ENERGY

Bladed User conference 2015

New aerodynamics modules

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29 September 2015

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Aim of work

- Develop a interface (API) that can be used for linking Bladed with any aerodynamic module given in state-space formulation
  - Enables linking Bladed to alternative aerodynamic models
  - Enables multiple rotors (Tidal Bladed)
  - Enables integrating the aerodynamic states together with all other states
  - Enables using the aerodynamic module in stability analysis and linearization
  - Improves maintainability and testability
- Rewrite the 'Classic' Bladed aerodynamics as an implementation of the API
  - Aerofoil sections including CL, CD, and CM rewritten with generalised Reynolds-number interpolation and tip-speed-ratio interpolation
  - Engineering extensions such as dynamic stall models written as an implementation of an interface (API)
  - Include a skew-wake correction providing a restoring yawing moment in cases with yaw misalignments
  - Elaborate detailed technical documentation of aerodynamic model
  - More rigorous handling of, coning, blade sweep etc

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New BEM aerodynamics

Axial momentum theory for an ideal rotor

- Originally developed by Rankine (1865) and Froude (1878) for marine propellers
- Used by Glauert (1935) for a rotor annulus assuming no interaction between neighbouring annuli
- Resulting thrust and torque acting on an annulus

$$\delta T = -2 v_n \delta \dot{m}$$

$$\delta Q = -2 v_t r \delta \dot{m}$$

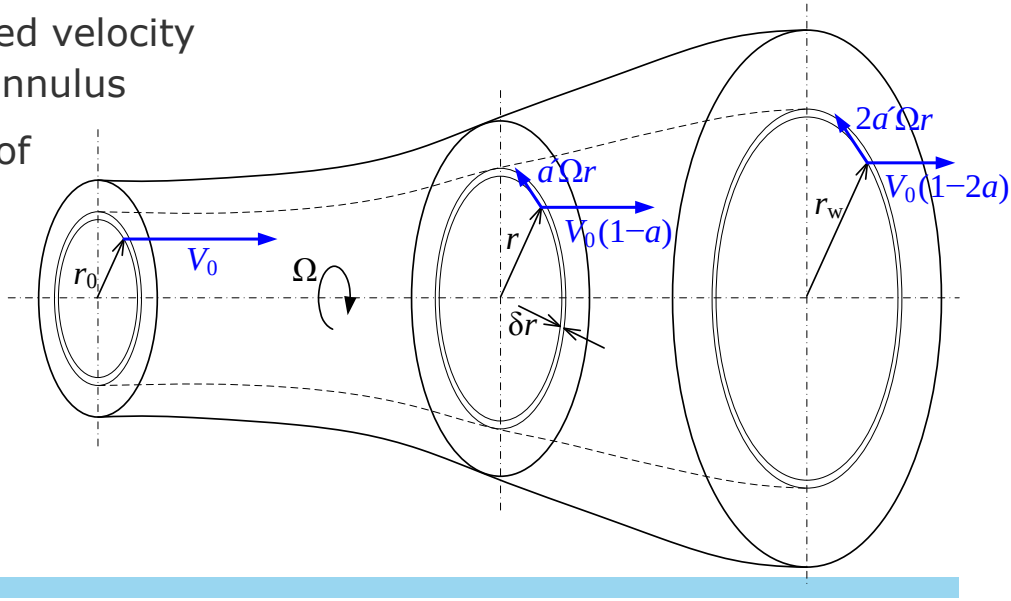
v_n, v_t: normal and tangential induced velocity

$\delta \dot{m}$: mass flow rate though the annulus

- Theory traditionally formulated in terms of induction factors defined as

$$a = -v_n / V_0$$

$$a' = -v_t / r\Omega$$



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Classical BEM theory (1)

- Orientation of aerofoil section

$$\mathbf{R}_a = \mathbf{R}_s \mathbf{R}_g = \left[\, \mathbf{i}_a \;\; \mathbf{j}_a \;\; \mathbf{k}_a \,\right]$$

  R_s: orientation of structure at aerofoil section
  R_g: additional relative rotation of outer geometry

