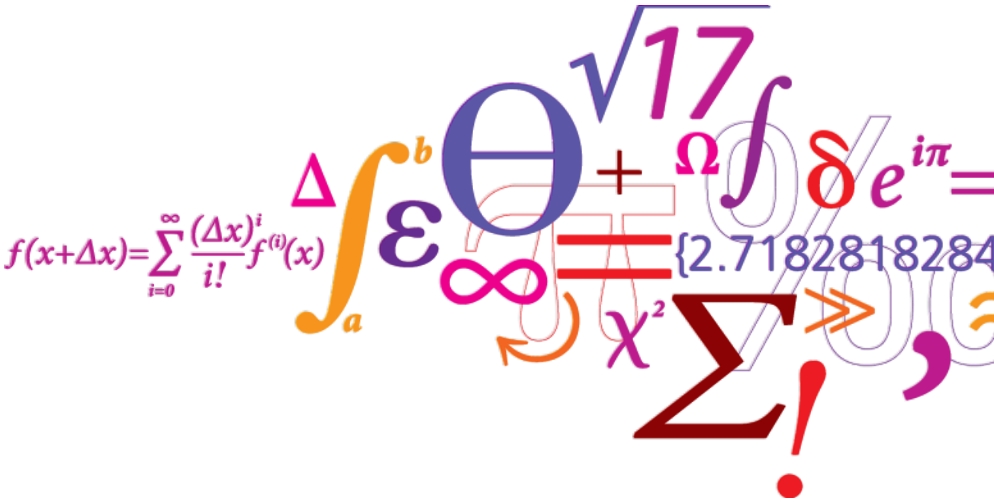
HAWC2 course

Lesson 3(b): Airfoil Section 2D Aerodynamics

Peter Bjørn Andersen



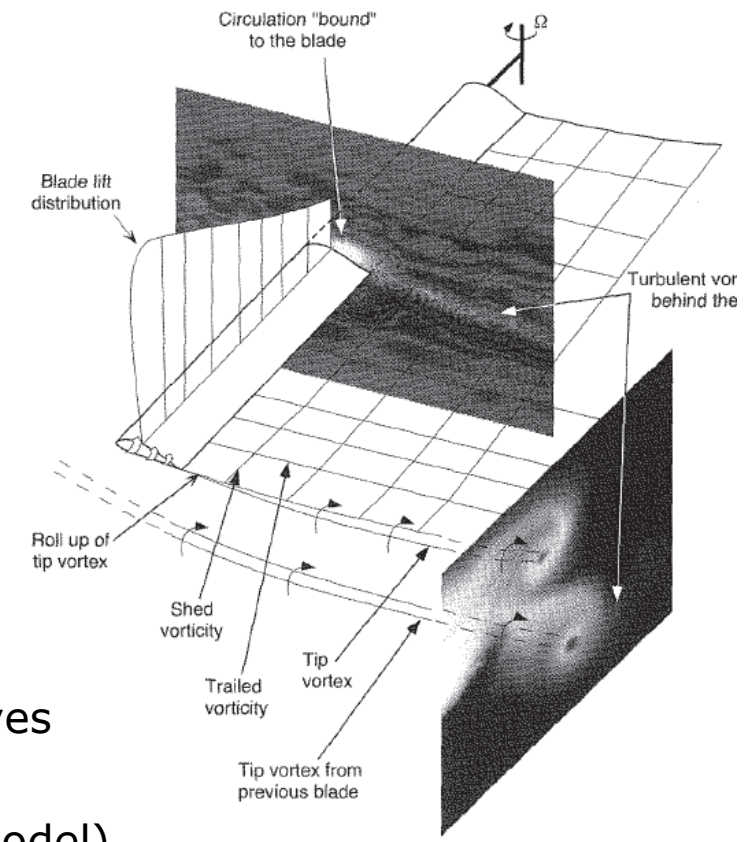
DTU Wind Energy
Department of Wind Energy

