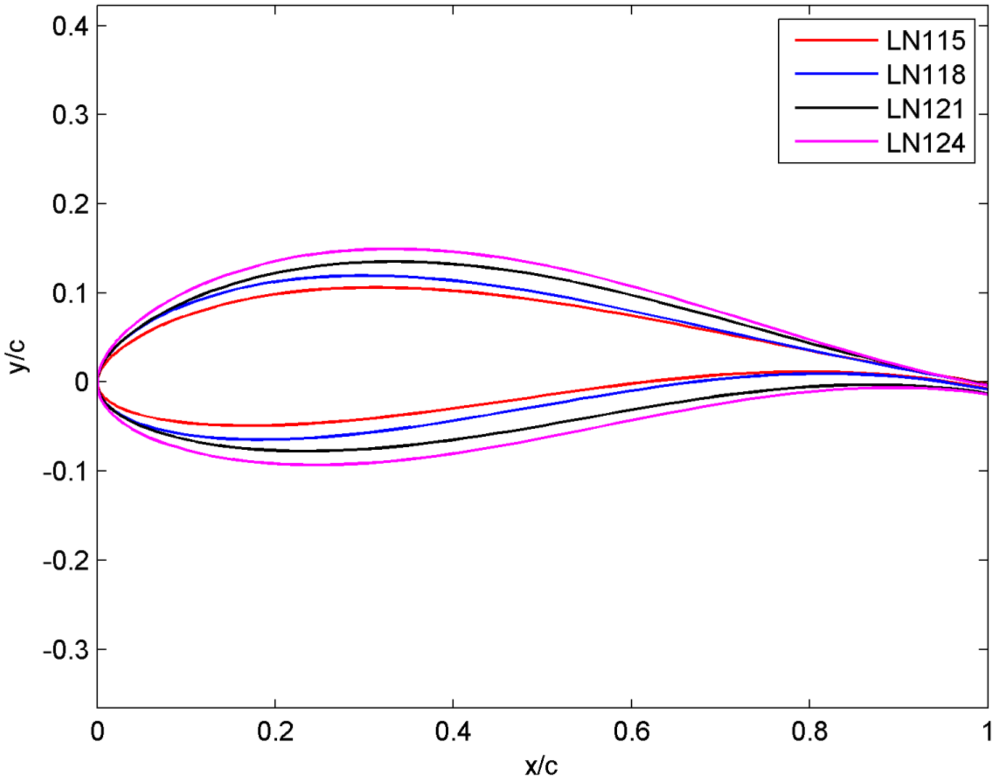


Some previous work / requirements

Design requirements:

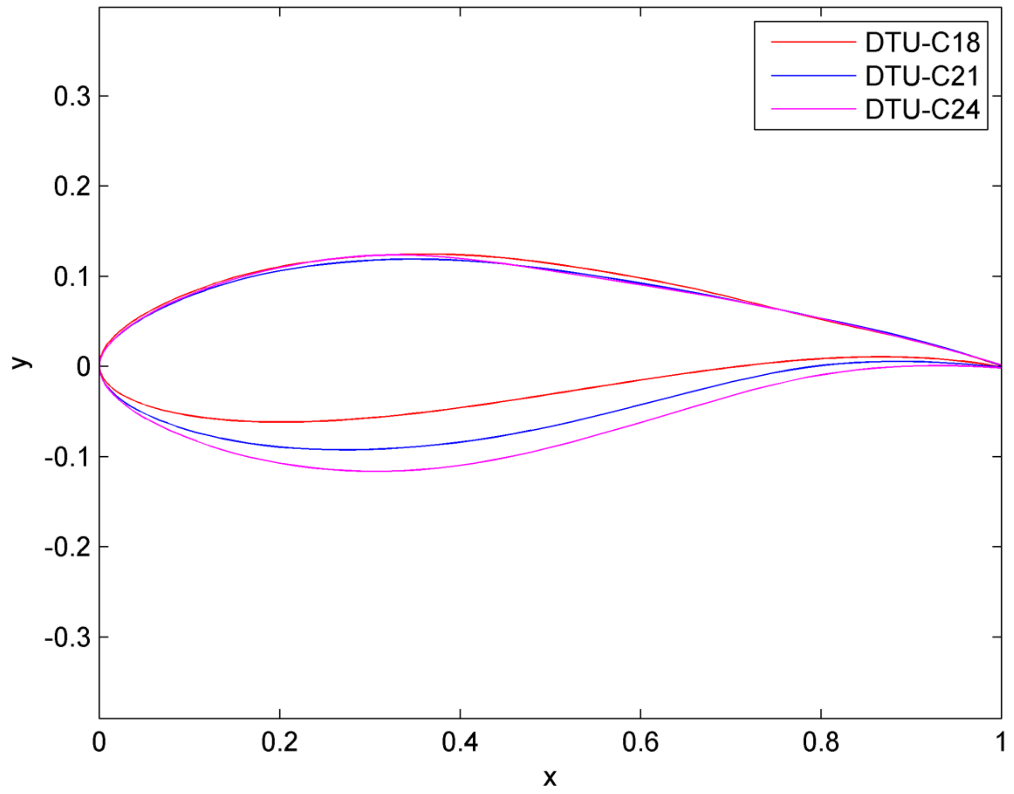
1. Low noise;
2. Reduce maximum lift (prevent extra gusts and storm loading);
3. Less sensitive to surface roughness;
4. Improve after-stall performance;
5. Improve structure properties: thickness distribution, bluntness, surface curvature, skewness.
6. High design Cl and Cl/Cd should still be aimed.

Some previous work / low noise airfoils



wind tunnel tested for aeroacoustics: **LN118**

Some previous work / high Cp airfoils



wind tunnel tested for aerodynamics: **C18,C21,C24**

Some previous work / Blade optimization

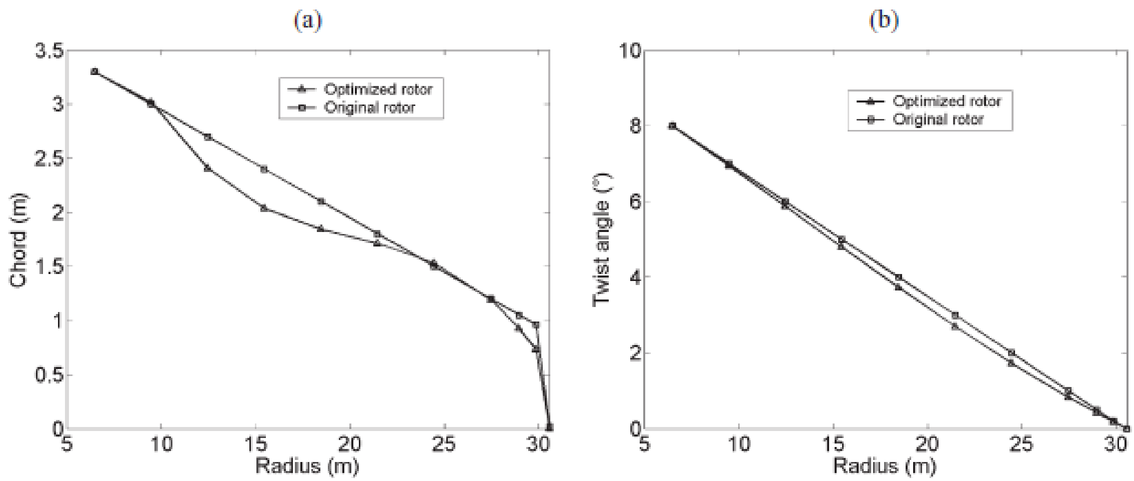


Figure 11. (a) Chord and (b) twist angle distributions of the original and the optimized Tjæreborg 2 MW rotor

