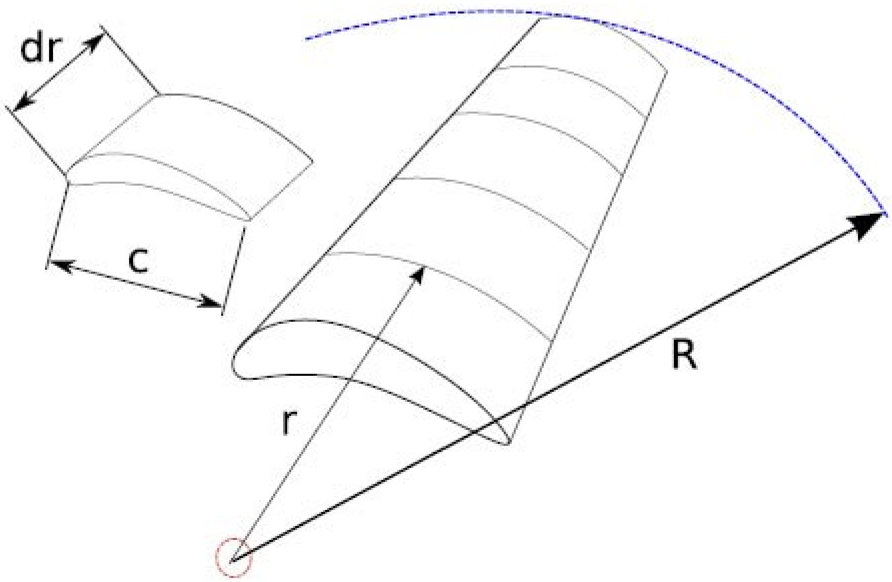
Design of Wind Energy Systems



[University of Strathclyde]

CIP Tutorial 02
Hints for Advanced BEM – Theory corrections

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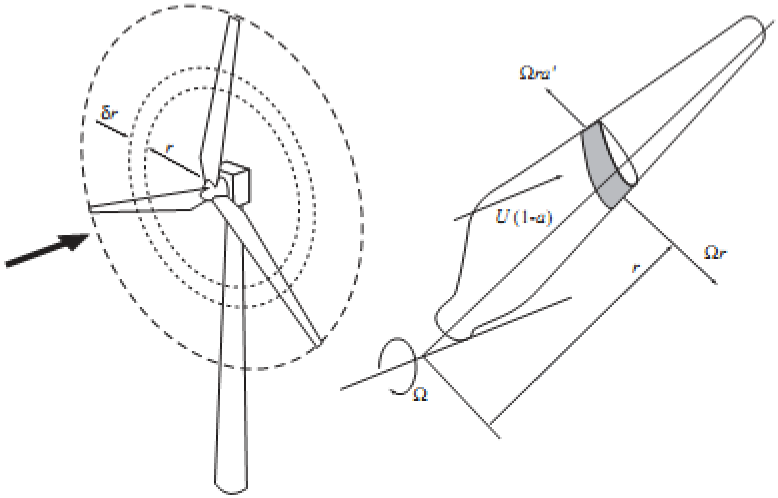
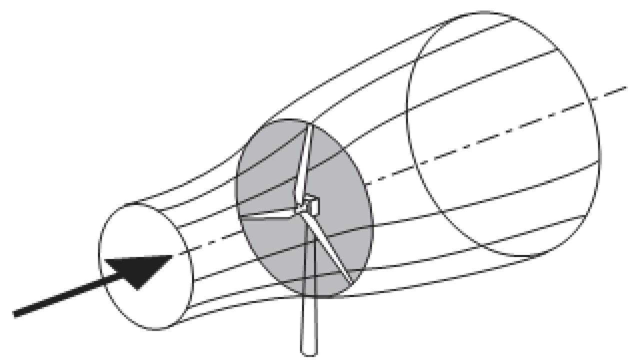
ForWind – Wind Energy Systems

Topics

- Basics of Blade Element Momentum Theory
- Advanced BEM Theory – Corrections
  - Neglected effects of the BEM
  - Influence of finite number of blades
  - 3D effects
- Influence of moment coefficient



Section I: Basics of Blade Element Momentum Theory

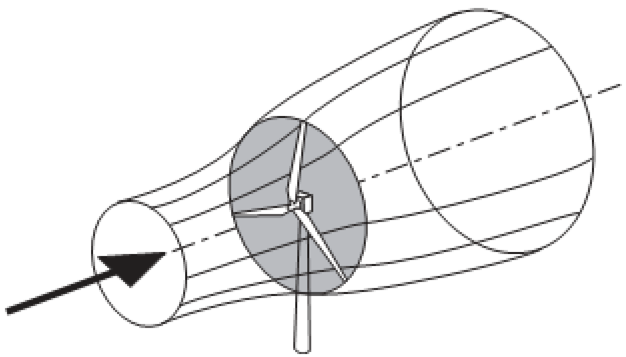


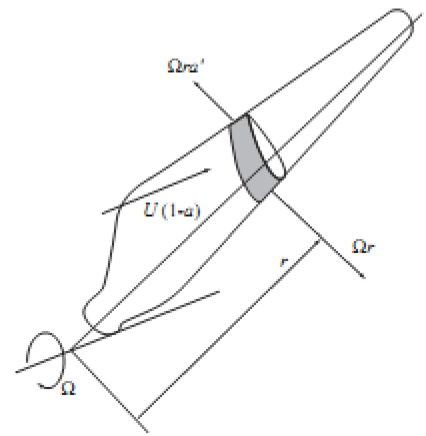
[Wind Energy Handbook]