Agenda

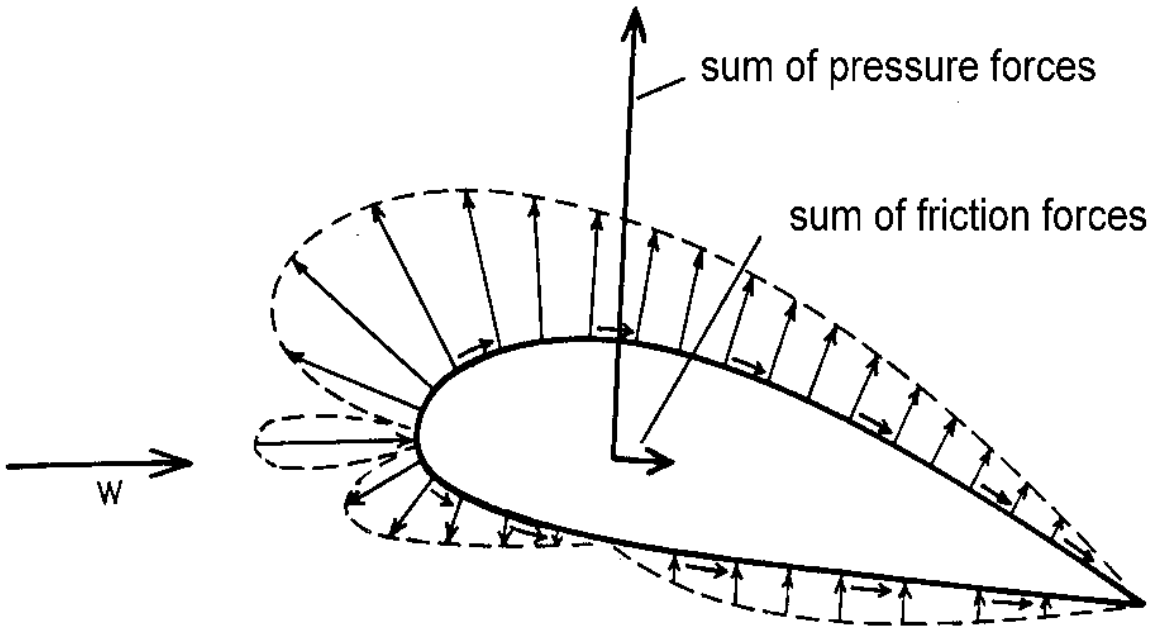
- **Rotor Aerodynamics**
  - Introduction
  - 1D momentum theory and BEM
  - BEM and induction model in HAWC2
  - Tip loss and yawed inflow corrections
  - Dynamic inflow

- **2D Aerodynamics**
  - Introduction
  - Aerodynamic forces and profile steady curves
  - Attached flow dynamics (indicial function)
  - Flow separation dynamics (dynamic stall model)

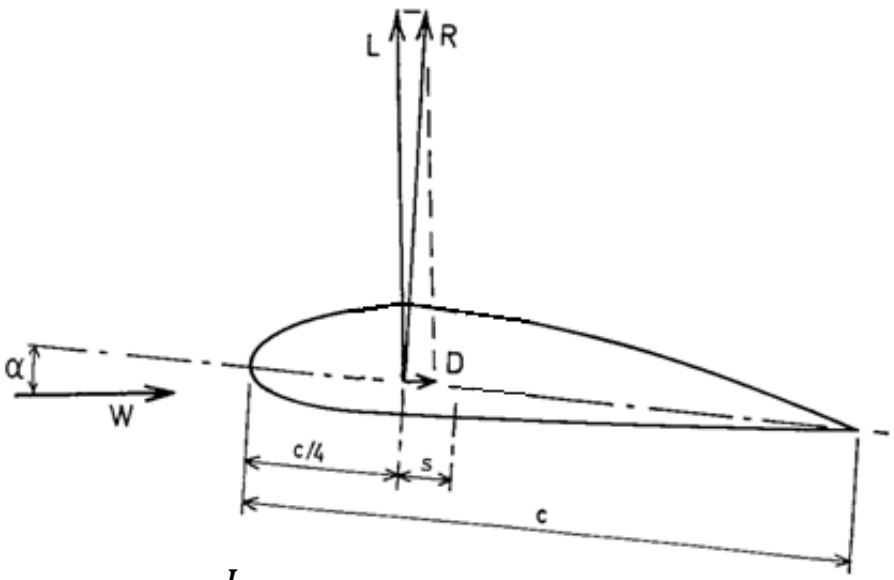
- **HAWC2 Aerodynamics; step 1-6**
  - **Small Exercise**: "Power up your turbine"



