Aerodynamics & blade technology II

Aerodynamics of modern curved wind turbine blades

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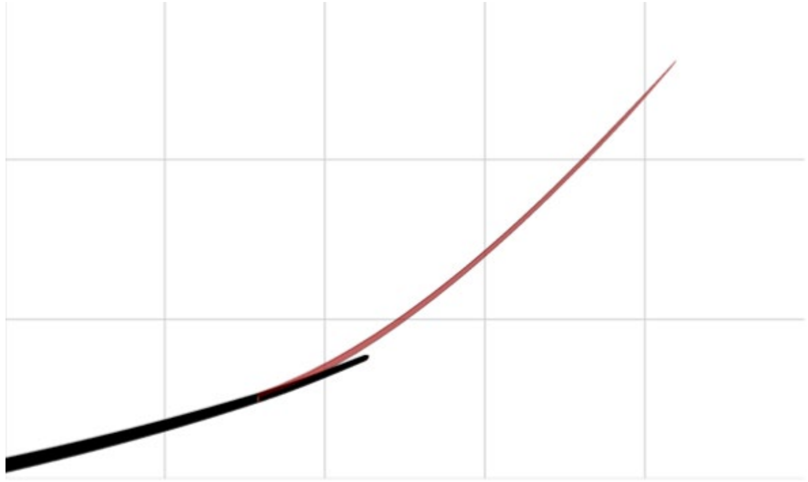
Motivation

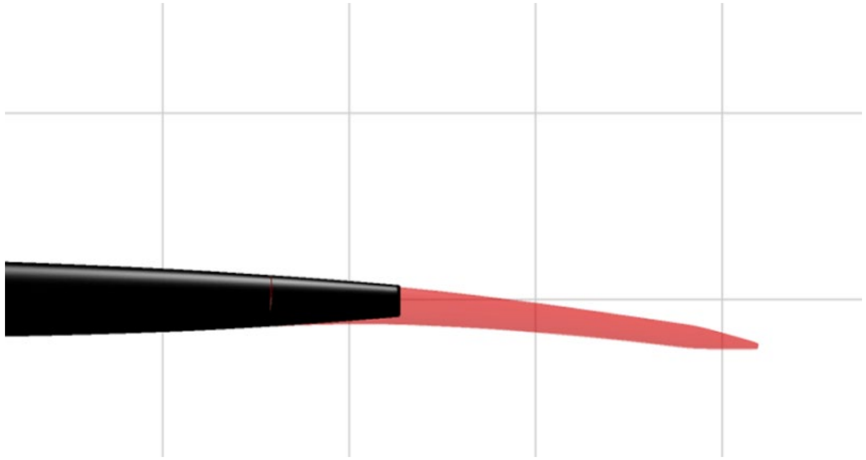
- Blade element momentum theory has been used for aeroelastic modeling for many years
  - Its speed makes it possible to compute thousands of load cases
- This presentation describes the main assumptions of most aeroelastic codes that are increasingly challenged for modern blades
  - From a modeling and experimental perspective
- Many people were involved in the work

  Athanasios Barlas, Ang Li, Mac Gaunaa, Néstor Ramos-Garcia, Sergio G. Horcas, Robert F. Mikkelsen, Anders S. Olsen

Aerodynamics of a rotor disc – BEM theory
How accurate is it today?

- A rotor outfitted with modern blades will not look like a planar disc
  – Further non-swept blades are implicitly assumed
- Example tip shapes from IFD SmartTip project