Blade Element Momentum theory

Basic idea: Balance of forces in axial (and tangential) directions

Forces from global momentum balance (dependent on induced velocity)	=	Forces at the local blade element (dependent on induced velocity)



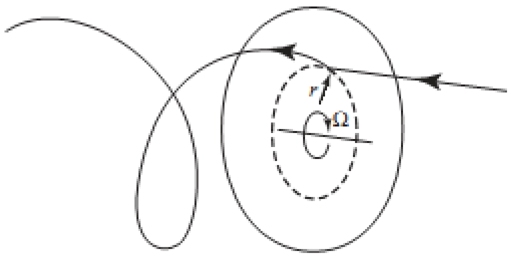


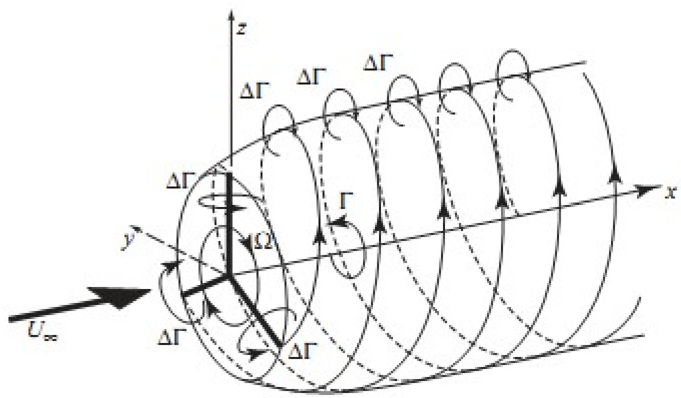
[Wind Energy Handbook]

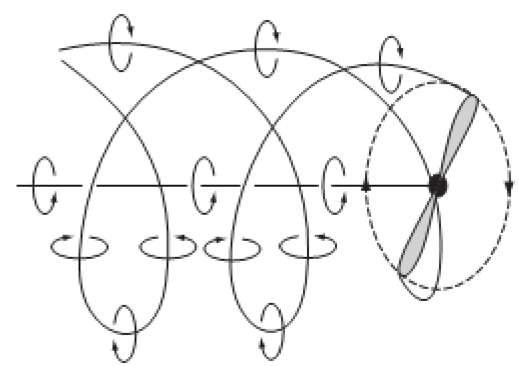
Summary of BEM

- Equilibrium of momentum balance with local forces on blade elements
- Unknown variables “induction factor” and “inflow angle” are dependent on each other -> iteration necessary
- Assumptions:
  - No radial interaction
  - No radial flow
  - No tangential differences in annuli

Section II: Advanced Blade Element Momentum Theory





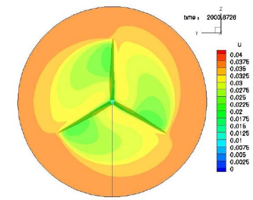


[Wind Energy Handbook]

Neglected Effects

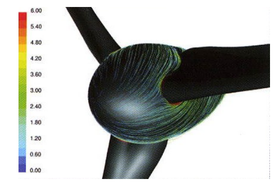
- Wake rotation
- Non-uniform induction factor over rotor disk
- Finite blade length
- Hub
- Stream tube blockage
- 3D effects
- Dynamics
- Yawed inflow

[Riso]

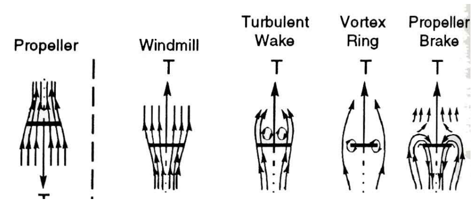


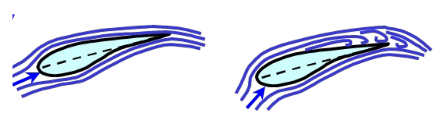
[Streiner]

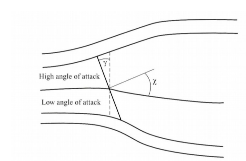
[www.bionik.tu-berlin.de]



[Enercon]



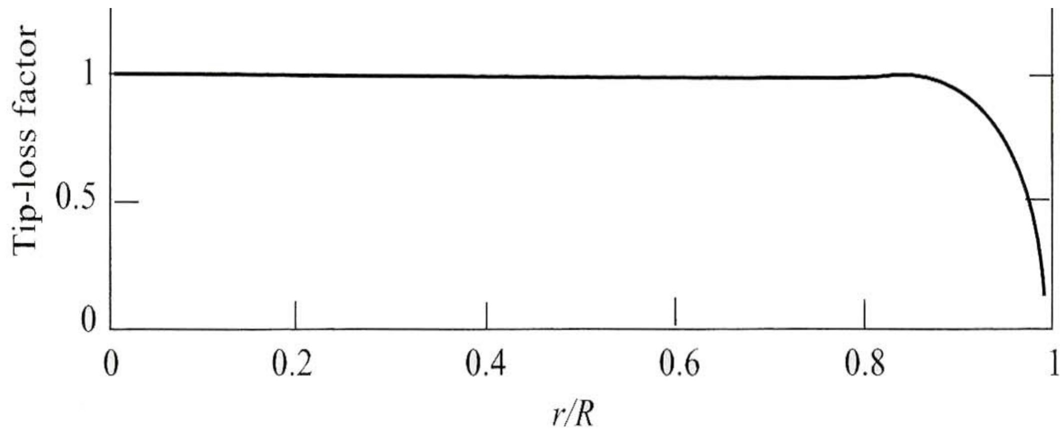




1. Influence of finite number of blades

- finite number of blades does not affect the whole rotor area
  => no constant induction within annulus
- Influence depends on
  - inflow angle α
  - arc length between blades *(2 π r)/N*
- Correction of thrust and torque
  as a function *F* (α, *N*, *r)* the so-called Prandtl tip-loss factor

