HAWC2 course

Lesson 3(b): Airfoil Section 2D Aerodynamics

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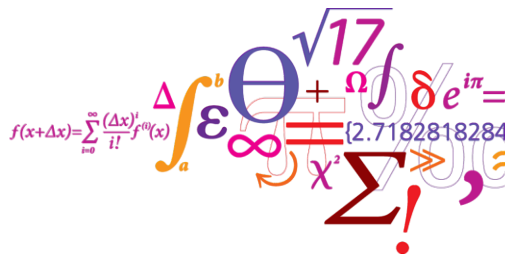
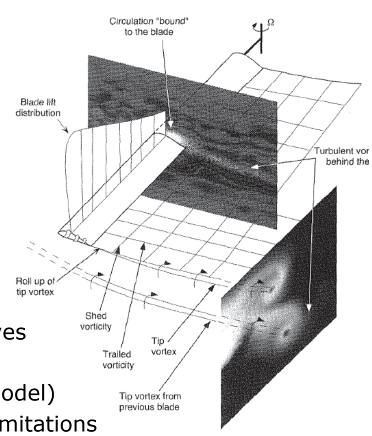


DTU Wind Energy
Department of Wind Energy

Agenda

What we have seen / what we will see…



- **Rotor Aerodynamics**
  - 1D momentum theory and BEM
  - BEM and induction model in HAWC2
  - Tip loss and yawed inflow corrections
  - Dynamic inflow
- **2D Aerodynamics**
  - Where does the aerodynamic come from
  - Aerodynamic forces and profile steady curves
  - Attached flow dynamics (indicial function)
  - Flow separation dynamics (dynamic stall model)
  - Aerodynamic models in HAWC2 and their limitations
- **Small Exercise**: "Power up your wind turbine"

What is aerodynamics, where does it come from?

Aerodynamics

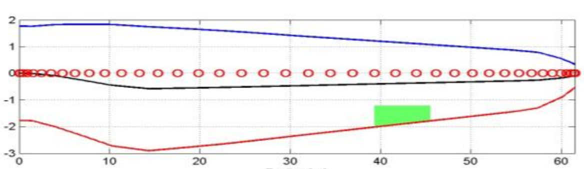
A branch of dynamics that deals with the motion of air and with the forces acting on bodies in motion relative to such fluids.

[Merriam-Webster]

Question:

Which components of the WT are the main responsible for aerodynamic effects?

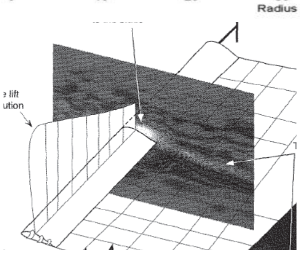
How to describe a blade in Hawc2



Discretize into *aerosections*

Commands (ref. manual):

- `aerosections` OR
- `aero_distribution`

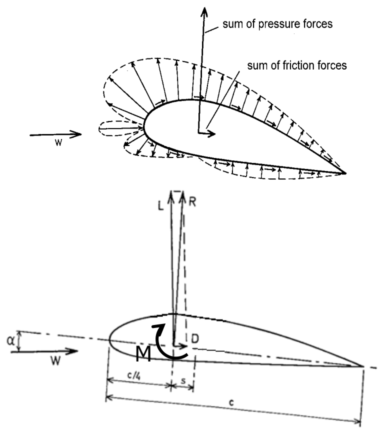


Aerodynamic forces:

- Computed at each aerosection.
- Each aero section is independent (BEM)
- Simplifies to:

Aerodynamics of a 2D airfoil section

2D profile aerodynamics



Interaction of 2D profile with fluid in motion:

- Lift
- Drag
- Pitching moment

All applied at ¼ chord point

Question:

How can we describe the profiles on the blade?

Which characteristics of the profile determine its aerodynamic properties?

What could be the input to the model?

2D aerodynamic inputs: the ae file

Aerodynamic properties depend on <u>geometric characteristics:</u>

- Chord length
- Profile geometry -> steady aerodynamic forces (complex relation, input: *profile coefficient tables*)

Input: *aerodynamic layout* of the blade.