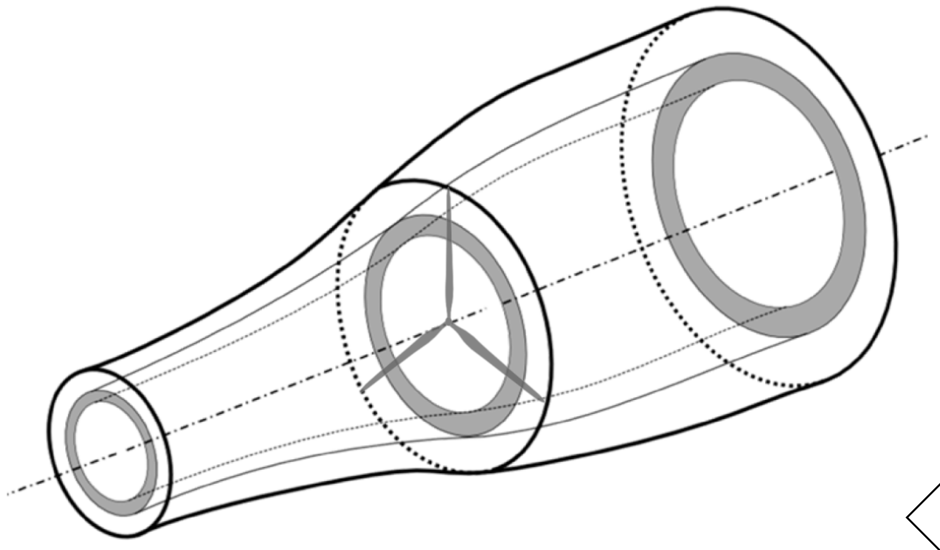




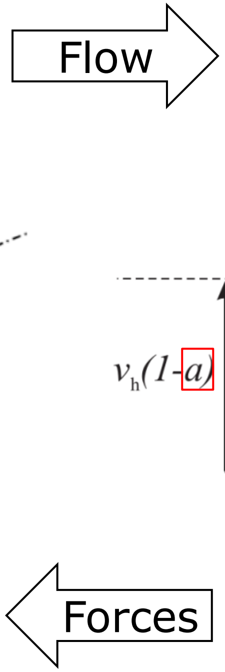
[Barlas, T., Ramos-García, N., Pirrung, G. R., and González Horcas, S.: Surrogate-based aeroelastic design optimization of tip extensions on a modern 10 MW wind turbine, Wind Energ. Sci., 6, 491–504, https://doi.org/10.5194/wes-6-491-2021, 2021.]

Aerodynamics of a rotor disc - BEM theory

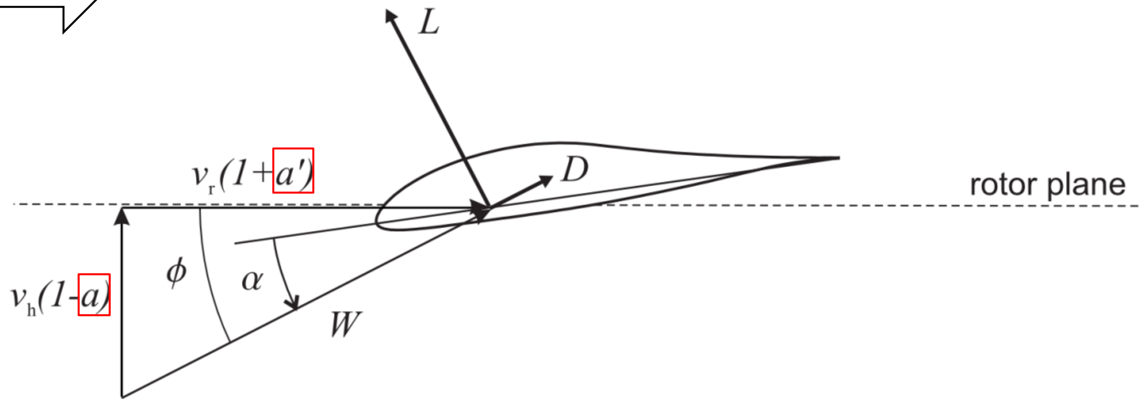
Momentum theory



[Adapted from E. Branlard,
Wind turbine tip-loss corrections, MSc thesis, 2011]