$$F_{Tip} = \frac{2}{\pi}\cos^{-1}\left[\exp\left\{\frac{-N/2(1-r/R)}{(r/R)\sin\alpha}\right\}\right]$$



[Fig. Wind Energy Handbook]

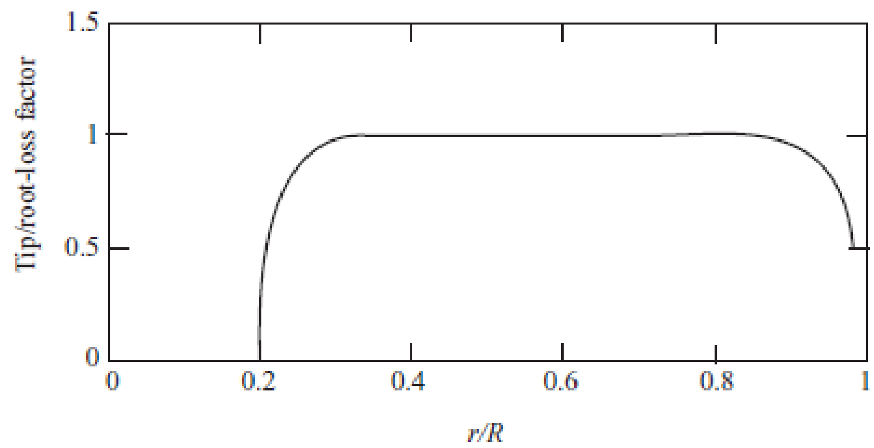
1. Influence of finite number of blades

- Flow circulation at the root must fall zero (analogous to the tip)

$$F_{Root} = \frac{2}{\pi}\cos^{-1}\left[\exp\left\{\frac{-N/2\left(1-r_R/r\right)}{\sin\alpha}\right\}\right]$$

- Tip- and root loss combined lead to an overall loss factor

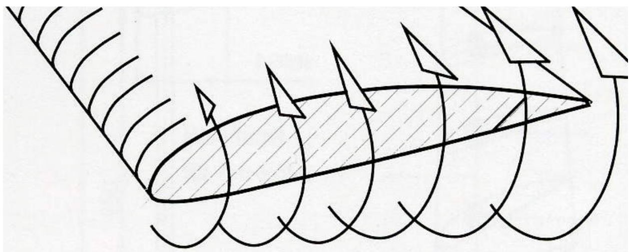
$$F = F_{Root} \cdot F_{Tip}$$



[Fig. Wind Energy Handbook]

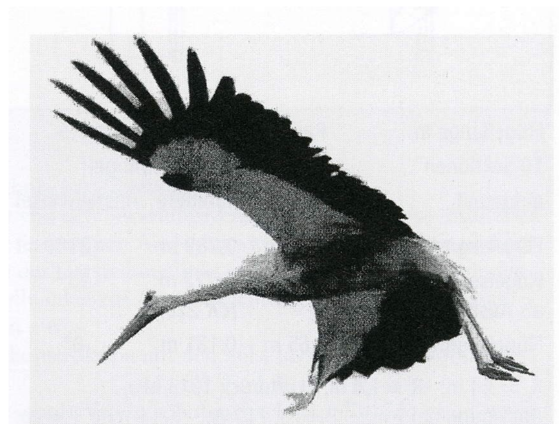
1. Comment concerning the flow at the blade tip

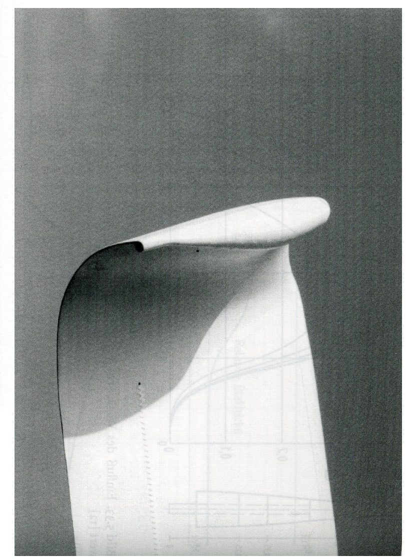
- Blade tip flow (induced drag) not directly considered by blade element momentum theory
  => Panel theory with vortex model required
  => indirect consideration by Prandtl‘s tip-loss factor



flow at blade tip
from pressure- to suction-side

- optimisation by blade geometry a
  and sometimes by winglets
  (compare Enercon)





winglet in nature (top)
and on rotor blade (right)