Given in the `ae_filename` file:

```
1 Aerodynamic planform
1 12
  0       3.5      100      1
  0.5     3.5      100      1
  2.1     3.5      99.9734  1
  4.9     4.2      74.46957 1
  7.7     4.9      48.96571 1
  10.5    5.6      35.71321 1
  21.7    4.9014   20.58616 1
  32.9    3.5489   17.32931 1
  35.7    3.24968  16.76627 1
  47.033  1.83467  15.65677 1
  52.26   0.913    14.99    1
  52.9    0.8      14.7875  1
```

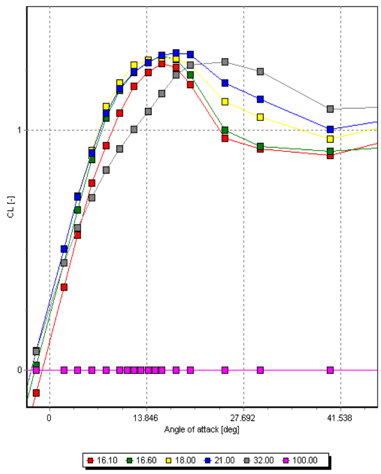
1. Total number of datasets given in the file
2. Set Id number , Tot. number of points given in the set

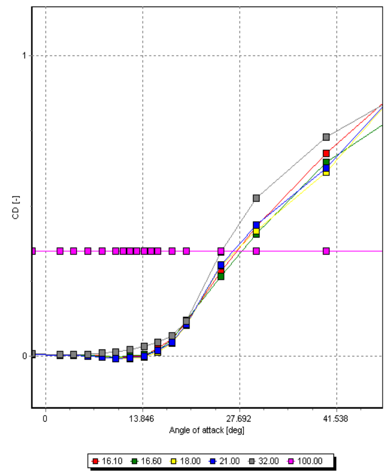
In the following lines:

- Spanwise position [m]
- Chord Length [m]
- Thickness/Chord ratio [%] (link to prof. coeff. tables)
- Profile Coefficient Set

2D aerodynamics inputs: the pc file

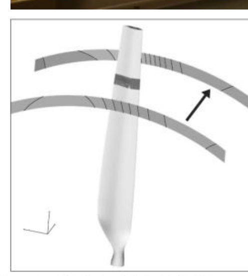
- 2D profile geometry: a set of steady profile coefficents -> relation angle of attack, steady aerodynamic forces (non dimensional)

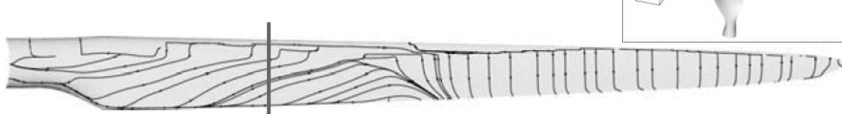




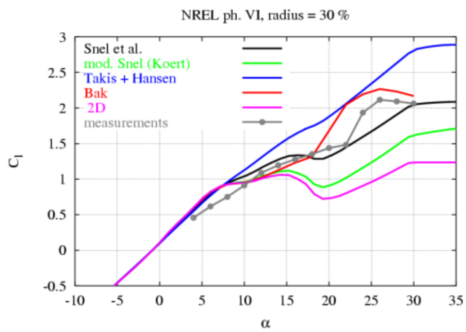
Profile coefficients: how to retrieve them

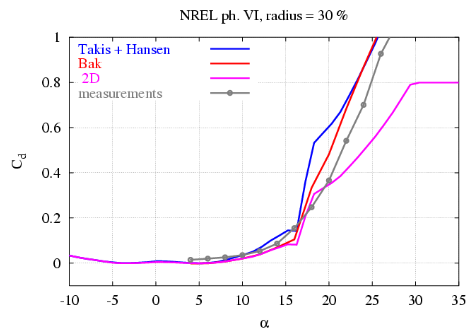
- Where to get the profile coefficients from:
  - 2D simulations (panel codes, CFD)
  - 2D wind tunnel tests
- Limited angle of attack range:
  - Extend airfoil data over a larger angle of attack range
- 2D simulation/measurements:
  - Apply 3D corrections: stall delay effects