Cost ⇩ 7.1%

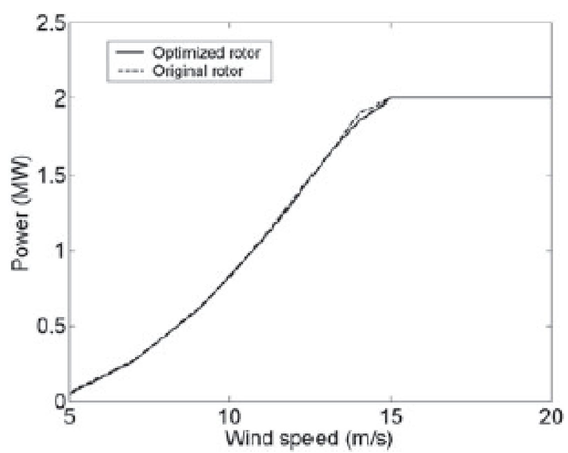


Figure 12. Power performance of the original and the optimized Tjæreborg 2 MW rotor

AEP ⇩ 4%

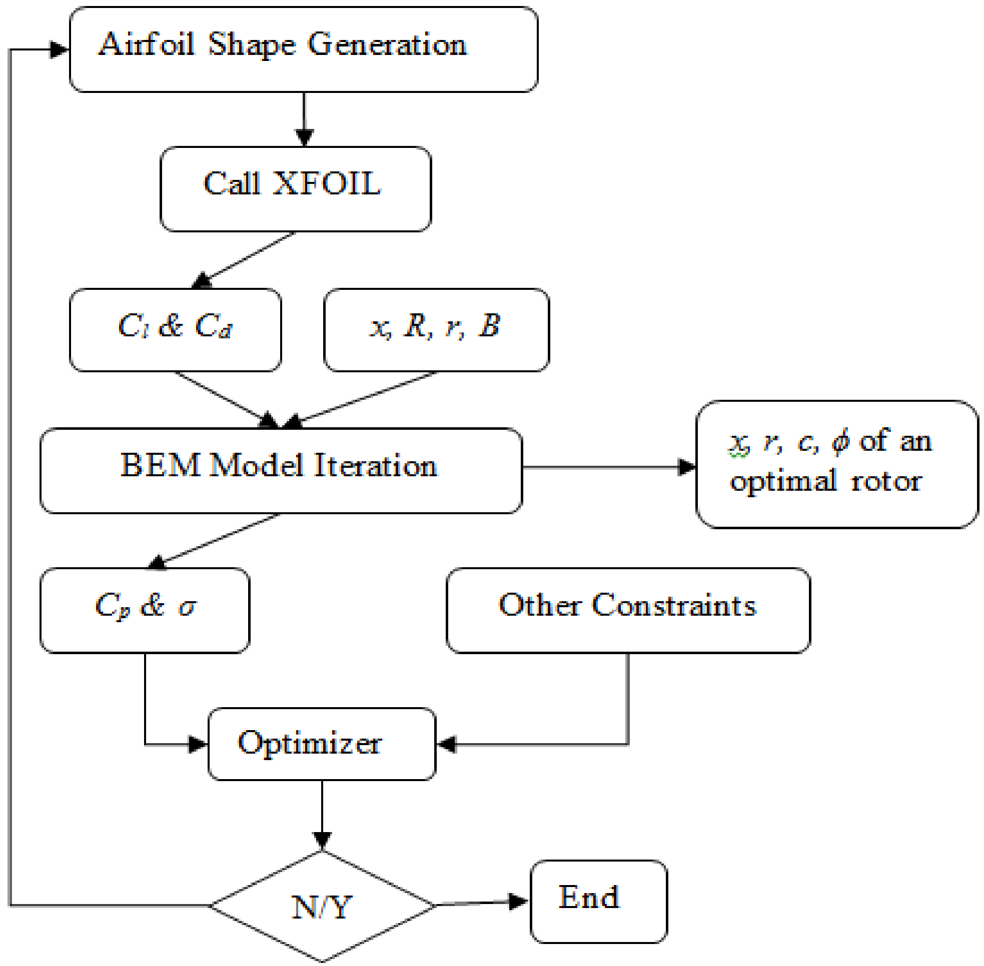
COE ⇧ 3.3%

Wind Energ. (2009)

Integrated design / method summary

- The core of the present optimization work is to develop large wind turbine blade with lower cost of energy (COE).
- At every local blade spanwise location, the design objective of each airfoil is high power coefficient and small chord length.
- The objective and constrains are different from each airfoil due to their different local flow condition.
- The flow geometry over the rotor is preserved such that the flow angle is maintained at its optimum position using the designed airfoils.
- As a result of integrated design, the obtained blade platform ensures optimum flow geometry over the rotor.

Integrated design / flow chart



Integrated design / BEM analyses

- The 2D-BEM connects the airfoil optimization and optimal blade design.

- The steps of BEM iteration:

1). Initialization: $C_p = 0$ and $\varphi = 0$;

2). Read C_l and C_d from airfoil calculations.

3). Compute tangential and axial force coefficients.

$$c_t = c_l(\sin\varphi - c_d/c_l \cos\varphi)$$

$$c_n = c_l(\cos\varphi + c_d/c_l \sin\varphi)$$

4). Compute induction factor a_t, flow angle φ and solidity.

$$a_t = (4\sin\varphi\cos\varphi/\sigma c_t - 1)^{-1}$$

$$\varphi = \operatorname{atan}((1 - a_n)/x(1 + a_t))$$

$$\sigma c_n = 2F\sin^2\varphi$$

5). Compute C_p

$$C_p = [(1 - a_n)^2 + x(1 + a_t)^2]x\sigma c_t$$

6). If $C_p(i+1) - C_p(i) > 10^{-3}$, goto 3).

Airfoil design / techniques

- Design condition:

  - The design Reynolds number is estimated to be about Re=15x10^6.
  - Design AoA is between 3 and 10degs.
  - Free transition simulation is based on the e^n model with n=9;

  Force transition simulation is carried out by fixing the upper and lower transition points at 5% and 10% chords measured from leading edge, respectively.