2D profile aerodynamics



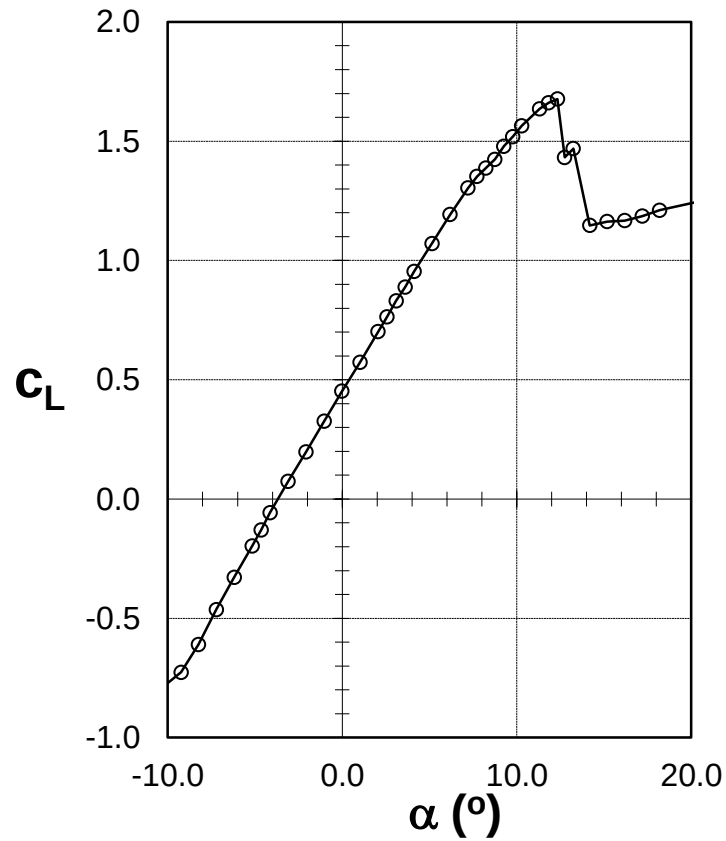
2D profile aerodynamics



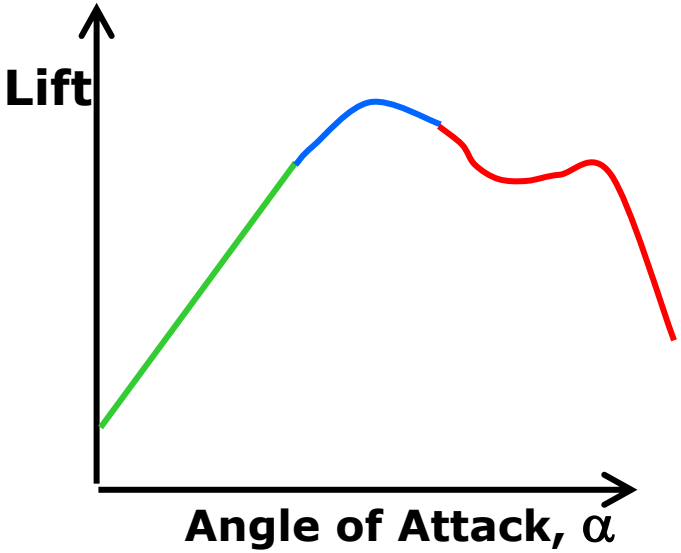
$$C_L = \frac{L}{1/2\,\rho c W^2}$$

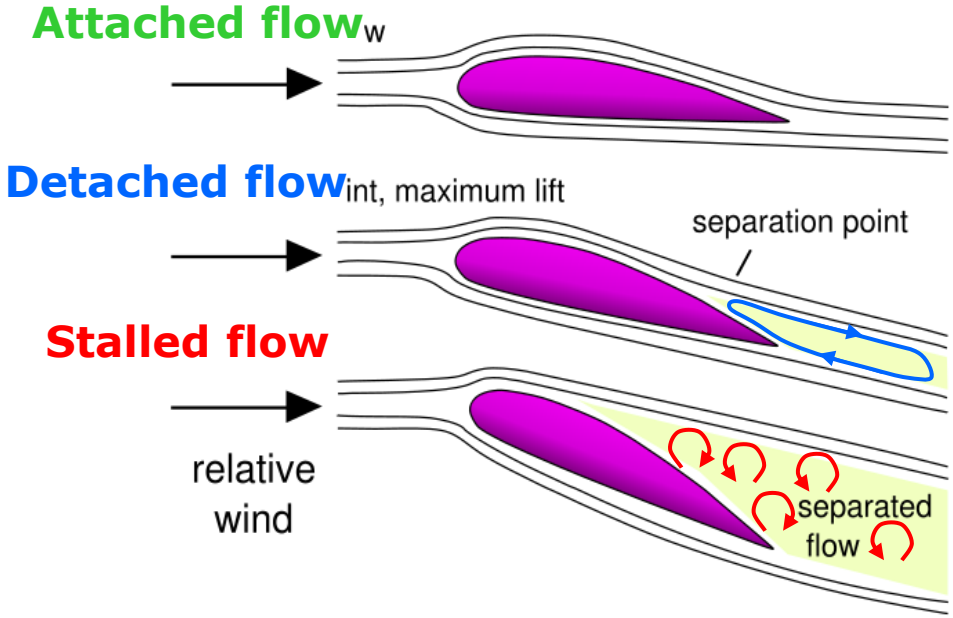