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

Profile Coefficients: input file

Profile coefficients collected in the `pc_filename` file:

```
1 Airfoil data for the nrel 5 mw turbine
8
1    127  17.0 comments here...
-180.00    0.000   0.0198   0.0000
-175.00    0.374   0.0341   0.1880
 ...               ... ...
+175.00    0.749   0.0955   0.3770
+180.00    0.659   0.2807   0.2747
2    127  21.0 comments here...
-180.00    0.000   0.0198   0.0000
-175.00    0.374   0.0341   0.1880
 ...               ... ...
+175.00    0.749   0.0955   0.3770
+180.00    0.659   0.2807   0.2747
 ...               ... ...
8    127  100 comments here...
-180.00    0.000   0.0198   0.0000
-175.00    0.374   0.0341   0.1880
 ...               ... ...
+175.00    0.749   0.0955   0.3770
+180.00    0.659   0.2807   0.2747
```

1. Total number of "sets"
2. Number of profiles in the first set.
3. First profile in the first set:

   Index | N rows | t/c profile *(link to ae)*

NB: The t/c in *increasing* order

Then for each profile, steady coefficients table:
- Aoa [deg] (arbitrary spacing)
- Cl
- Cd
- Cm

Recap: inputs for 2D aerodynamics

- The aerodynamic originates on the rotor blades
- Structural layout of the blades given by *c2_def* (twist angle)
- Link blades to structure
  `link` and `hub_vec`
- Give blade(s) description in the model:
  - Discretize into *aero sections*
    `aerosections` or `aero_distribution`
  - Define the *aerodynamic layout*
    `ae_filename` (+ file)
  - Give the steady *profile coefficients*
    `pc_filename` (+ file)

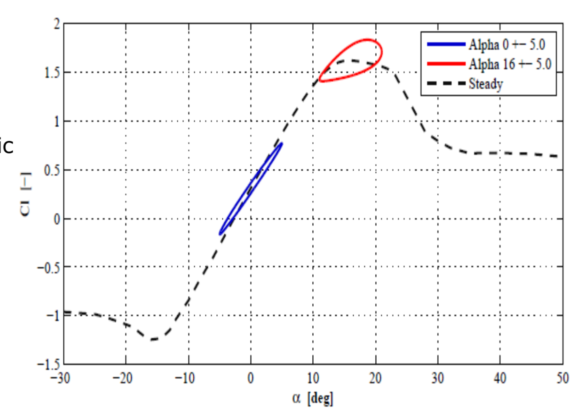
```
begin aero ;
  nblades  3;
  hub_vec shaft -3 ;
  link 1 mbdy_c2_def blade1;
  link 2 mbdy_c2_def blade2;
  link 3 mbdy_c2_def blade3;
  induction_method    1 ;
  aerocalc_method     1 ;
  tiploss_method      1 ;
  aerosections        30 ;
  ae_filename         ./data/ae_Ex.txt;
  pc_filename         ./data/pc_Ex.txt;
  ae_sets             1 1 1;
  dynstall_method     2 ;
  ; …
  ; other optional inputs…
  ; …
end aero ;
```

→ Obtain steady aerodynamic description

Life is dynamic…

2D aerodynamic model should account for dynamics (unsteady forces) in:

- ***Attached flow*** :
  Memory effects of vorticity shed into the wake.
- ***Flow separation*** (dynamic stall):
  Dynamics of the boundary layer, delay in flow separation.
- ***Non-circulatory terms***:
  added mass, acceleration terms.

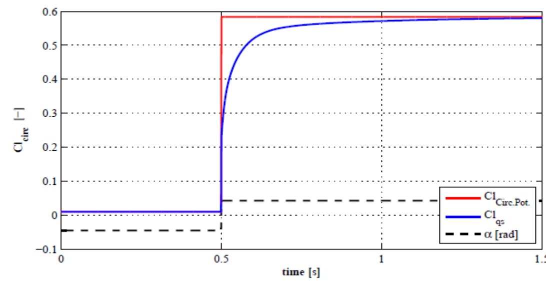


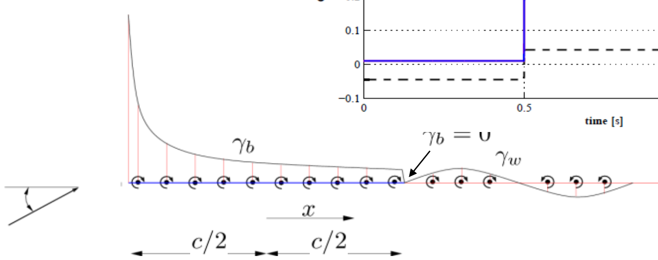
Attached flow dynamics

- Classic formulation (Von Karman and Sears):