- Design variables:

  - The shape perturbation function

$$\Delta y_u(i) = \sum_{k=1}^{N} f_u(k) P_u(k,i) \qquad \Delta y_l(i) = \sum_{k=1}^{N} f_l(k) P_l(k,i)$$

where, $P_u(k,i) = \sin^{\xi}(\pi x_u(i)^{g(k)})$ $\qquad P_l(k,i) = \sin^{\eta}(\pi x_l(i)^{g(k)})$

g=[0.1 0.2 0.3 0.4 0.5 0.75 1 1.5 2 2.5 3 4 7 8].

  - total number of design points: dofs=2*N+2

Airfoil design / techniques

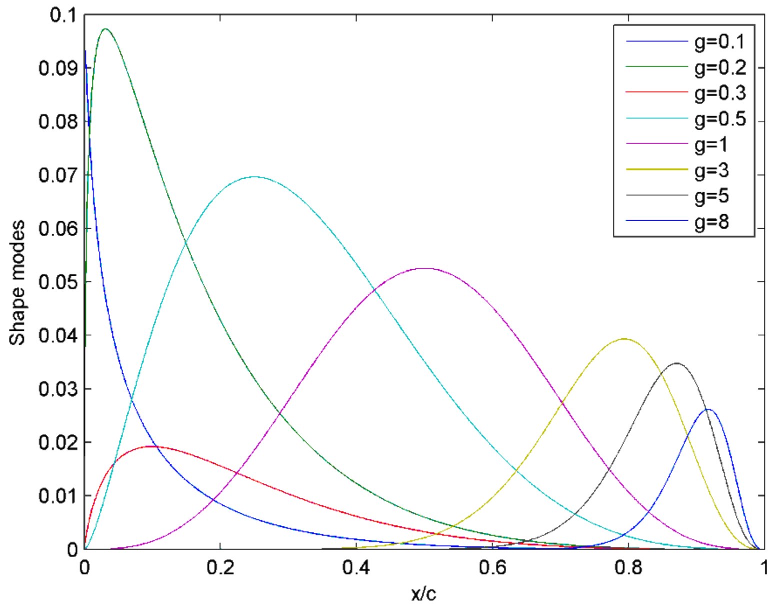


Fig. Example of shape perturbation functions.

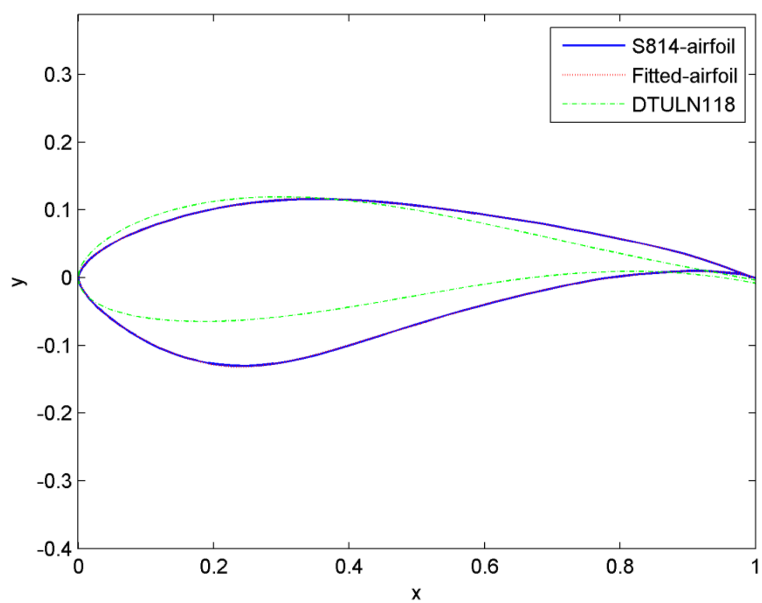


Fig. Example of profile fitting: begin with LN118 and start with randomly seed of design variables.

Airfoil design / techniques

- *Design objectives:*

  - The design objective is the blending of power coefficient and the rotor solidity, such as

$$obj = kC_p + (1-k)/\sigma$$

  - The power coefficient is weighted between clean and rough conditions with the AoA range from 3 to 10 degs.

$$C_p = 0.25\sum_{a=3}^{10} C_p^{clean} + 0.75\sum_{a=3}^{10} C_p^{rough}$$

- *Design constrains:*

  - thickness to chord ratio;
  - limited difference in maximum lift for clean and rough cases;
  - maximum thickness location x/c between 0.25-0.35;
  - minimum thickness near the trailing edge;
  - surface curvature.

Airfoil design / techniques

- *Summarise of the key design steps:*

  - ✓ Random seed of design variables
  - ✓ Set lower and upper boundaries for the design variables
  - ✓ Set shape, aerodynamic, structure constraints
  - ✓ Read a reference profile
  - ✓ Using the shape pertubation function to create a new profile
  - ✓ Call Xfoil, compute Cl, Cd at AoA=[3:10]degrees.
  - ✓ Call BEM, compute the objective function: Cp
  - ✓ Call optimization function and evaluate Cp