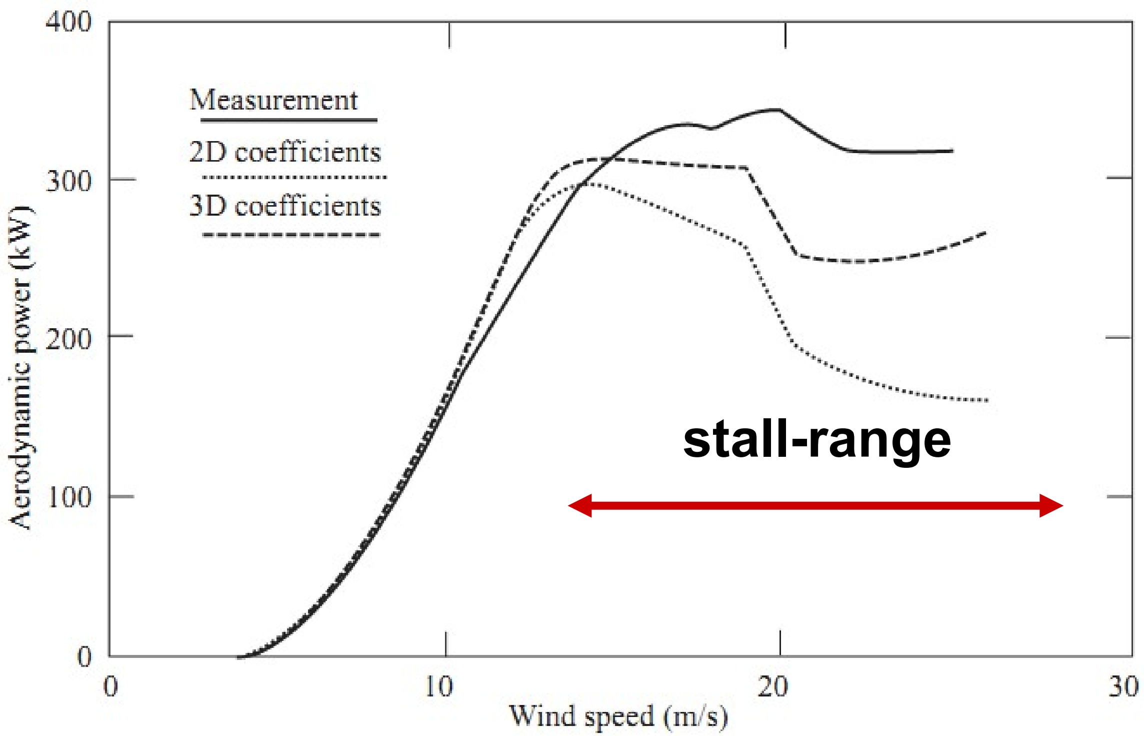
[Fig. Crome, Crome, Hau]

2. Influence of three-dimensional (3D-) effects
3D-correction especially relevant for stall turbines

Problem:
Stall turbines sometimes show significant higher power in stall range compared to calculations with basic theory

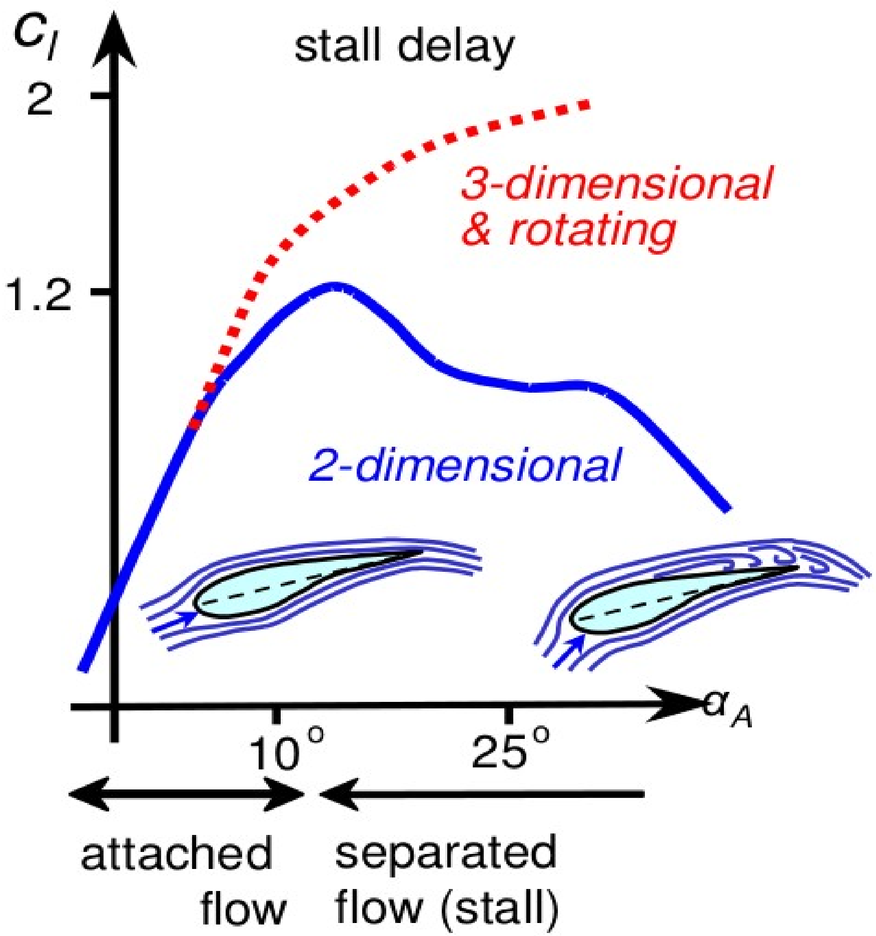
(Semi-)empirical solution:
Correction of the airfoil coefficients, which are measured in wind tunnel experiments two-dimensional (2D-) models