- Relative wind velocity at aerofoil section

$$\mathbf{W} = \mathbf{V}_0 + \mathbf{V}_s + \mathbf{v}$$

  V_0: undisturbed wind velocity V_s: structural motion at c/4 point

  $\mathbf{v} = v_n \mathbf{n} + v_t \mathbf{t}$: induced wind velocity

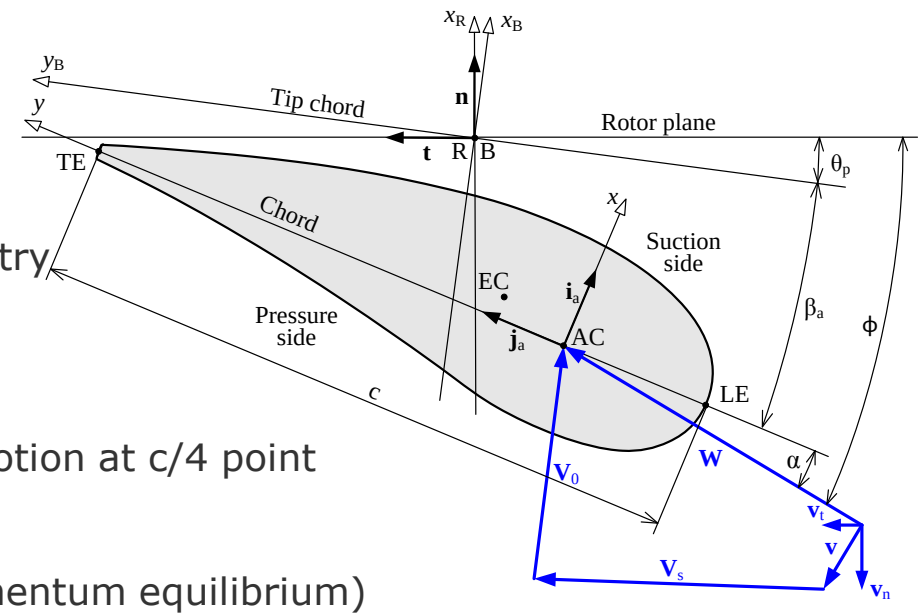
- Induced velocity components (fundamental momentum equilibrium)

$$v_n = -\, p_n / 2J\dot{m}'$$
$$v_t = -\, p_t / 2J\dot{m}'$$

$p_n = \mathbf{n}\cdot\mathbf{i}_a\, p_x + \mathbf{n}\cdot\mathbf{j}_a\, p_y$: aerodynamic normal force (p_x, p_y: local components)

$p_t = \mathbf{t}\cdot\mathbf{i}_a\, p_x + \mathbf{t}\cdot\mathbf{j}_a\, p_y$: aerodynamic tangential force

$\dot{m}' = \rho V_m 2\pi r / B$: mass flow rate (B: blade number, V_m: wind speed)



Classical BEM theory (2)

- Angle of attack depending on relative wind velocity

$$\alpha = \arctan \frac{\mathbf{i}_a \cdot \mathbf{W}}{\mathbf{j}_a \cdot \mathbf{W}}$$

- Lift and drag forces calculated from lift and drag coefficients, CL = CL(α) and CD = CD(α), as