Airfoil design / Airfoil shape max(t/c)=18-30%

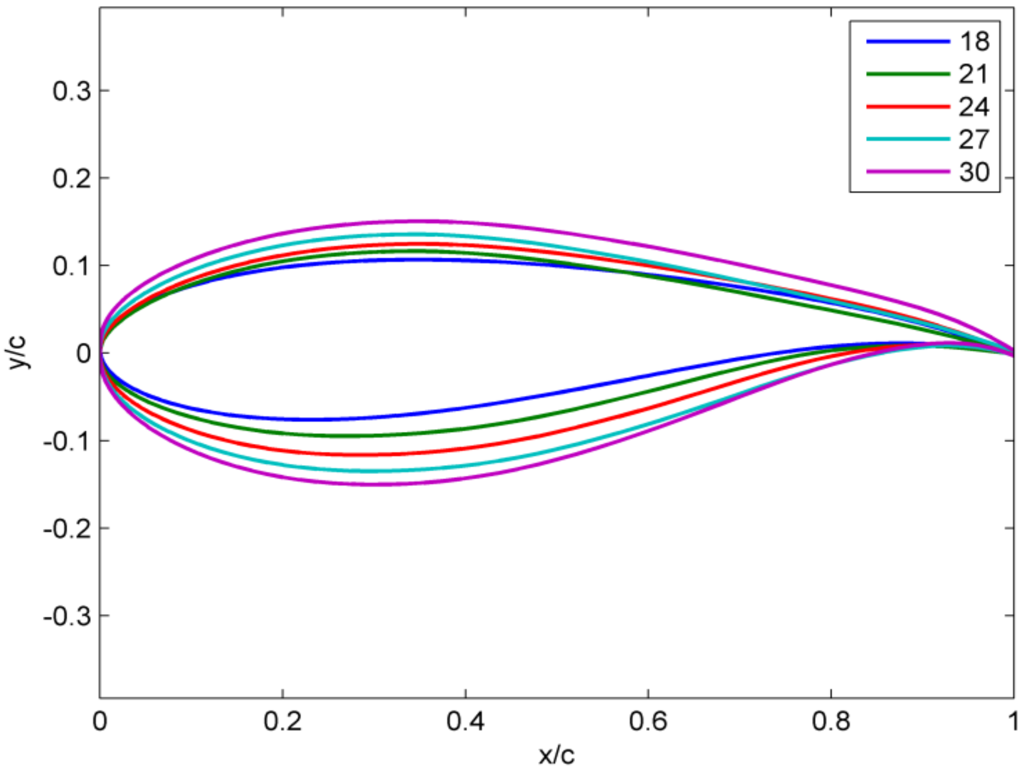


Fig. The DTU-R130-xx airfoils

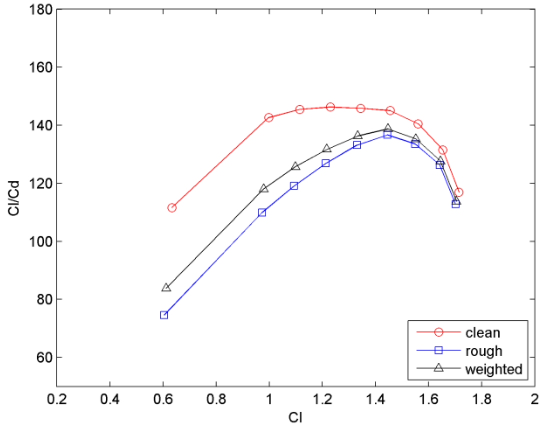
Airfoil design / key parameters

Thickness	18	18	18	21	24	27	30	50	100
Step1: Pre-define blade length and TSR									
r (m)	130	125	110	80	65	50	40	30	0
λ	8	7.69	6.77	4.92	4	3.08	2.46	1.54	-
Step2: Airfoil design based on the local TSR									
Bluntness	-	-	0.2	0.23	0.3	0.5	0.6	-	-
x_{max}/c	-	0.278	0.278	0.308	0.314	0.314	0.327	-	100
C_{Lde}	-	-	1.24/1.21	1.25/1.21	1.4/1.34	1.39/1.29	1.41/1.24	-	-
C_{Lmax}	-	-	2.04/2.03	1.97/1.96	1.97/1.95	1.89/1.86	1.89/1.85	-	-
$(C_L/C_D)_{max}$	-	-	146/137	160/130	150/ 119	151/108	132/84	-	-
Step3: Blade construction based on the optimal airfoils									
Chord(m)	0	2.4	3.57	4.91	5.37	6.99	8.67	10	7
β(°)	-	0.62	0.68	1.65	2.34	4.96	7.7	11	-
ϕ (°)	-	5.62	5.68	7.65	9.34	11.96	14.7	18	-
Solidity	-	0.009	0.015	0.029	0.039	0.668	0.10	-	-
Re ($\times 10^6$)	-	12.4	16.3	16.4	14.8	15.1	15.4	10	5

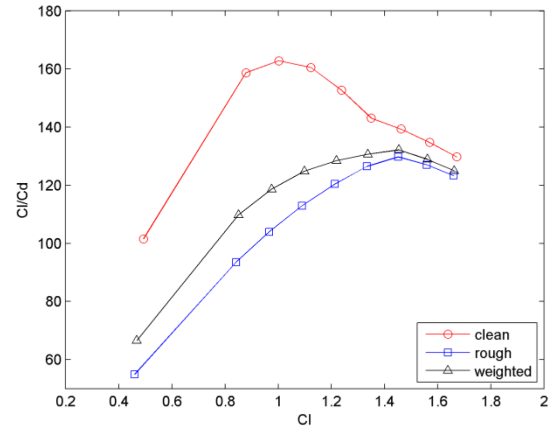
Table. Airfoil characteristics and blade parameters.