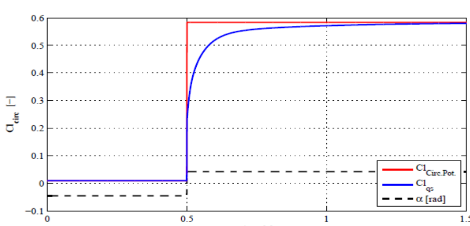
  Lift = Quasi-Steady term + *Lift* deficiency + Non Circ. term

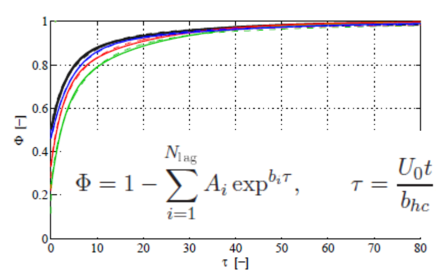
- Lift deficiency: effects of vorticity in the wake

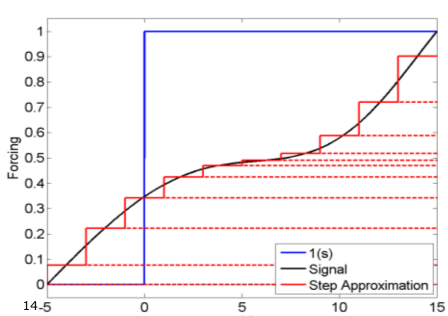




Attached flow: indicial response function

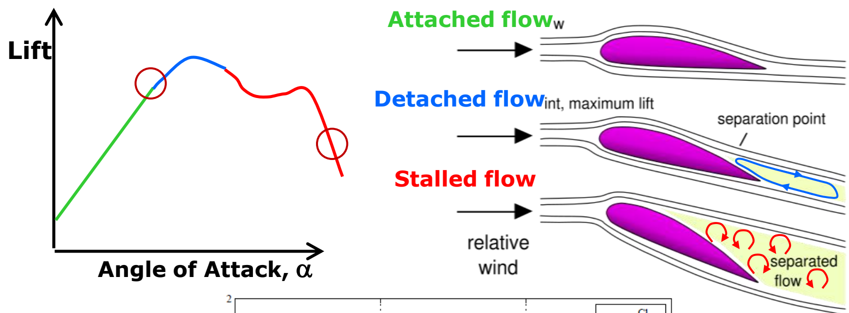


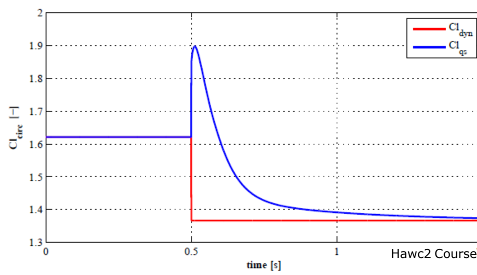




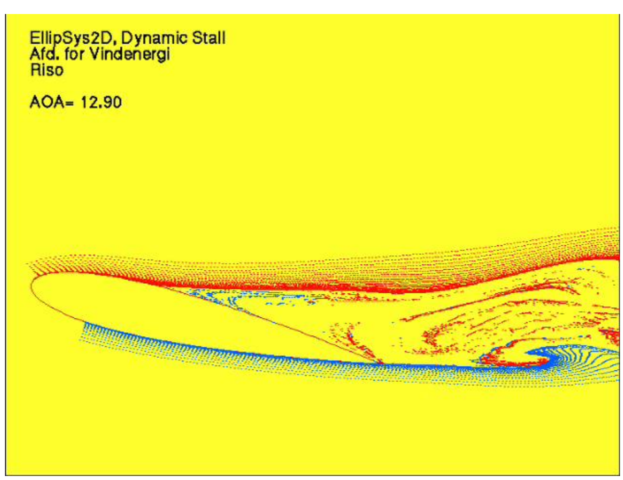
- Response to step, described by *Indicial lift response function* Phi.
- Response to arbitrary motion: superposition of step responses.
- Convenient time-stepping integration of Duhamel’s superposition integral.