Example: application of Snel's model to measurements



[Fig. Wind Energy Handbook]

2. Example for three-dimensional (3D-)effects



- 3-dimensional:
  finite blade length & rotation
- 2-dimensional:
  wind tunnel

Attention:
Airfoil coefficients often only measured for αA ≈ – 10o to ≈ 20o
=> empirical or „estimated“ extension for ± 180o to consider starting and storm conditions

2. Example for 3D corrections

- Approximation

$$c_{l,3D} = c_{l,2D} + f_{c_l} \cdot \Delta c_l$$

$$c_{d,3D} = c_{d,2D} + f_{c_d} \cdot \Delta c_d$$

where Δcl is the difference between stalled and potential lift coefficient $2\pi(\alpha_A - \alpha_0)$

and Δcd is the difference between minimum drag and actual drag

according to Snel (1994): $f_{c_l} = 3\left(\frac{c}{r}\right)^2$

according to Chaviaropoulos und Hansen (2000):

where αtwist= local blade twist angle

$$f_{c_l}, f_{c_d} = 2.2\left(\frac{c}{r}\right)\cos^4(\alpha_{twist})$$

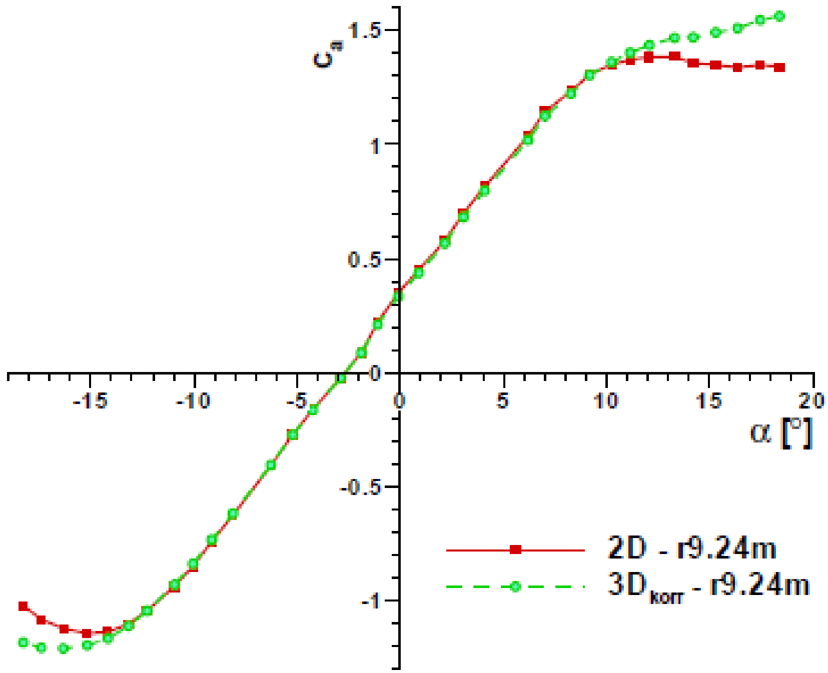
- Approximation according to Snel and Lindenburg (2003):

$$c_{l,3D} = c_{l,2D} + 3.1 \cdot \left(\frac{\Omega r}{((1-a)v_1)^2 + ((1+a')\Omega r)^2}\right)^2 \left(\frac{c}{r}\right)^2 \left(2\pi(\alpha_A - \alpha_0) - c_{a,2D}\right)$$