Airfoil design – lift and drag 18,21,24,27%

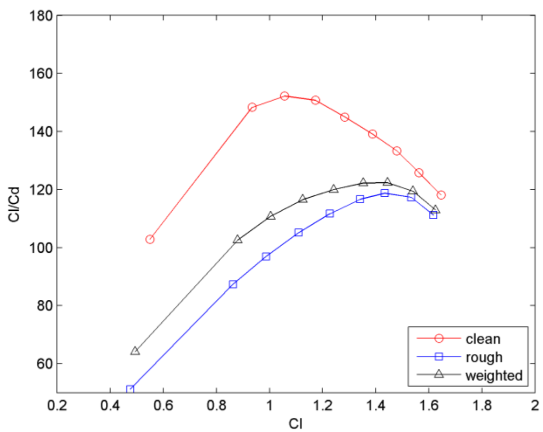
18%



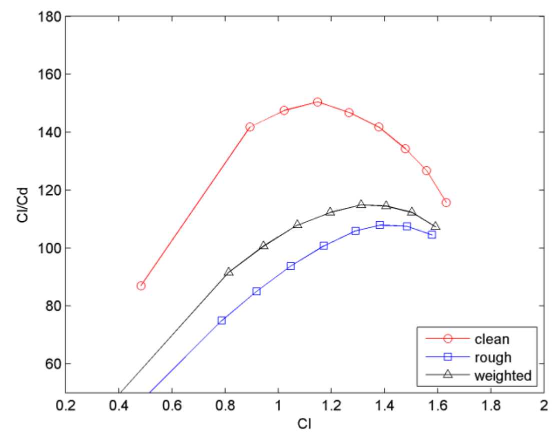
21%



24%

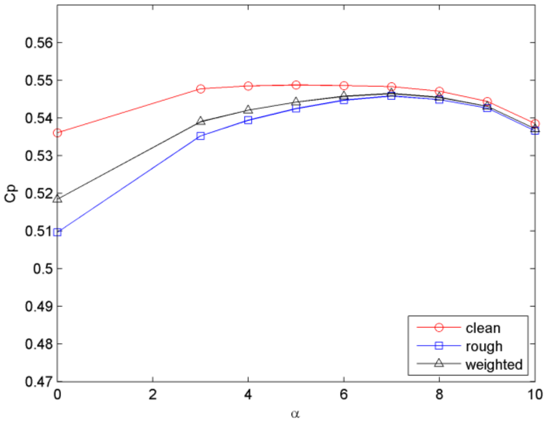


27%

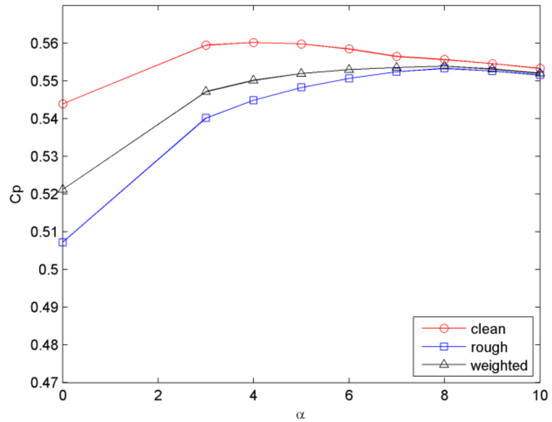


Airfoil design – power coefficient 18,21,24,27%

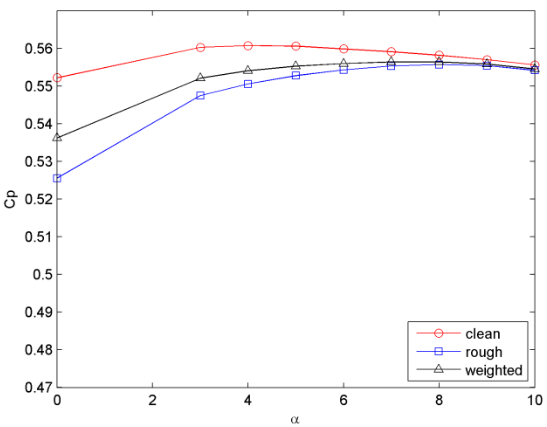
18%



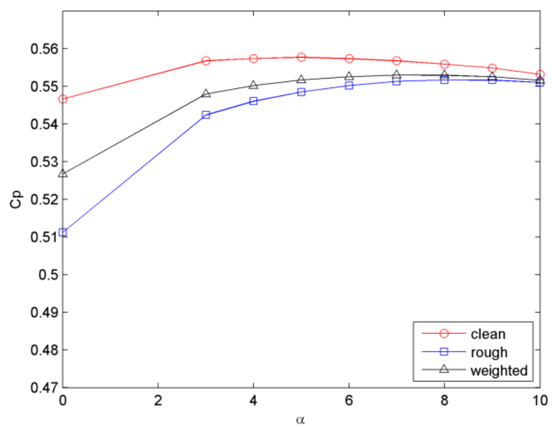
21%



24%

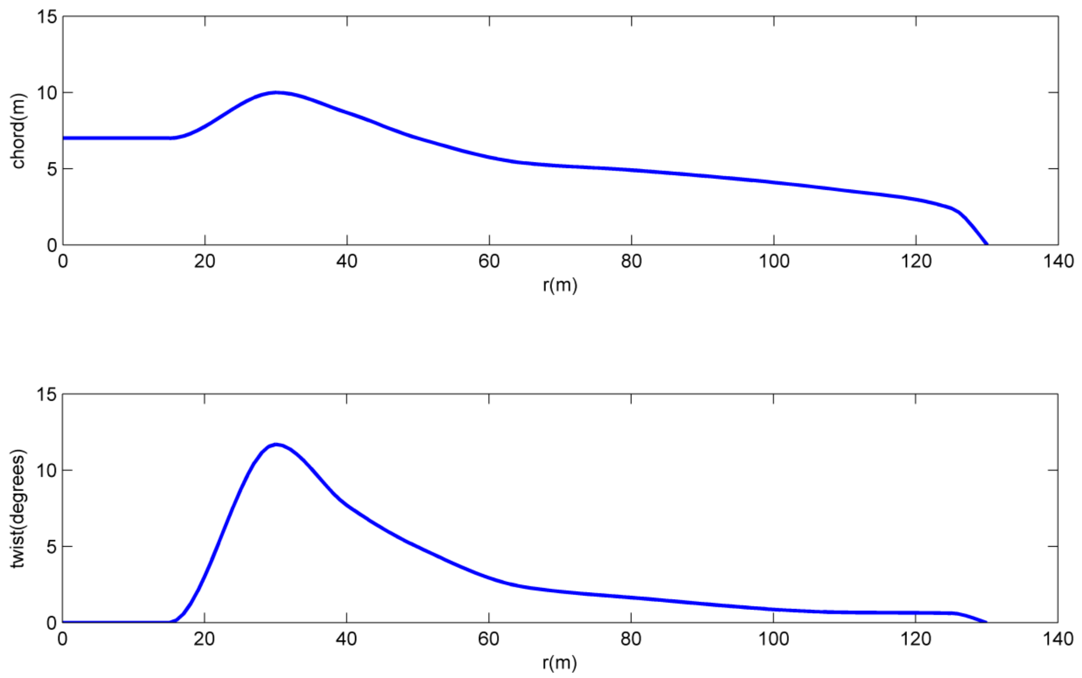


27%



Blade platform design – chord and twist

When the local high Cp is found, the corresponding optimal chord and flow angle are obtained.



Simulations / full blade BEM

BEM approach:

A standard momentum theory is applied on each blade element such that the thrust and torque are calculated as

$$dT = d\dot{m}(V_0 - V_1) = 2\pi r \rho V (V_0 - V_1) dr = 4\pi r \rho V_0^2 a(1-a) dr$$

$$dM = \dot{m} r V_\theta = 2\pi r^2 \rho V \cdot V_\theta dr = 4\pi r^3 \rho V_0 (1-a) \cdot \omega a' dr$$

The axial and tangential induction factors *a* and *a’* are iteratively calculated including the tip loss effect

$$a = \frac{2 + Y_1 - \sqrt{4Y_1(1-F) + Y_1^2}}{2(1+FY_1)} \qquad a' = \frac{1}{(1-aF)Y_2/(1-a) - 1}$$

Simulations / full blade BEM

BEM approach continue:

$$Y_1 = 4F \sin^2\phi / (\sigma C_n F_1) \qquad Y_2 = 4F \sin\phi \cos\phi / (\sigma C_t F_1)$$

The factor F_1 is introduced to model the tip effect about airfoil data. The 2D lift and drag coefficients are corrected near the tip with 3D effect such that

$$C_n^r = F_1 \cdot C_n \qquad C_t^r = F_1 \cdot C_t$$

$$F_1 = \frac{2}{\pi} \arccos\left[\exp\left(-g \frac{B}{2} \cdot \frac{R-r}{r \sin\phi} \right) \right]$$

$$g = \exp\left[-0.125(B\lambda - 21) \right] + 0.1$$

Simulations / full blade CFD

CFD approach:

- The numerical validation code used here is the incompressible flow solver EllipSys3D.

- The solver was developed at Technical University of Denmark (DTU) since 1990s.