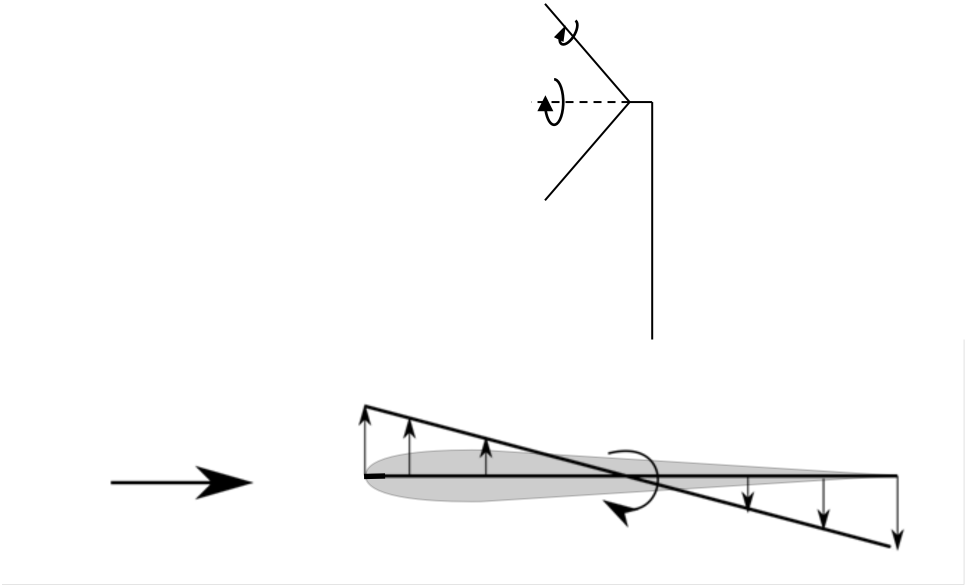
Blade element theory



W = relative velocity
α = angle of attack
ϕ = inflow angle
L = Lift
D = Drag

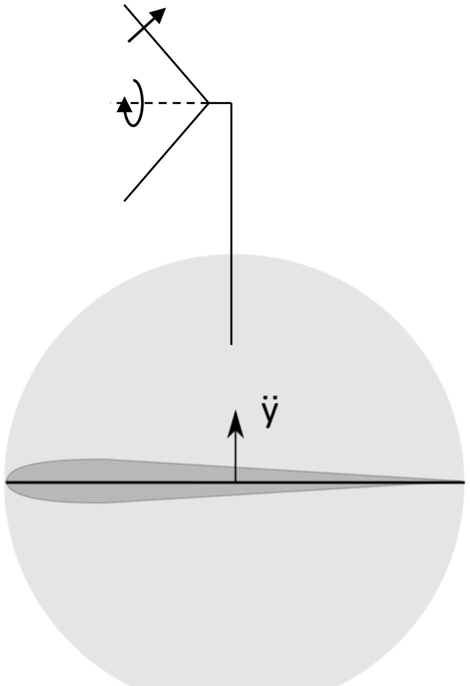
Effects of curved blades on blade element part: Cone/prebend/deflection

Rotation of section



1) behaves as camber => additional lift
2) $AoA_{1/4} \neq AoA_{3/4}$
   => potentially wrong prediction of thrust/power