$$C_D = \frac{D}{1/2\,\rho c W^2}$$

$$C_M = \frac{M}{1/2\,\rho c^2 W^2}$$

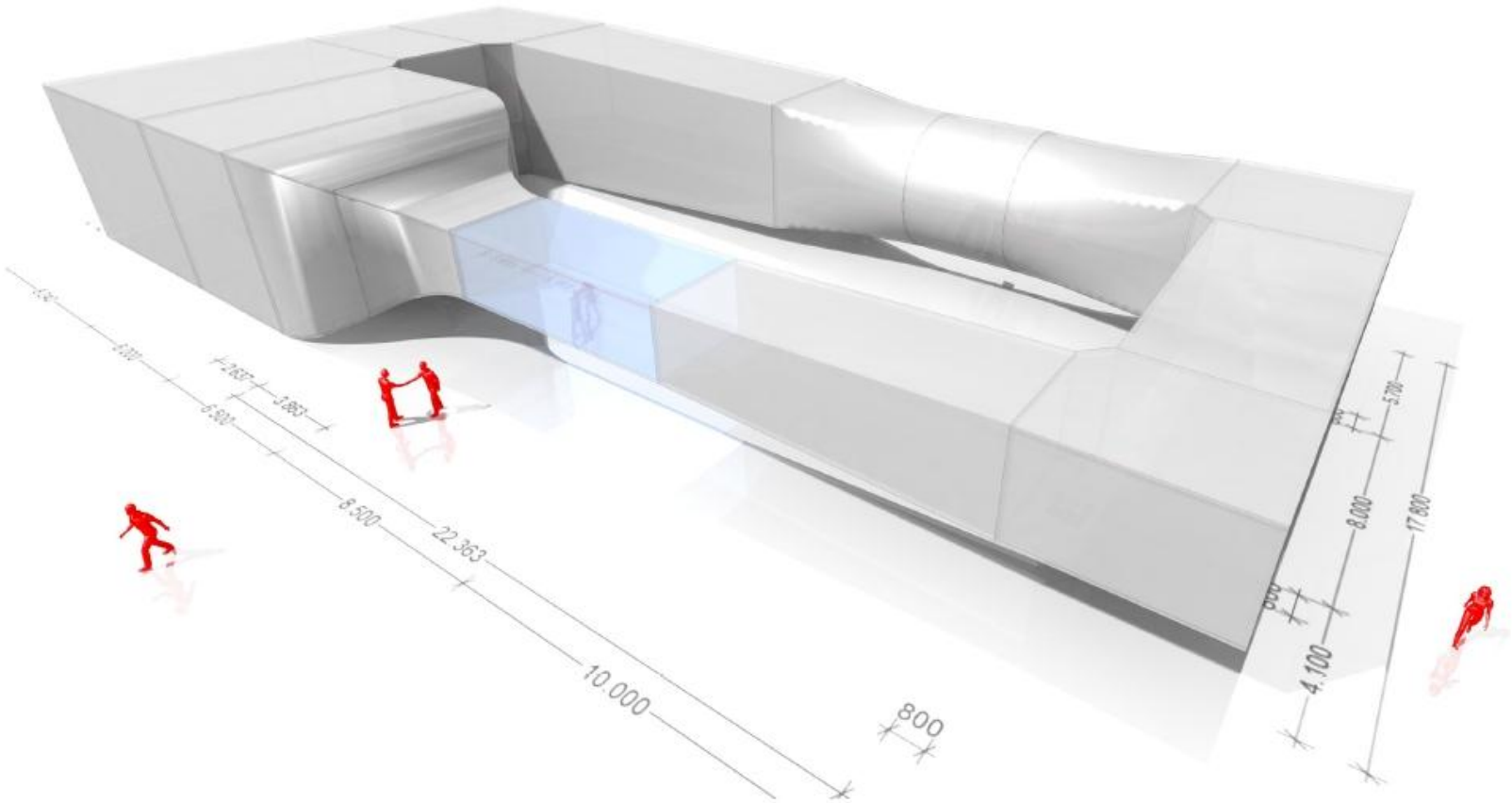


2D profile aerodynamics





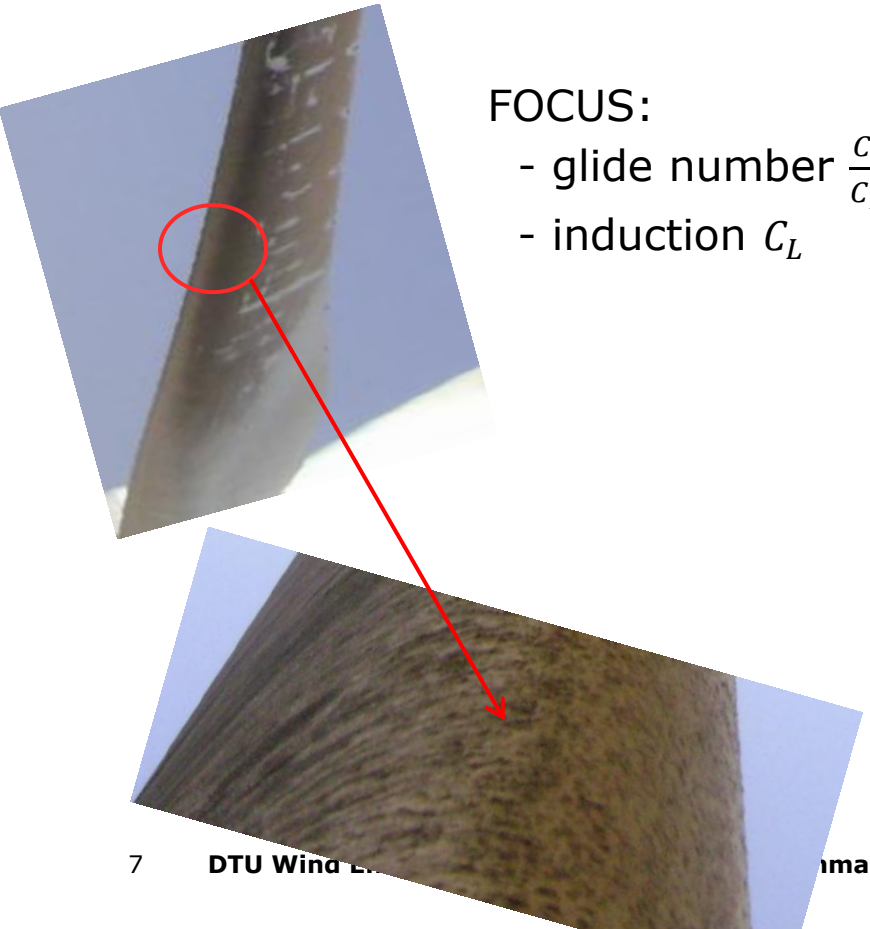
2D profile aerodynamics, new wind tunnel