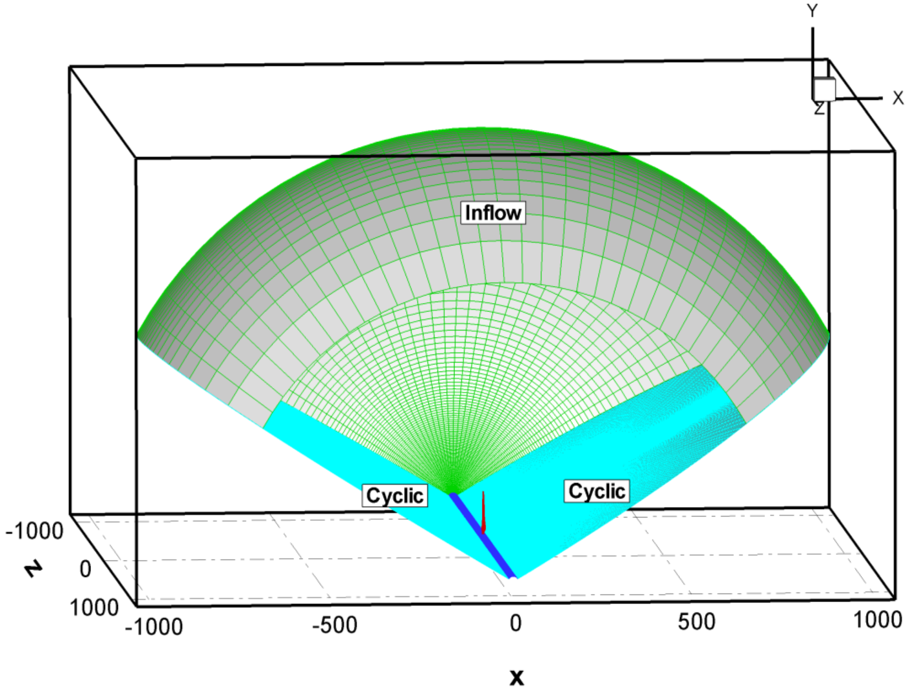
- It is a general-purpose Navier-Stokes code based on a second-order multi-block finite volume method.

- For wind turbine application, the Navier-Stokes equations are solved in a 3D polar rotating frame. The velocities relative to a fixed frame are $\begin{pmatrix} \hat{v}_r \\ \hat{v}_\theta \\ \hat{v}_z \end{pmatrix} = \begin{pmatrix} 0 \\ \Omega r \\ 0 \end{pmatrix} + \begin{pmatrix} v_r \\ v_\theta \\ v_z \end{pmatrix}$, the relative velocity components (v_r, v_θ, v_z) are solved in the polar system.

Simulations / full blade CFD

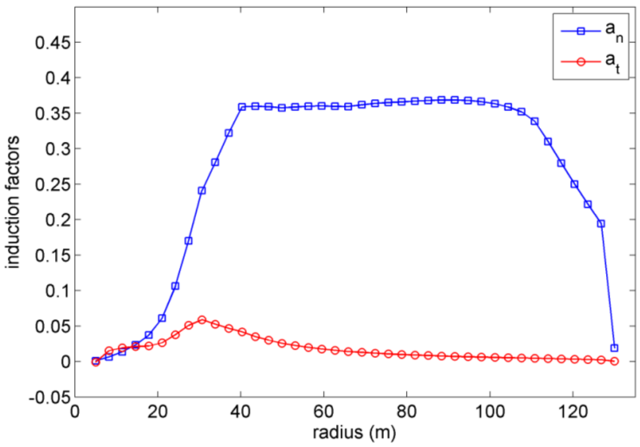
CFD approach continue:

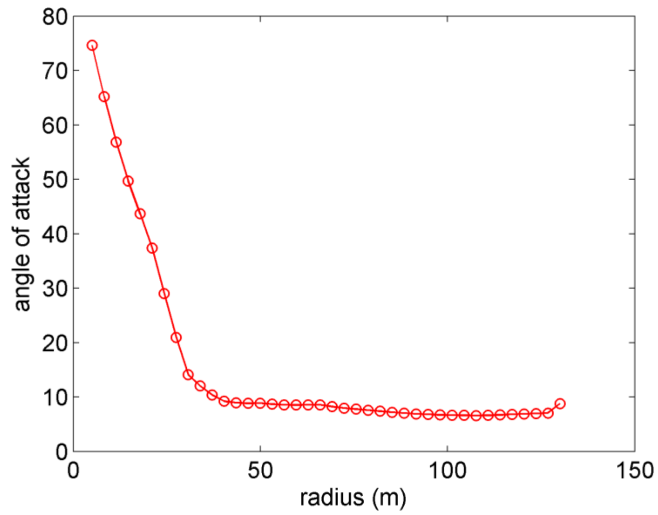
- The blade surface mesh is generated orthogonally with 53248 mesh points.
- The volume mesh is created between the blade wall surface and the outer boundaries.
- The wind goes through the z-axis and the blade rotates in the clockwise direction seen from the upwind direction.
- The total number of grid points is about 10.5 million which is divided into 40 blocks with 64^3 grid point per block.
- To resolve flow around the wall boundary, the smallest cell size near the wall surface is in the order of 10^{-6}.



Simulations / results

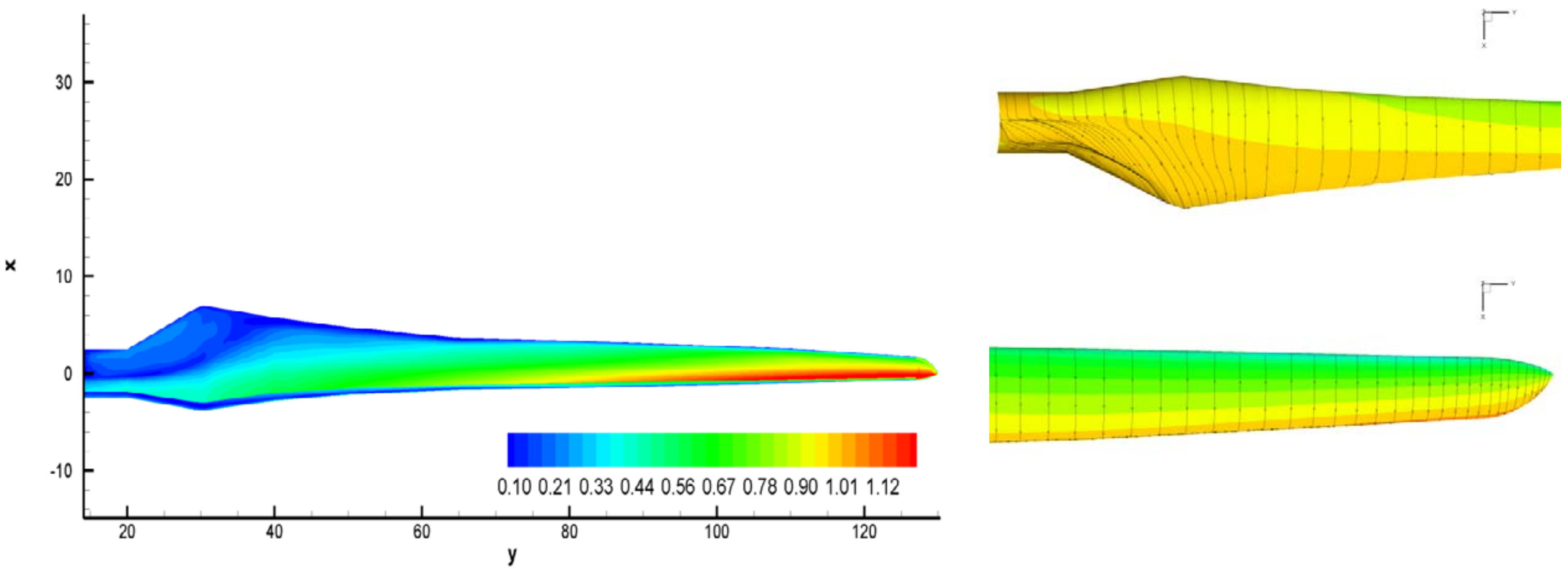
- Computations are performed at the design wind speed of *U = 10 m/s* and *TSR = 8*.
- For the BEM computation, the blade is divided into 40 elements.
- The elastic model is deactivated in the unsteady BEM code. Also the tower, wind shear effects are not included.
- From r = 40 m to r = 110 m, the normal induction factor is around 0.35.
- From r=40 m towards tip, the angles of attack are well below 10 degrees. This indicates attached flow over most part of the blade which ensures the high power performance.