$$L' = \tfrac{1}{2} C_L \rho W^2 c$$

$$D' = \tfrac{1}{2} C_D \rho W^2 c$$

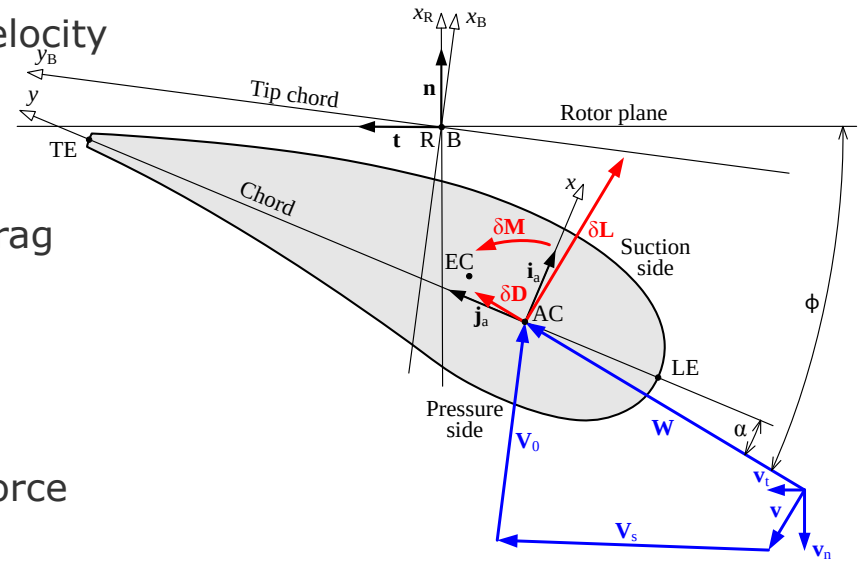
- Resulting local components of aerodynamic force

$$p_x = L' \cos\alpha + D' \sin\alpha$$

$$p_y = D' \cos\alpha - L' \sin\alpha$$

- Wind speed appearing in the mass flow expression

$$V_m = \begin{cases} \left| \mathbf{V}_0 + v_n \mathbf{n} \right| & \text{for Glauert momentum theory} \\ \mathbf{n} \cdot \mathbf{V}_0 + v_n & \text{for axial momentum theory} \end{cases}$$



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Dynamic wake model - Øye

$$\tau_1 \frac{d\bar{u}}{dt} + \bar{u} = \bar{v}_{qsn} + k_w \tau_1 \frac{d\bar{v}_{qsn}}{dt}$$

$$\tau_2 \frac{d\bar{v}}{dt} + \bar{v}_n = \bar{u}_n$$

Where:

- τ_1, τ_2: time constants dependent on relative rotor radius, wind speed
- V_{qsn}: quasi-steady axial induction
- u_n: intermediate velocity value
- v_n: final time-lagged induced velocity

- Same equations can also be applied to the tangential induced velocity.
- If dynamic tangential induced velocity is switched on, then there is no iteration needed on every time step

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Dynamic wake model – Pitt & Peters

$$2\bar{v}_{qsn}\delta\dot{m}' = 2\bar{v}_n\delta\dot{m}' + \dot{\bar{v}}_n\delta m'_A$$

Where:

- V_{qsn}: quasi-steady axial induction
- $m_{A:}$: added mass per unit length ($8/B\rho r^2$)
- $v_{n:}$: final time-lagged induced velocity