2D profile aerodynamics, in real life

$C_{L,D,M} = C_{L,D,M}(\alpha, \text{Re, Mach})$

$C_{L,D,M} = C_{L,D,M}(\text{dirt, age, paint, environment, site, ice, turbulence, …})$



FOCUS:

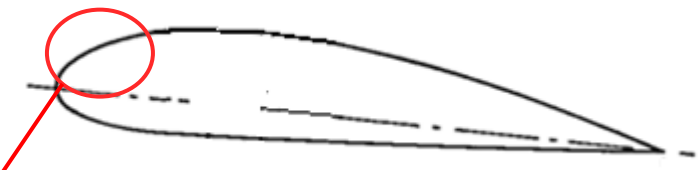
- glide number $\frac{C_L}{C_D}$
- induction C_L

Picture with courtesy of Egyptian WT operator

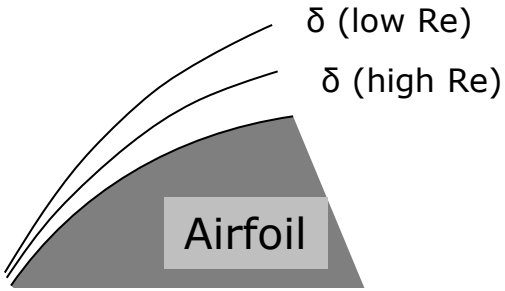
Profile coefficients: Re corrections

”Low” wind speed, low Re

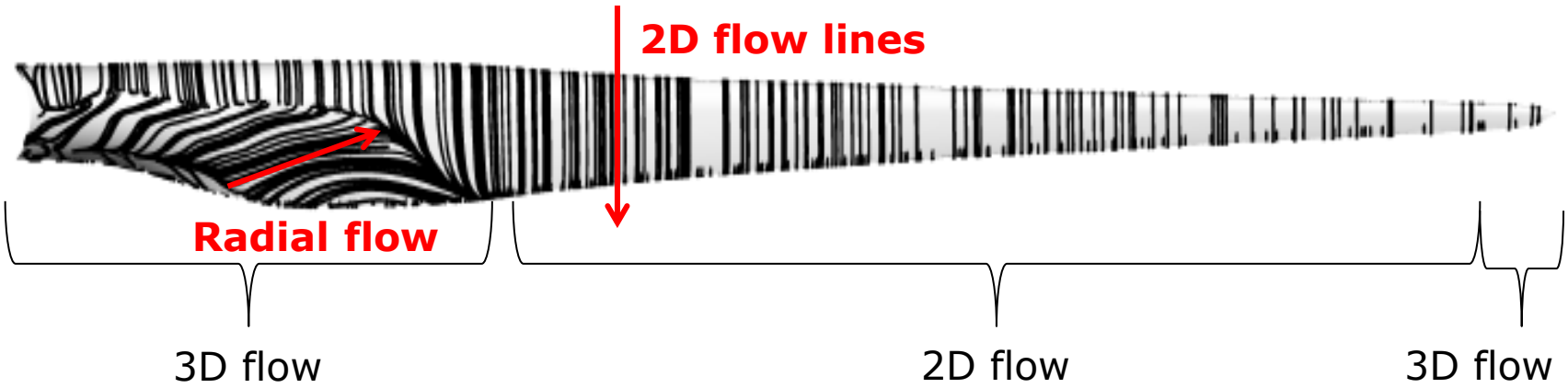
”High” wind speed, high Re



Effect on the laminar and turbulent boundary layer growth and size along with laminar to turbulent transition



Profile coefficients: 3D corrections



Some useful references:

- B. Montgomerie, *Methods for root effects, tip effects and extending the angle of attack range to +-180 deg, with application to aerodynamics for blades on wind turbines and propellers.* FOI - Swedish Defence Research Agency, 2004, URL: http://www2.foi.se/rapp/foir1305.pdf
- C. Lindenburg, *Investigation into Rotor Blade Aerodynamics*. 2003, URL: www.ecn.nl/publications/PdfFetch.aspx?nr=ECN-C--03-025
- S.-P. Breton, F. N. Coton, and G. Moe, "*A study on rotational effects and different stall delay models using a prescribed wake vortex scheme and NREL phase VI experiment data*," Wind Energy, vol. 11, no. 5, pp. 459-482, 2008, doi:10.1002/we.269