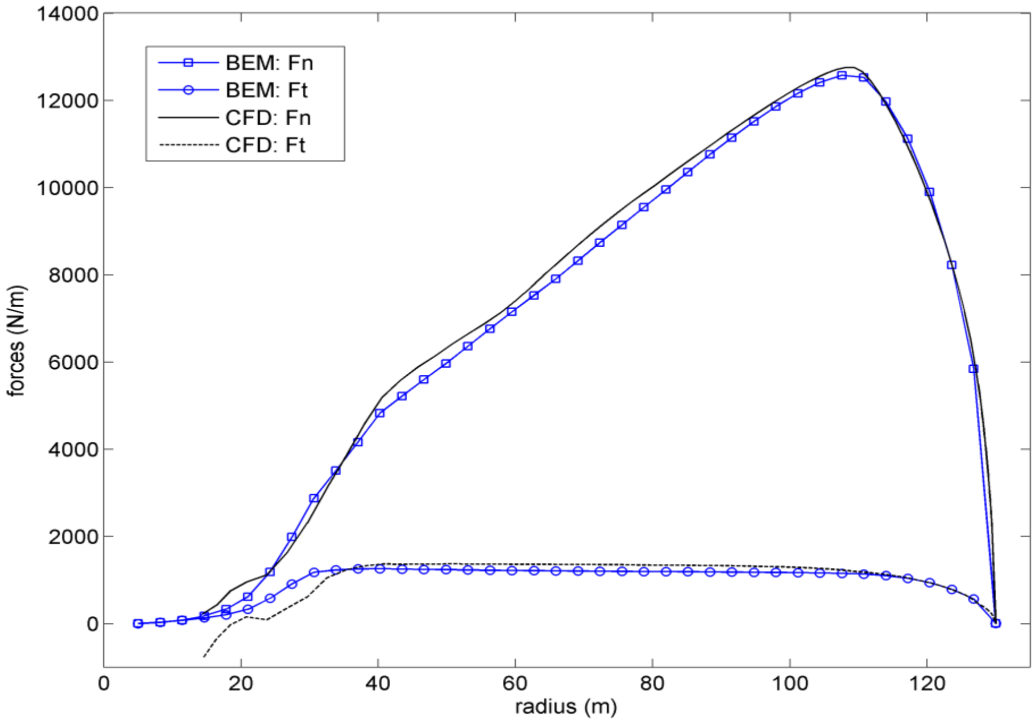
Simulations / results

Since the Reynolds number is so high in the present case, it is necessary to check the mesh resolution near the wall. A plot of y^+ value on the blade surface is one of the straight forward ways to check the wall resolution. the largest y^+ value is less than 1.2 which is located at the leading edge of the blade out part. This ensures the viscos sub-layer being well resolved.



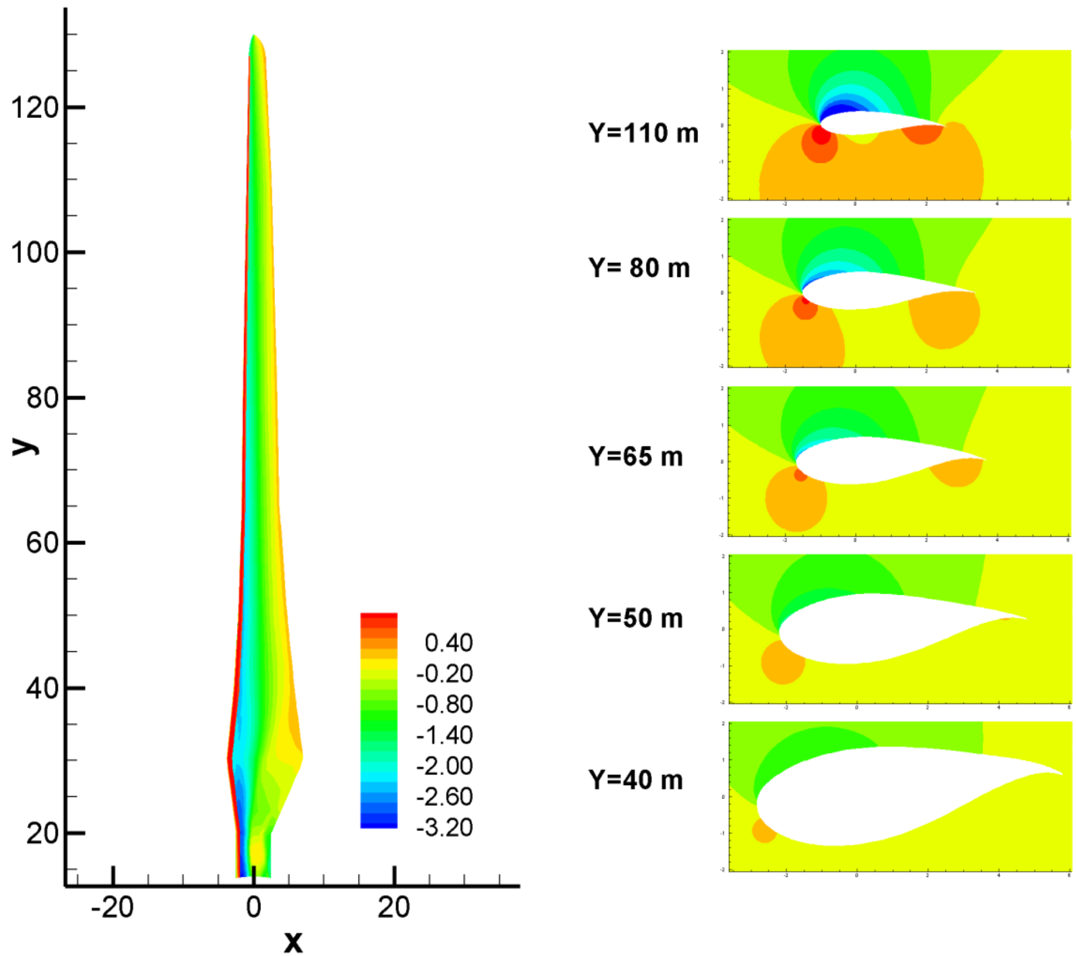
Simulations / results

Good agreements are observed between results from BEM and CFD methods. CFD predicts slightly higher forces than BEM which is observed from 40m<r<130m. Such a difference is often caused by the rotational effect that has been modelled by CFD but not enough counted by BEM.