Flow separation dynamics





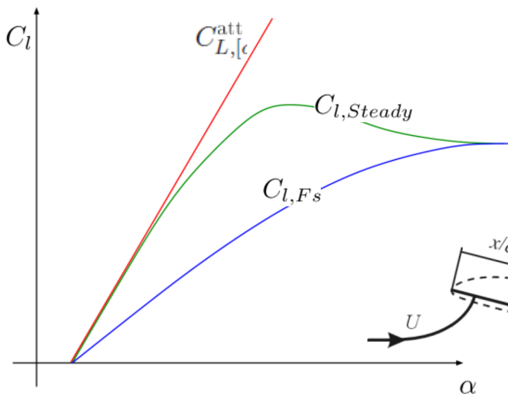
Flow separation dynamics (2)



Dynamic stall model (1)

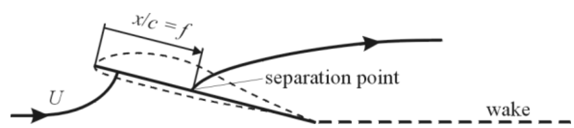
• Lift as weighted sum:

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



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

• Dynamics from weight, separation function *f*



Dynamic stall model (2)

• Dynamics are modeled by the separation function *f*.

• Beddoes-Leishmann model: series of two low pass filters (1st order)

1. Lift from attached flow is lagged:

$$\dot{C_l}^{\mathrm{lag}} = -\frac{U_0}{b_{hc}}\frac{1}{\tau_P} C_l^{\mathrm{lag}} + \frac{U_0}{b_{hc}}\frac{1}{\tau_P} C_l^{\mathrm{Pot}}.$$

2. Intermediate separation function corresponding to the lagged lift retrieved from steady input data:

$$f^{C_{l,\mathrm{lag}}} = f^{st}_{[\alpha^*]} \qquad \alpha^* = \frac{C^{\mathrm{lag}}_{l,\beta=0}}{\partial C_l/\partial\alpha} + \alpha_0$$

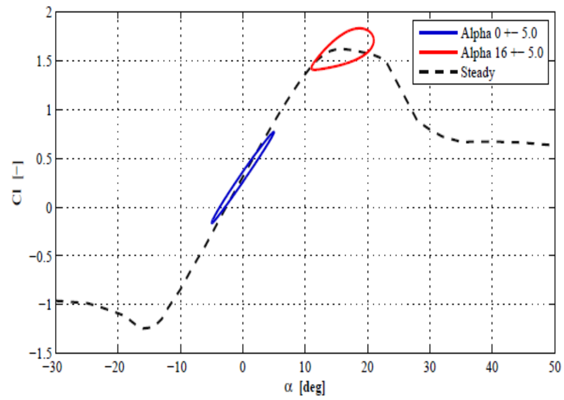
3. The intermediate separation function is lagged:

$$\dot{f}^{dyn} = -\frac{U_0}{b_{hc}}\frac{1}{\tau_B} f^{dyn} + \frac{U_0}{b_{hc}}\frac{1}{\tau_B} f^{C_{l,\mathrm{lag}}};$$

Wrap up: dynamics for 2D flow

1. Steady aerodynamic inputs are provided to the model *(ae* and *pc)*
2. Aerodynamic models in HAWC2 account for 2D dynamics of aerodynamic forces(unsteady forces):

- ***Attached flow*** :
  Indicial response function superposition.
- ***Flow separation:***
  Dynamic stall model.
- ***Non-circulatory terms***:
  added mass, acceleration terms.



2D aerodynamic model limitations

- Dynamic stall model: accounts only for trailing edge separation
- 2D model…
  - No rotational effects (stall delay)
    (3D correction in prof.coeff.)
  - BEM annular independency
  - …

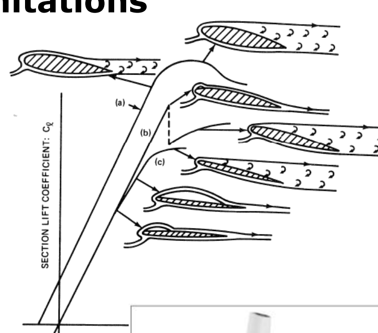
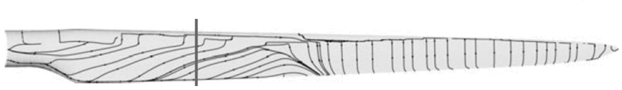
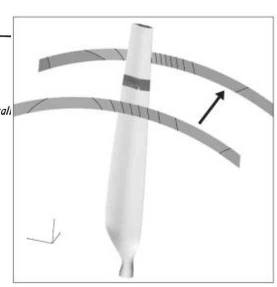