- The tangential induction is found on each time step by iteration

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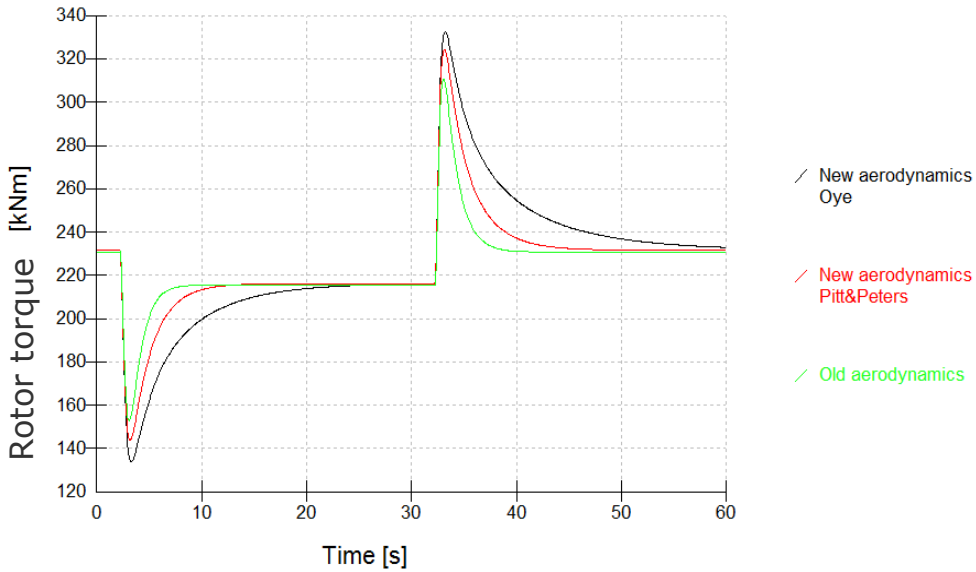
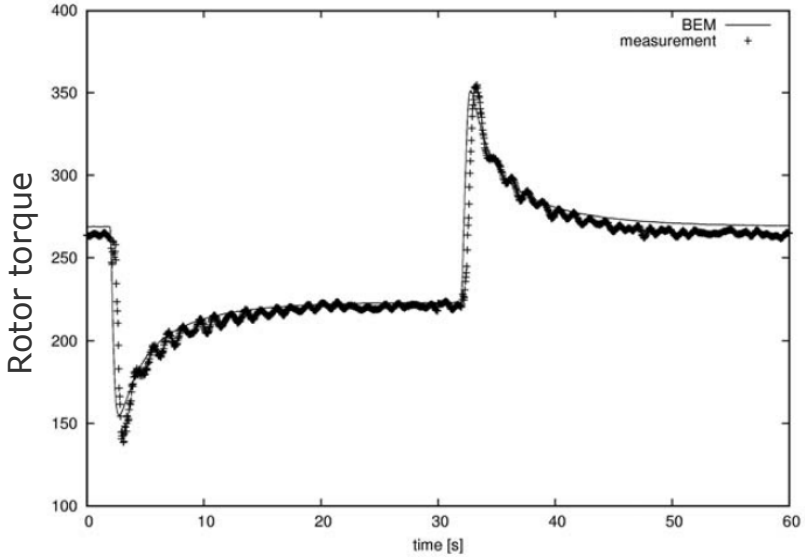
Dynamic wake model – Differences between Øye and Pitt & Peters

- Replicating a step change in pitch angle from the Tjaereborg machine.
- The Øye model shows a more gradual recovery of the rotor torque
- Pitt & Peters showing a more rapid recovery
- In old (pre-4.7 aerodynamics) the added mass term is interpreted differently, giving even faster recovery

Bladed



Measurements



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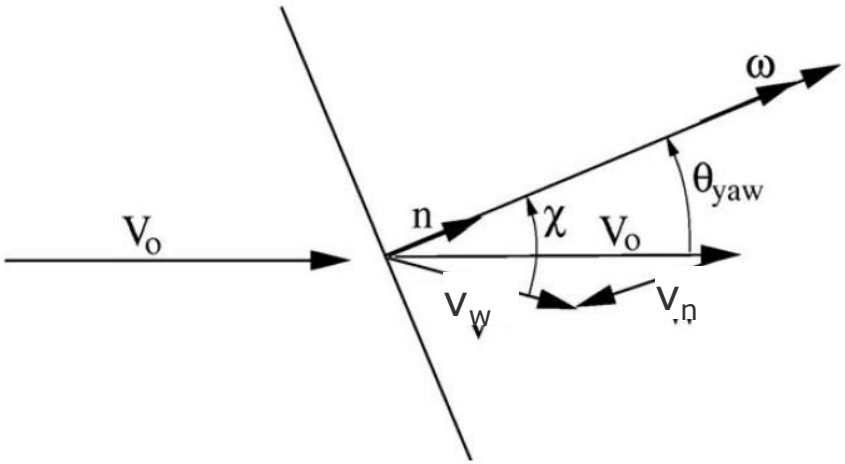
Skew Wake correction model - Theory

- A skew wake model is implemented according to theory of Glauert

$$v_n = \bar{v}_n\left(1 + F\tan\left(\frac{\chi}{2}\right)\cos(\psi - \psi_{rel})\right)$$