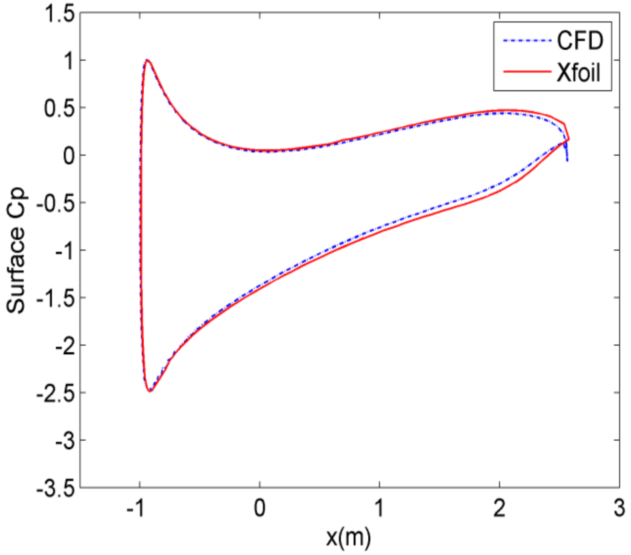


Simulations / results

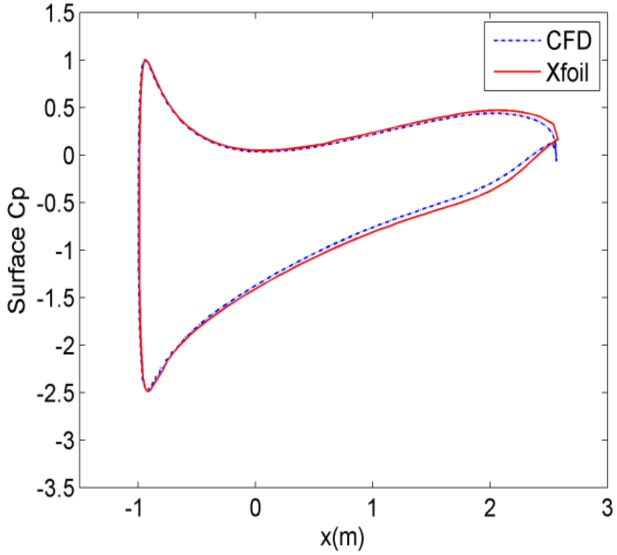
- Cp plot shows smooth pressure distribution along the blade.
- The R130-18, R130-21, R130-24, R130-27 and R130-30 airfoils are seen from the five spanwise locations.
- The increase of chord length and twist angle along the blade is illustrated in the figure.



Simulations / results

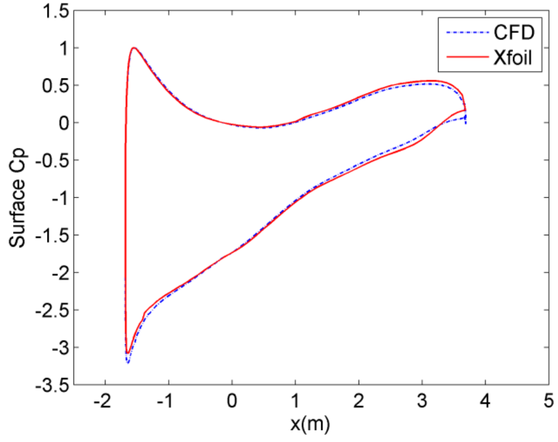


(a) r=110m;

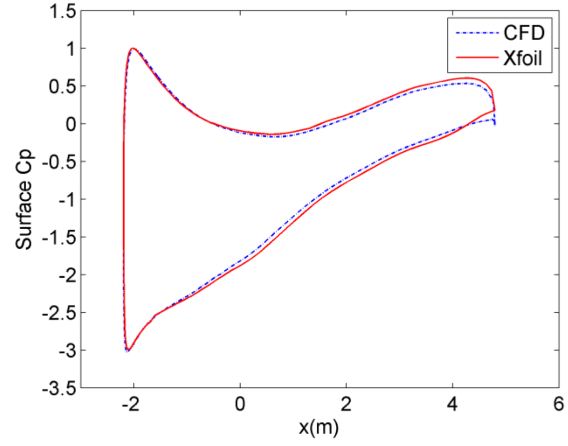


(b) r=80m;

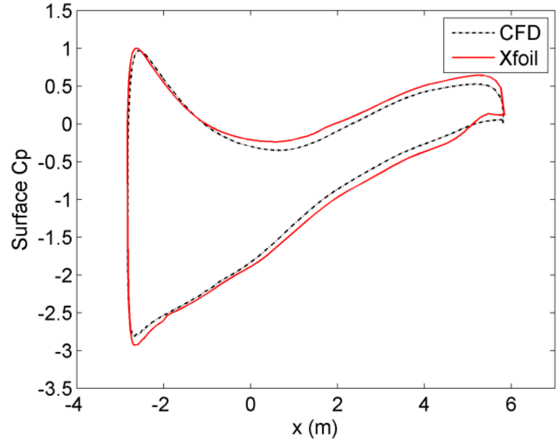
Simulations / results



(c) r=65m;



(d) r=50m;



(e) r=40m.

Conclusions

- The integrated airfoil and blade design method has been introduced. The BEM connects the airfoil optimization and blade design.
- Airfoil design is based on the shape perturbation method which allows the optimization to start with any existing airfoil.
- The airfoils are insensitive to surface roughness and mantain high power coefficients at a wide range of AOA.
- The optimal blade platform is automatically generated when optimal airfoils are obtained.
- Validations carried out by full BEM and CFD have both shown good aerodynamic characteristics.
- Results indicate that the integration of the simplified BEM and Xfoil can be regarded as a reliable tool for airfoil and rotor platform design.

Future work

- All the results are based on the assumption that axial induction factor is 1/3. It is possible to carry out future work that calculates the wake induction through the airfoil optimization.

- An interesting task in the future is to combine the Q^3UIC code with the blade design. The code uses the concept of UNSTEADY VISCOUS-INVISCID STRONG INTERACTION via transpiration velocity.
  - Inviscid flow → Unsteady potential flow, Panel Method.
  - Viscous flow → Quasi 3-D integral BL equations + Closures.

Thank you for your attention!