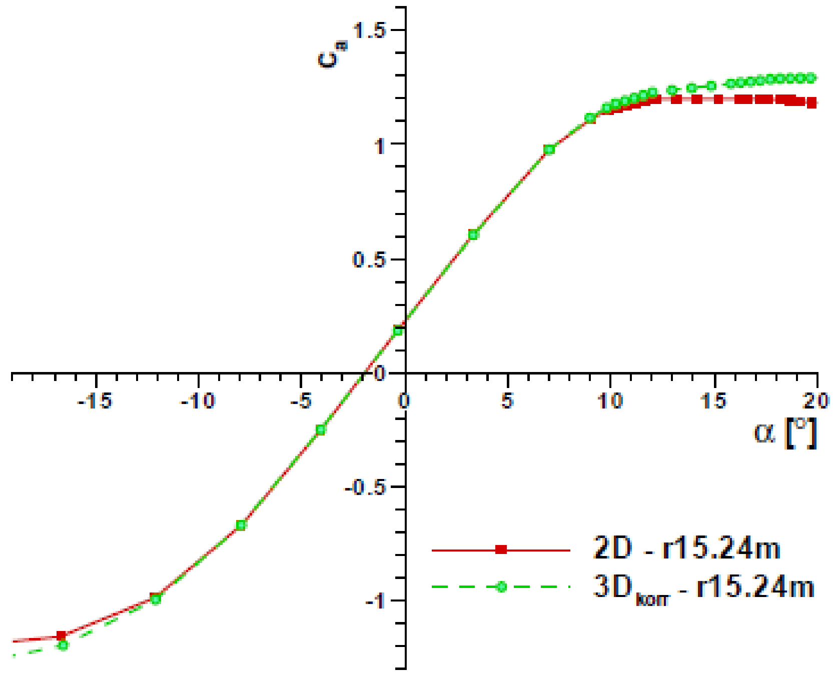
where αA= inflow angle at blade element

α0= zero lift angle

2. Lift-curves 3D corrected



lift-curve at r/R=~23%

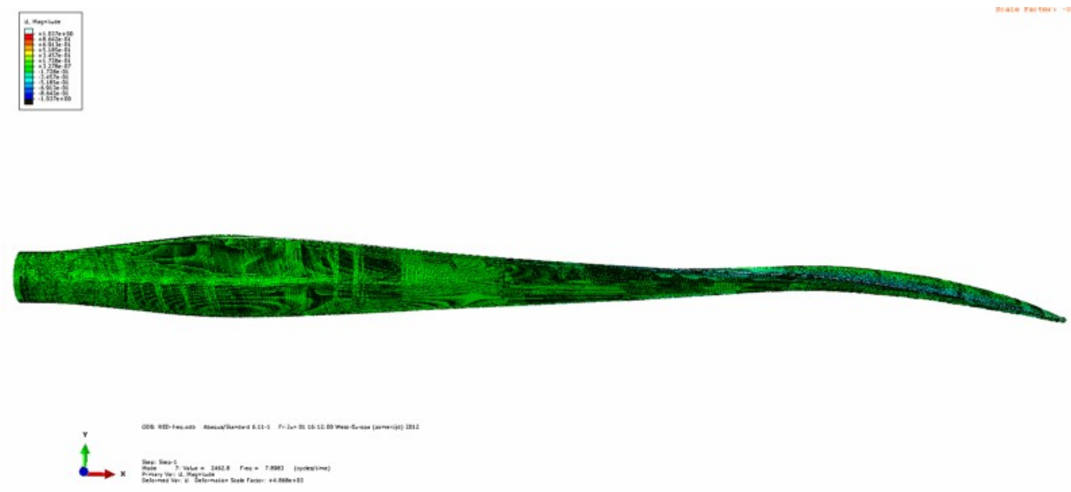


lift-curve at r/R=~38%

[Fig. Streiner]

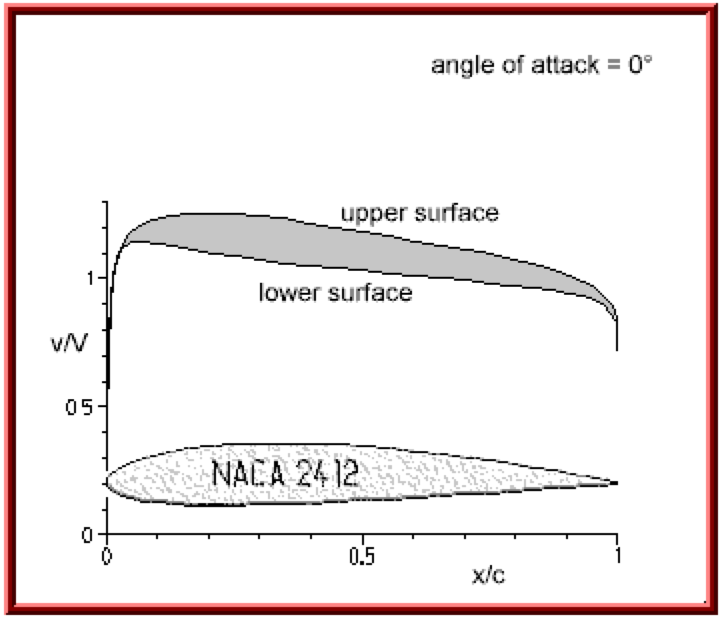
Approximation according to Snel and Lindenburg

Section III: Influence of the moment coefficient

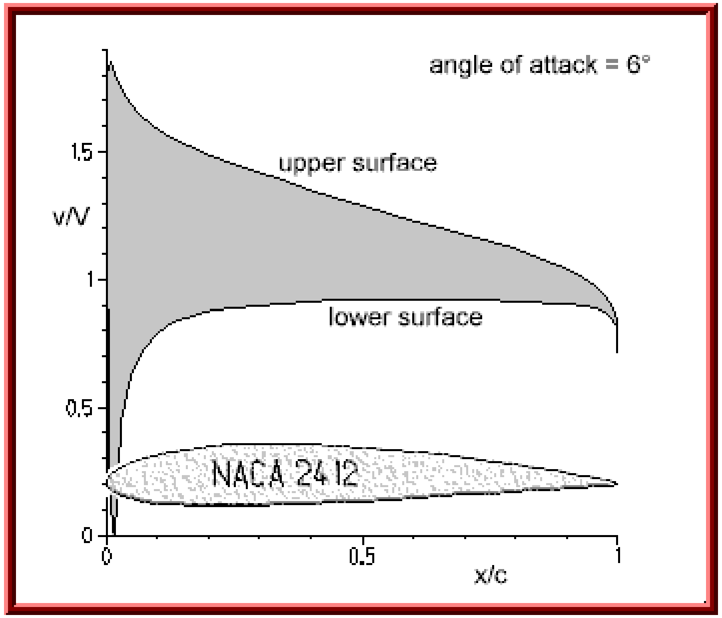


[University of Gent]

Pressure, lift and moment



[mh-aerotools]