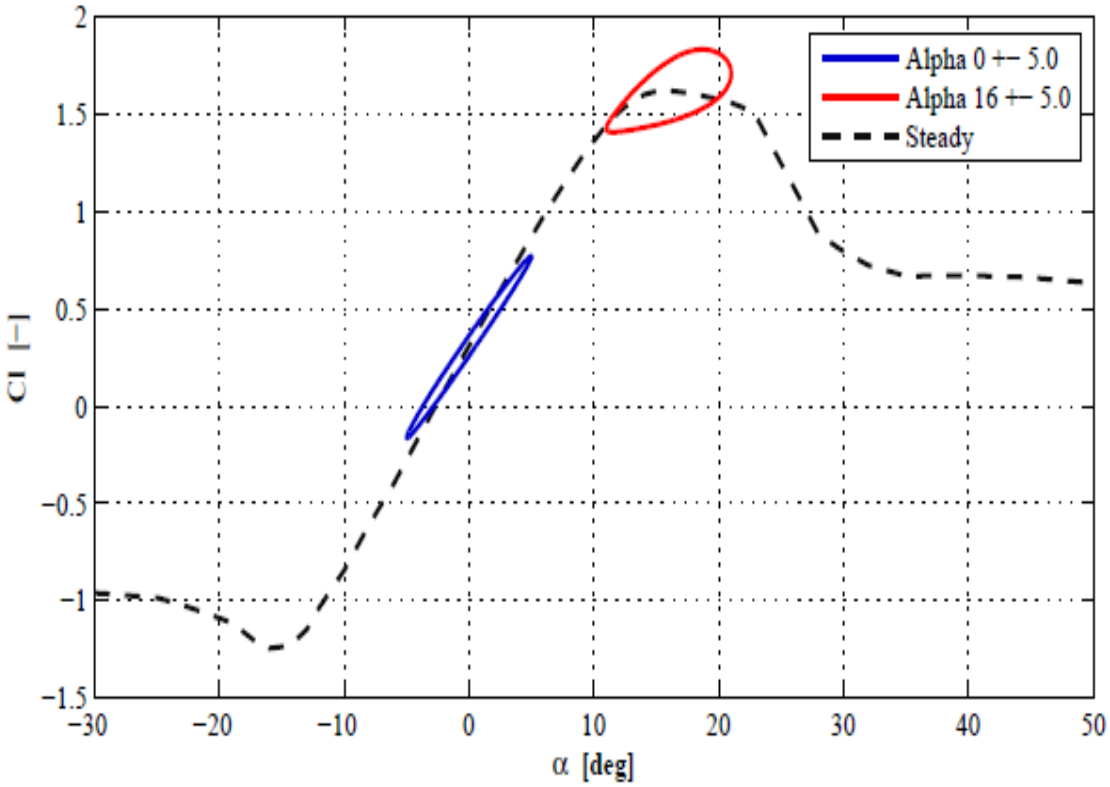
2D aerodynamic models in HAWC2

- ***Attached flow***

  Memory effects of vorticity shed into the wake.

- ***Flow separation*** *(dynamic stall)*

  Dynamics of the boundary layer, delay in flow separation.