Acceleration of section

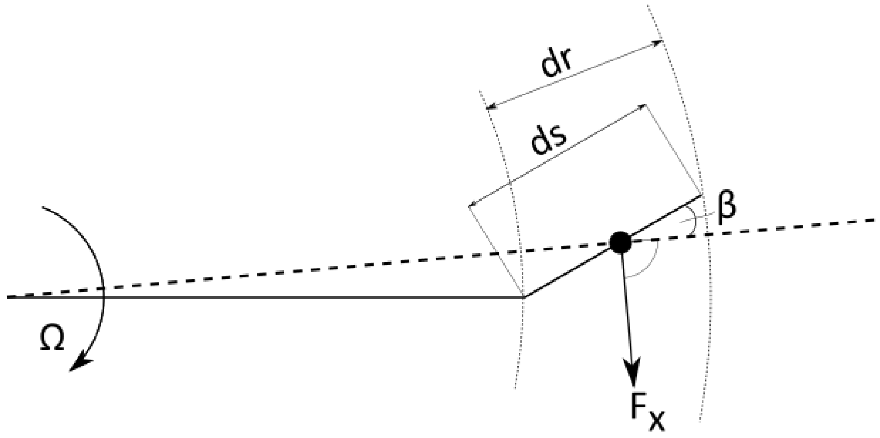


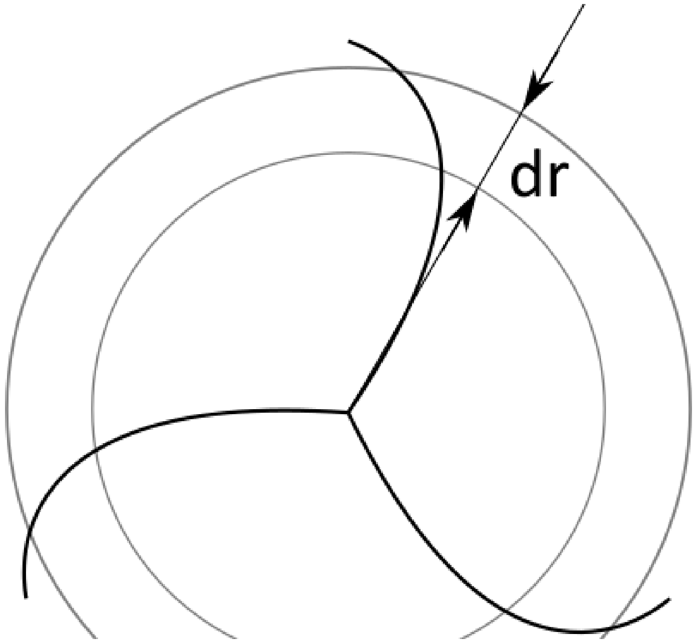
Generates lift that balances steady contribution from 1)

Effects of curved blades on blade element part

- Necessary projections of velocities into airfoil section
- Necessary projection of forces into the ‘rotor coordinates’ (in-plane, out-of-plane, radial)

- Typically forces are given per meter span
  – A correction factor ds/dr is necessary if the blade span is not following the rotor radius





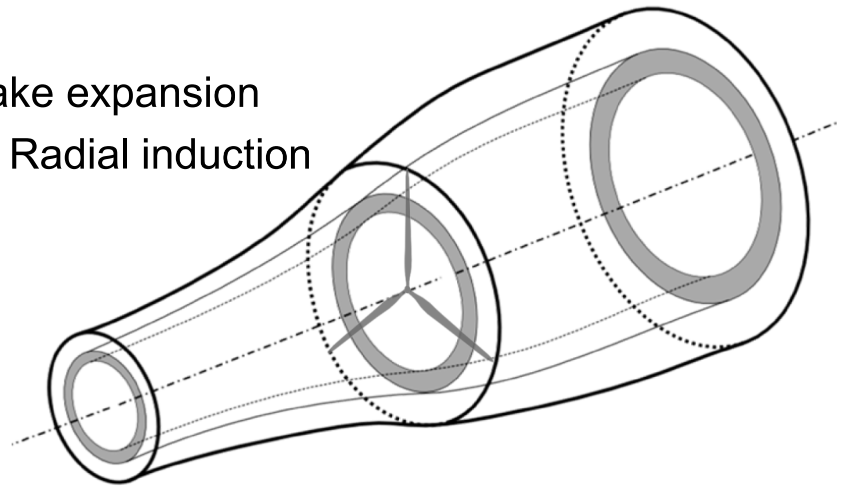
Effects of curved blades on blade element part

- Concluding: Solutions for the blade element part of BEM are there
  - BUT some details that are less important for straight blades become much more important for modern rotors
  - Worth double checking the implementations in aeroelastic tools

Effects of curved blades on momentum part

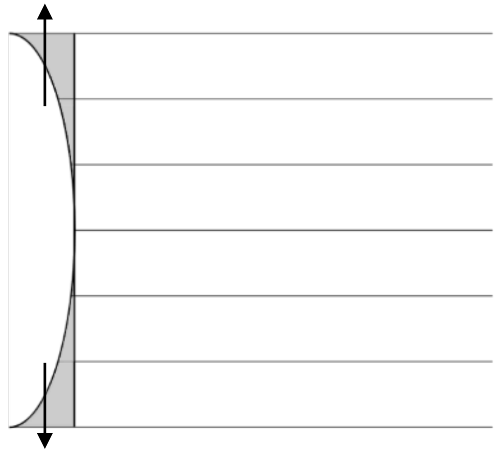
1) Sections are no longer radially independent
2) Radial induction becomes important