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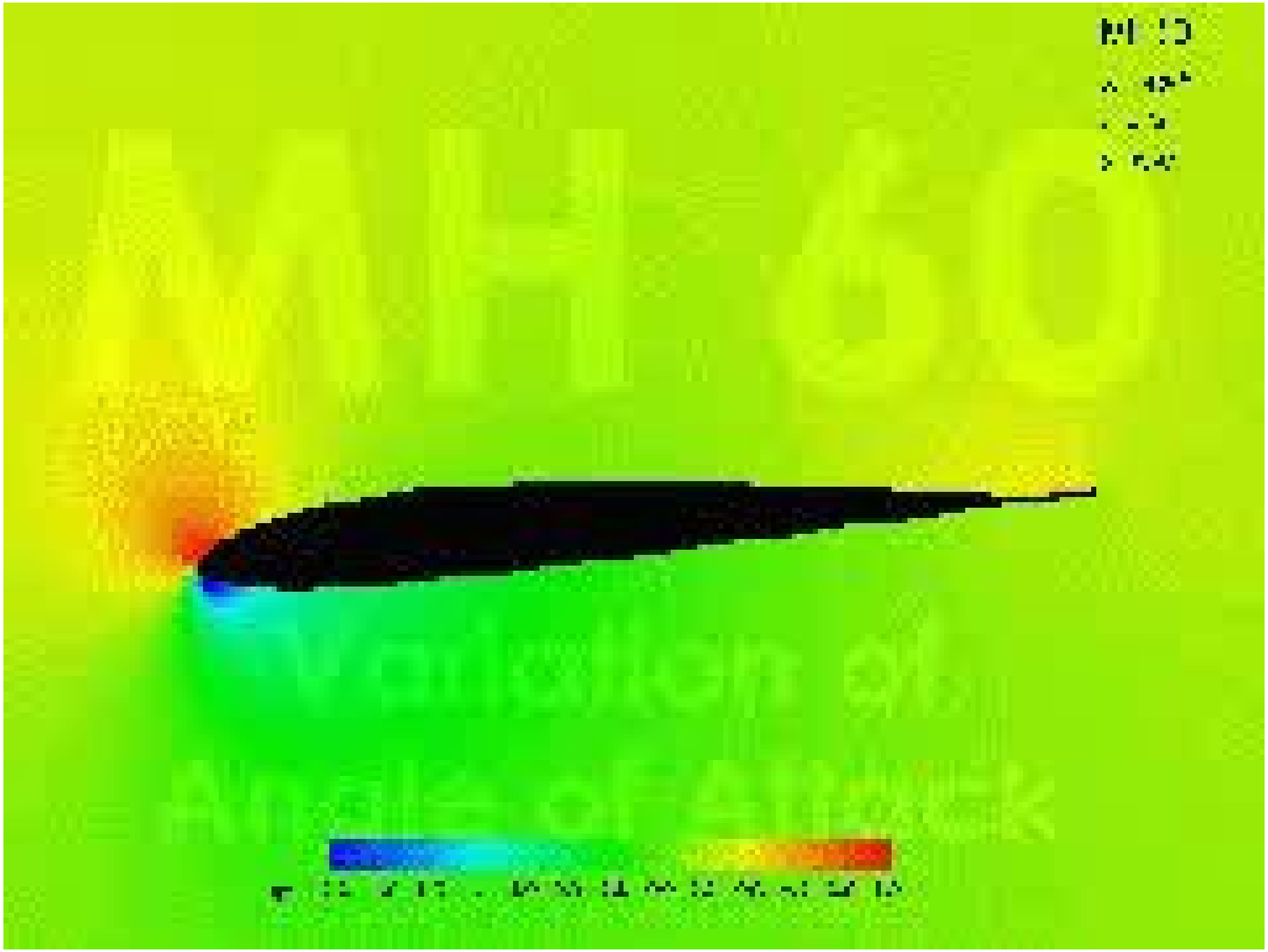

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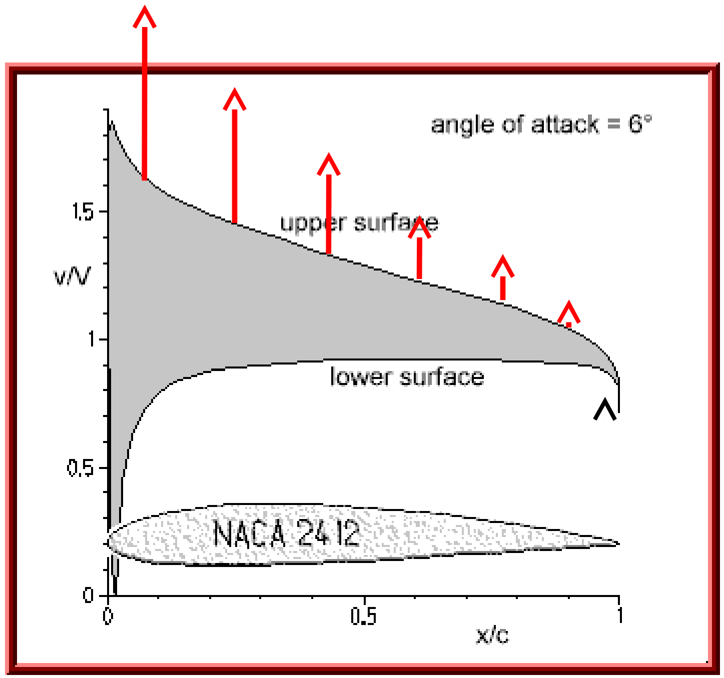
Pressure, lift and moment