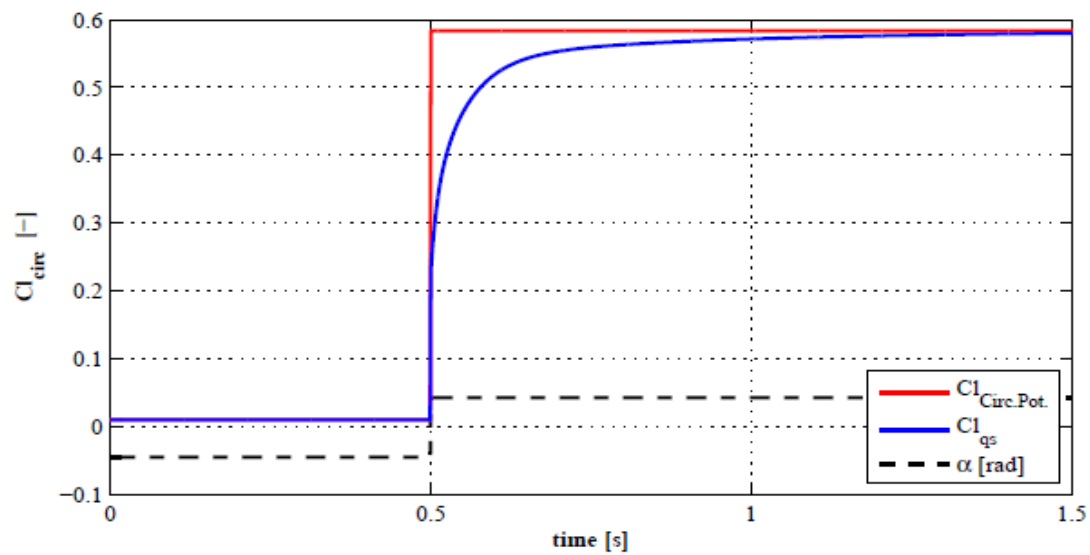


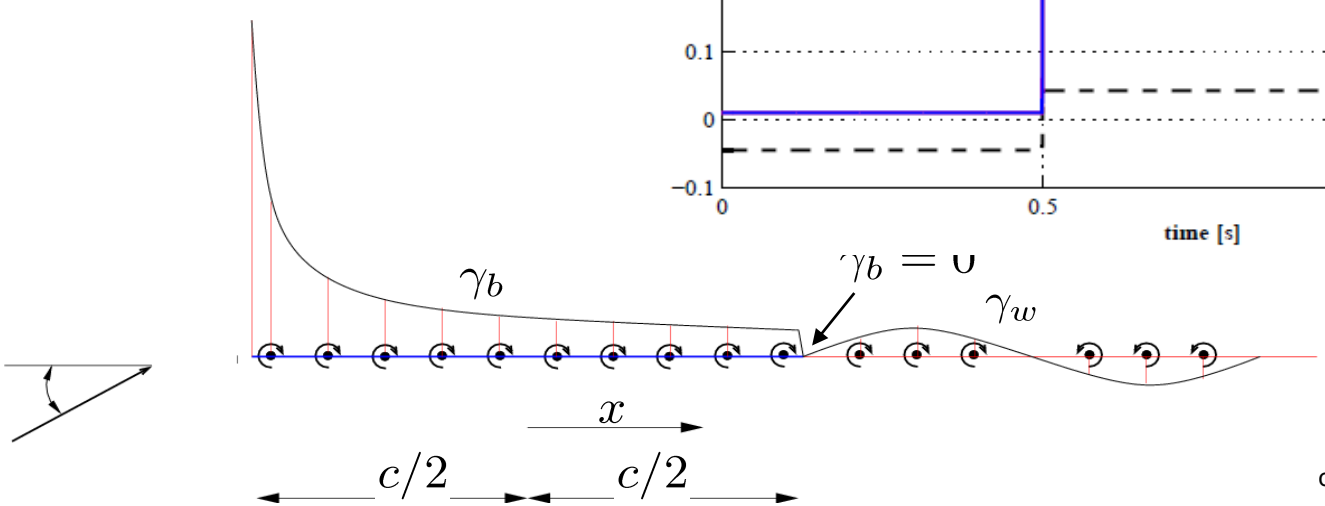
Attached flow dynamics

- Classic formulation (Von Karman and Sears):

  Lift = Quasi-Steady term + *Lift* deficiency + Non Circ. term

- Lift deficiency: effects of vorticity in the wake

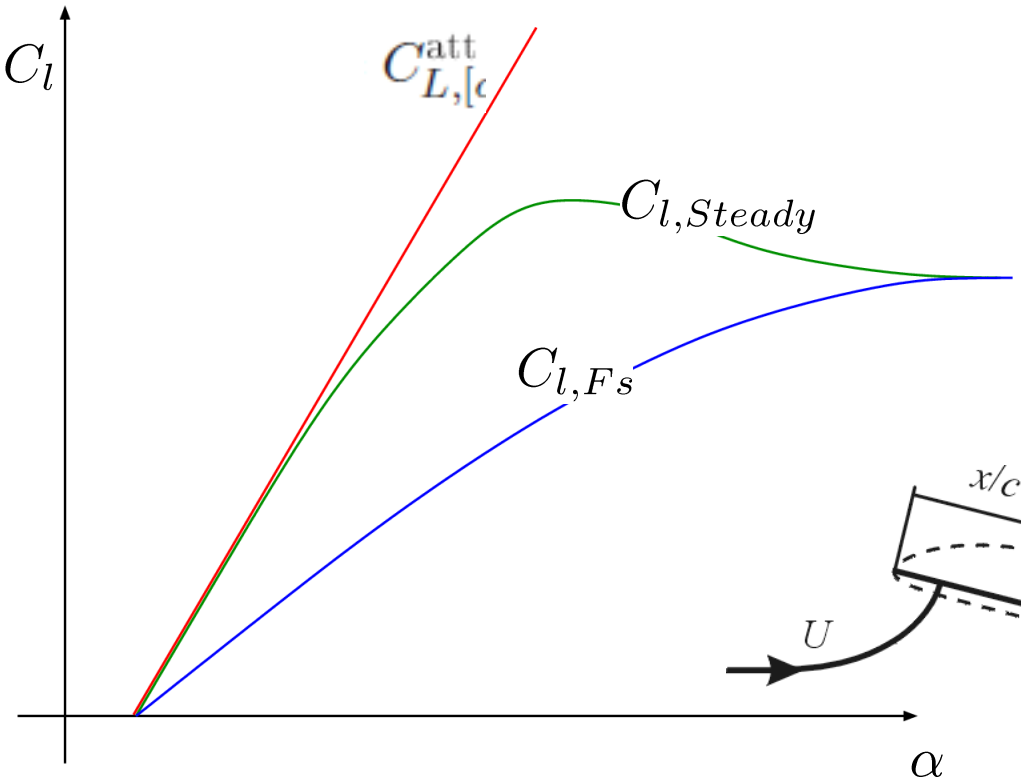




Dynamic stall model

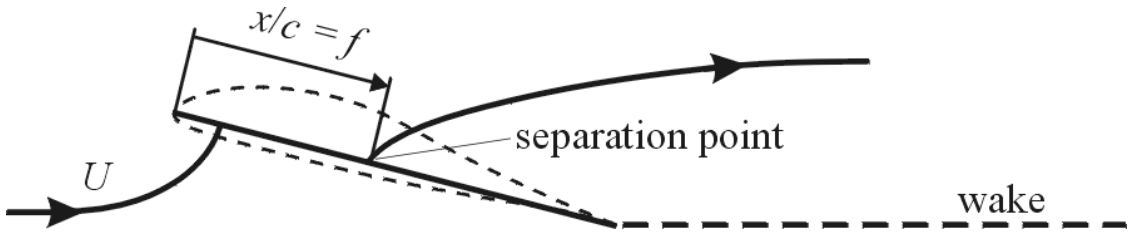
- Lift as weighted sum:

$$C_L^{\mathrm{Circ.Dyn}} = C_{L,[\alpha_{\mathrm{eff}};\beta_{\mathrm{eff}}]}^{\mathrm{att}} f^{dyn} + C_{L,[\alpha_{\mathrm{eff}};\beta_{\mathrm{eff}}]}^{\mathrm{fs}} \left(1 - f^{dyn}\right)$$



- Cl^{att} and Cl^{fs} computed from steady input data.