Figure 6.18 Three types of stall





2D aerodynamic models in HAWC2

```
begin aero ;
  ; …
  dynstall_method      2 ;
  ; …
  ; other optional inputs…
  ; …
  ; sub-block with model
specific inputs
  ; …
end aero ;
;
begin aerodrag ;
  begin aerodrag_element ;
  ; …
  end aerodrag_element ;
  ; …
end aerodrag ;
```

Aerodynamic models:

0. Quasi-steady

1. Stig Øye:

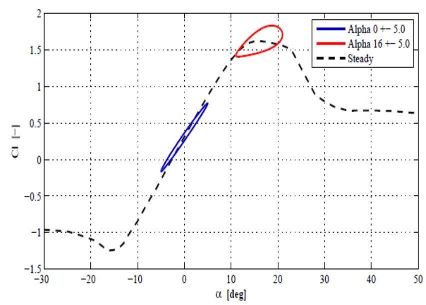
1 lag dyn.st., QS attached

2. Morten H.'s Beddoes-Leishmann:

Attached flow dynamics, 2 lags dynamic stall model

3. ATEFlap model:

as 2, includes TE flaps effects



Aerodrag command block:

- Additional command block (outside aero)
- Accounts for (steady) drag on additional w.t. components
- Refer to the manual

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.

Exercise: Power up your turbine

Starting from the NREL 5MW wind turbine structure you prepared before:

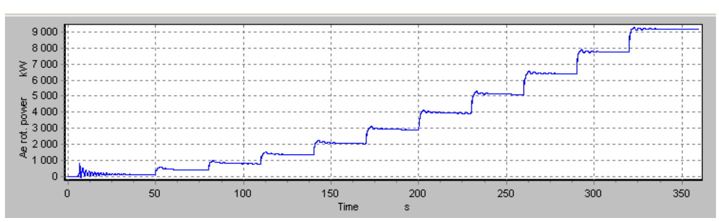
- Add the command block for the aerodynamics
- Include all the relevant inputs
- Perform simulation for step changes in wind (constant rpm and pitch), wind speeds ranging from 4-14m/s.
- Check the output:
  - Does it work? Does it make sense?
  - *Are the aerodynamic input data OK*?

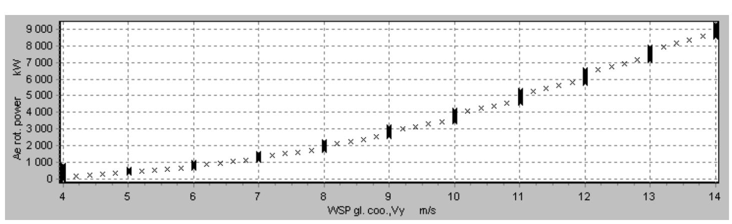
- Repeat the simulation with the induction turned off. What does it change?
- Include tower shadow effects, simulate with MHH model, repeat with Quasi-Steady aerodynamics. What does it change?

HINTS:

- Use as base the *Ex_BaseHtc.htc* file in the *Exerc_Aerodynamics* folder
- Use the data provided in the *ExAero_Data.xlsx* spreadsheet.
- Define the aerodynamic layout (*ae file*) and the profile coefficients *(pc file)* in two files.
- Complete the .htc file by adding the relevant *aero* commands.
- Check the .log file for errors

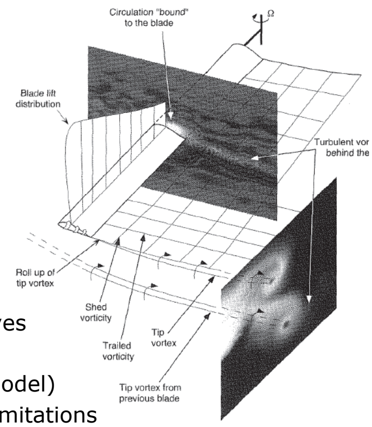
Exercise: Power up your turbine





Lesson 3: Aerodynamics

Points discussed in the lesson:



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- **Small Exercise**: “Power up your wind turbine”