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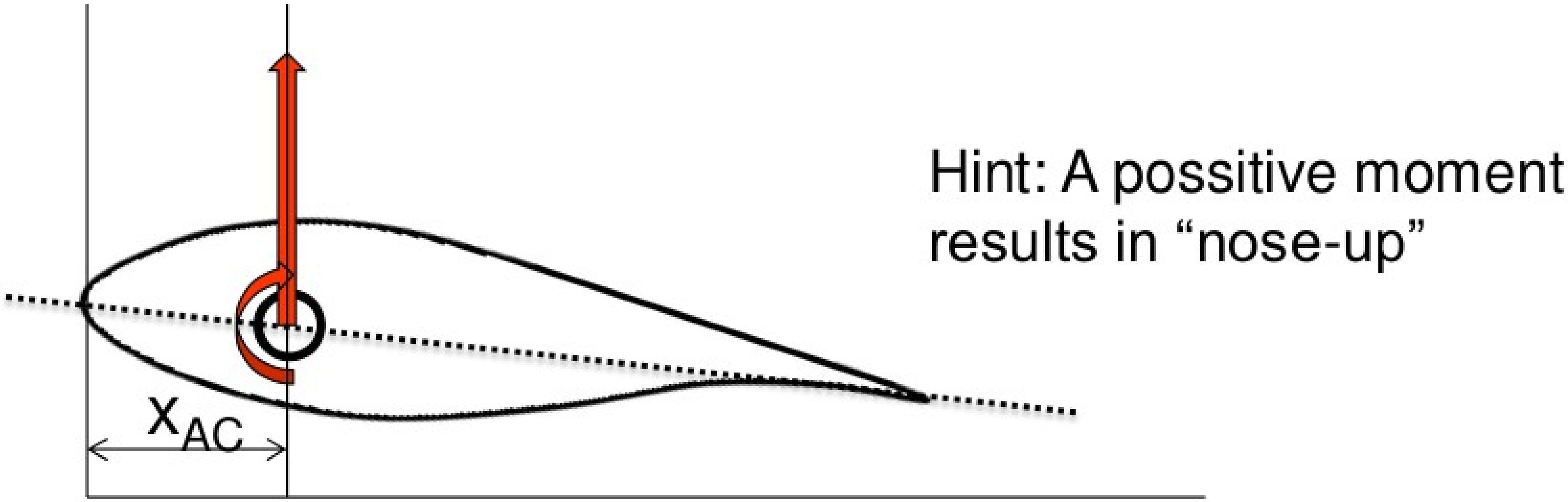
Pressure difference between upper and lower side results in forces

The unequal distribution of forces along the chord leads to a moment. Calculation similar to lift and drag forces with dynamic pressure, area and chordlength

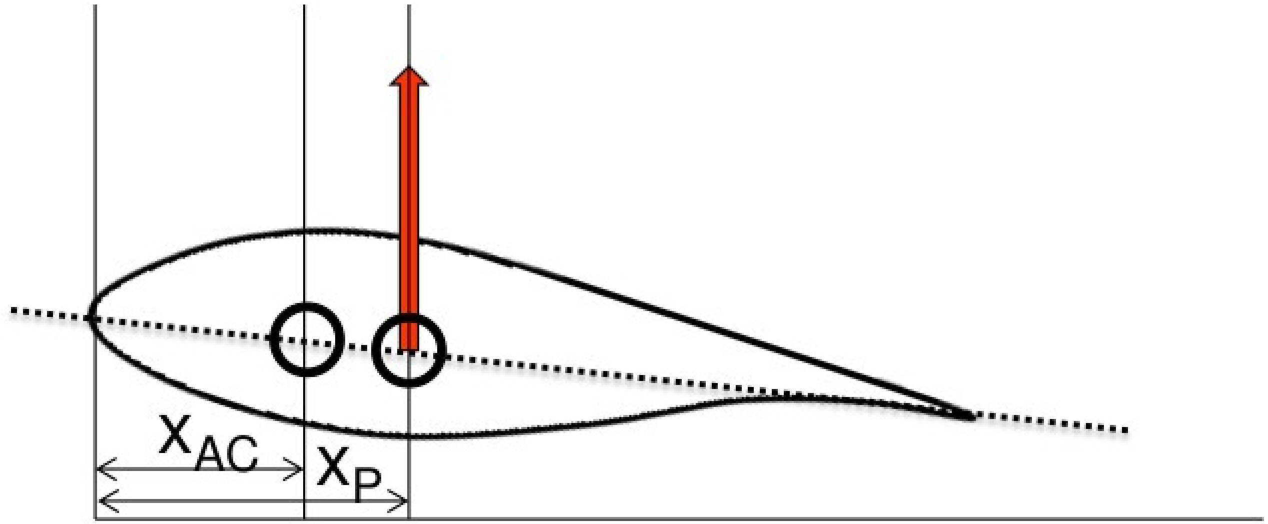
Aerodynamic center



“The aerodynamic center is the point, where **the moment is not changed** in case of an increasing or decreasing lift coefficient”

For thin profiles below stall for low wind speeds, the aerodynamic center is found at ¼ of the chord

Pressure center



"The pressure center is defined as the point, where the **<u>moment is equal to zero</u>**"

The position of the pressure center changes with the angle of attack

Summary / Conclusions

- We recall basic concepts of BEM theory
- We enumerated some of its limitations
- We described some corrections of BEM theory
- We reviewed the concept of moment coefficient