- Dynamics from weight, separation function *f*



2D aerodynamic models: references

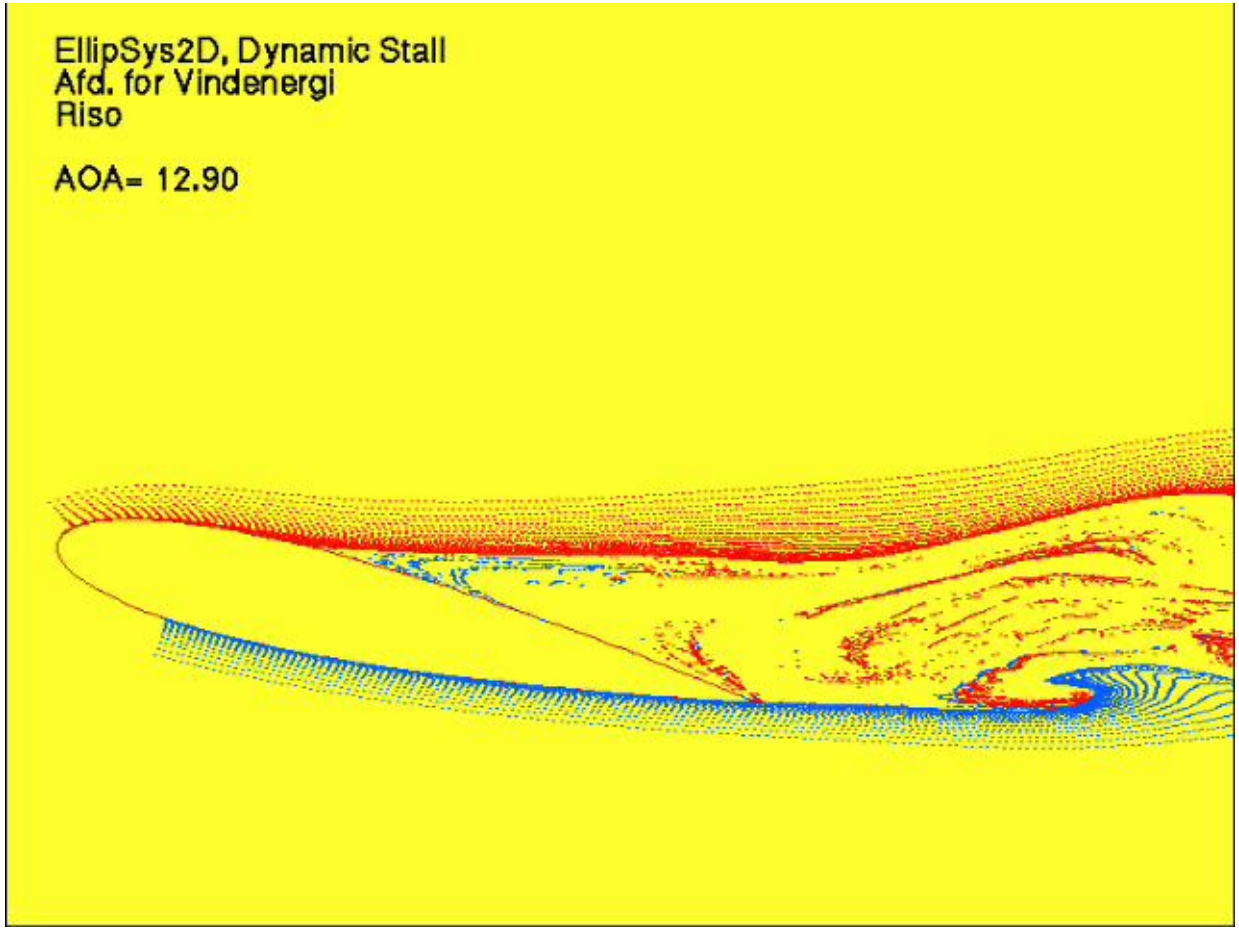
- Larsen, Torben Juul. *How 2 HAWC2 the User's Manual*. R-1597(EN). Risø National Laboratory. Technical University of Denmark, 2009.

- Larsen, J.W., S.R.K. Nielsen, and S. Krenk. 'Dynamic Stall Model for Wind Turbine Airfoils'. *Journal of Fluids and Structures* 23, no. 7 (October 2007): 959–982.

- Hansen, Morten Hartvig, Mac Gaunaa, and Helge Aagaard Madsen. *A Beddoes-Leishman Type Dynamic Stall Model in State-space and Indicial Formulations*.

  R-1354(EN). Risoe National Laboratory, Roskilde (DK), 2004.

- Bergami, Leonardo, and Mac Gaunaa. *ATEFlap Aerodynamic Model, a Dynamic Stall Model Including the Effects of Trailing Edge Flap Deflection*.

  R-1792(EN). Roskilde, Denmark: Risoe¸ National Laboratory. Technical University of Denmark, February 2012.

CFD visualization