Wake expansion
=> Radial induction



[Adapted from E. Branlard]

Radial induction changes AoA for non-planar rotor



3) Curved bound vortex becomes important
4) Change of the tip vortex position relative to the rest of a swept blade

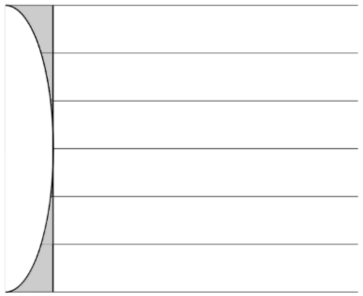
Effects of curved blades on induction

Near Wake model

- First ¼ revolution.
- Influence of sweep (in-plane shapes) on trailed vorticity

Cylinder Wake model

- Influence of winglet/prebend (out-of-plane shape) on trailed vorticity
- Radial induction

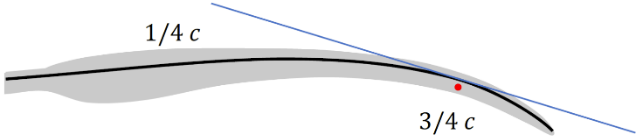


Far Wake model

- Based on a far-wake BEM model.

Curved Bound Vorticity

- Self induction of non-straight lifting lines

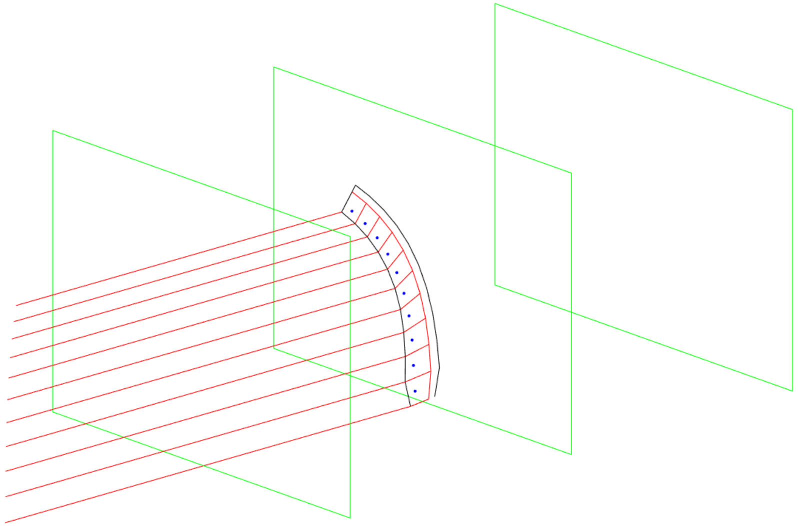


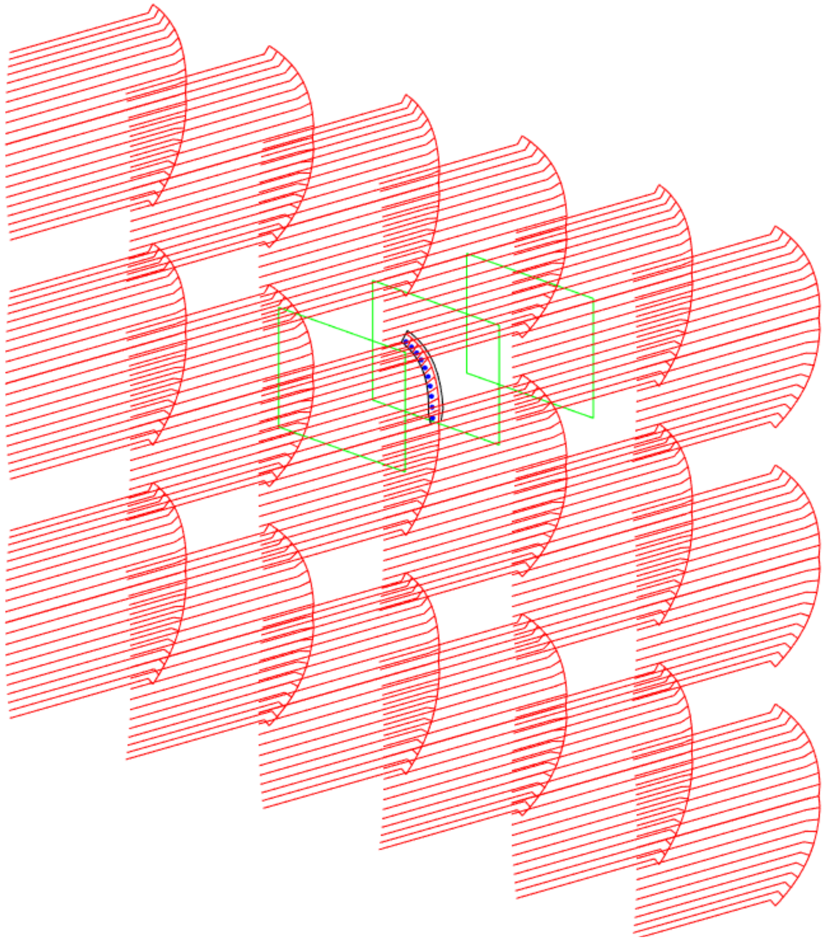
Experiments: Wind tunnel

1.65 meter tall swept tip designed and placed in poul la cour wind tunnel

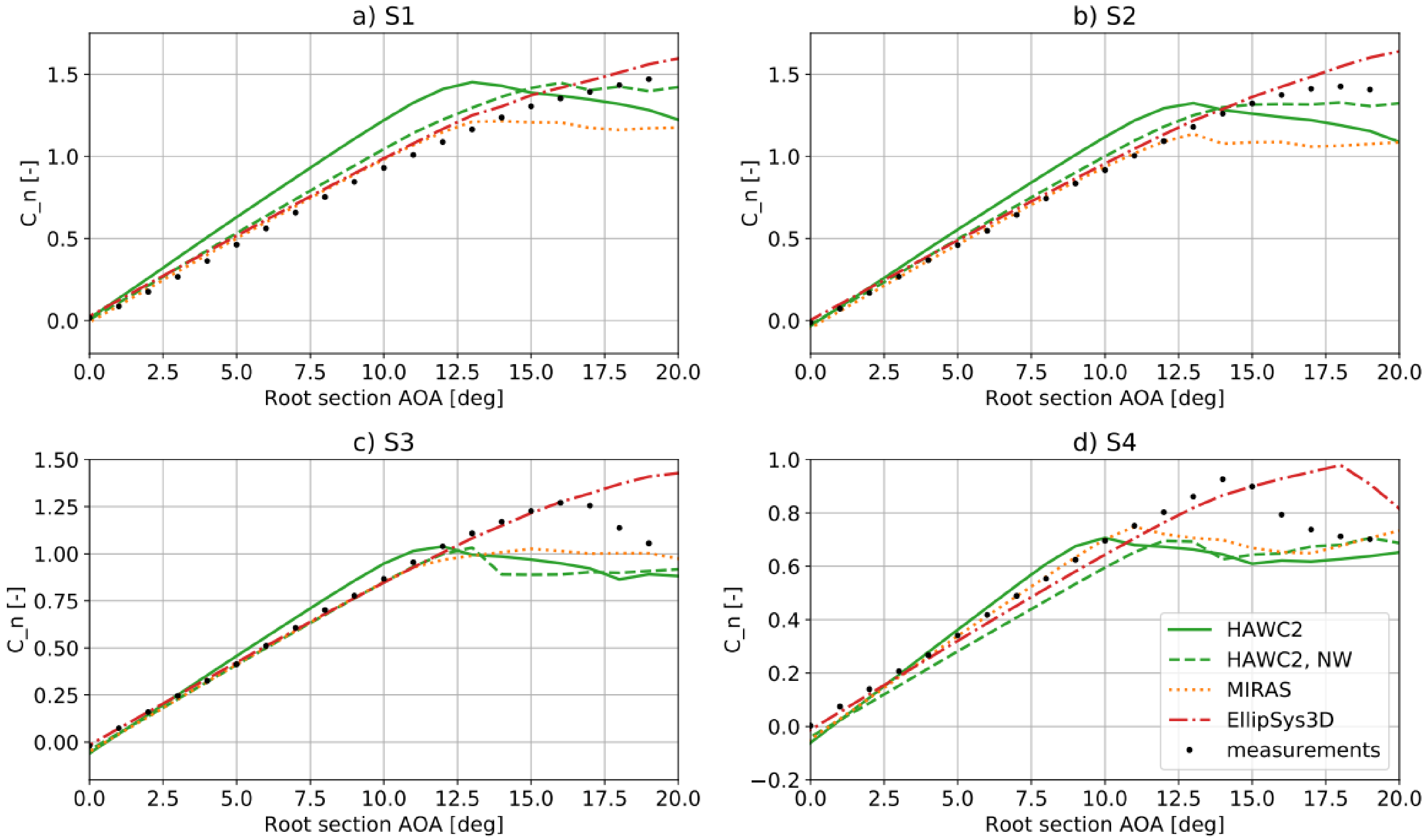
Experiments: Wind tunnel

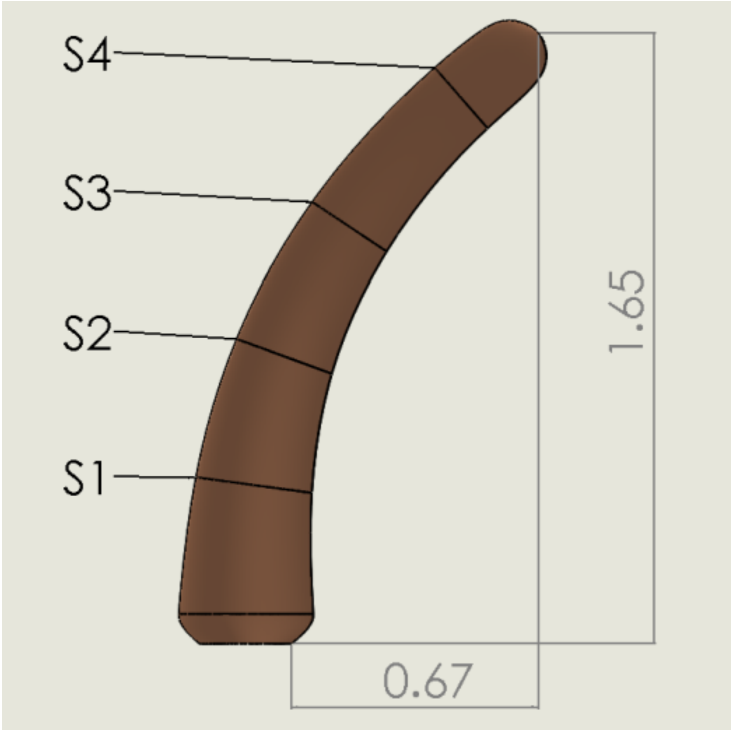
Estimation of tunnel effect





Experiments: Wind tunnel, clean configuration





Experiments: Rotating rig

- 3.5 m long swept tip section produced by Olsen Wings mounted on rotating test rig
- Test campaign done, detailed evaluation of measurements ongoing

Conclusions

- BEM theory needs to be used carefully for curved blades
  - The Blade Element part needs to be implemented correctly
    - Projection of forces and velocities is crucial
    - Some terms that vanish for straight blades become important
    - Can lead to errors in power and thrust
  - The Momentum part needs to be modified or replaced
    - Radial induction becomes important
    - Simplified vortex models can improve accuracy

- Experiments are necessary to evaluate engineering models and CFD
  - Some steps in this direction are made
  - Detailed aerodynamic measurements on real rotors are crucial in the future

- There are other cases where BEM theory doesn’t apply, such as stand still

References

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