- Where:
  - $\bar{v}_n$ mean wake induced velocity
  - v_n Final skew corrected induced velocity
  - F tip loss factor
  - ψ the azimuth angle of the rotor
  - ψ_{rel} azimuth for which blade is deepest into the wake
  - χ skew wake angle



$$\cos(\chi) = \frac{\boldsymbol{n} \cdot \boldsymbol{V_W}}{|\boldsymbol{V_W}|}$$

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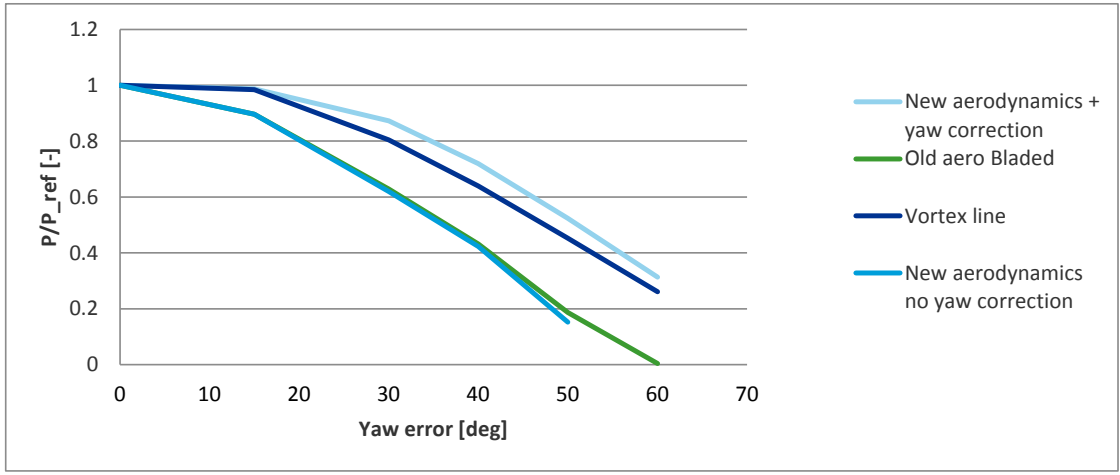
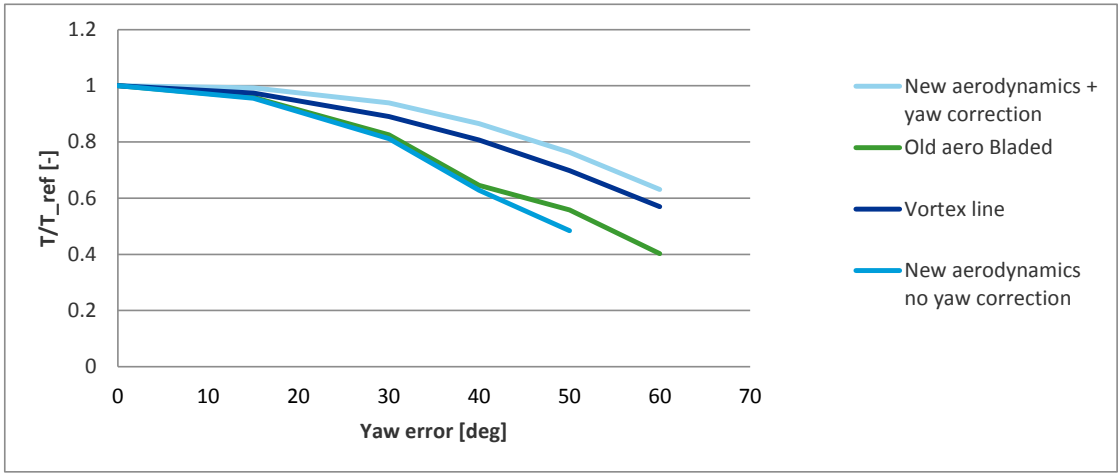
Skew Wake correction model – Verification (1)

- A comparison is conducted with a free wake lifting line method
- Without the skew wake correction there is a stronger decay in rotor loads with yaw error
- With skew wake correction a better match is found with the lifting line code

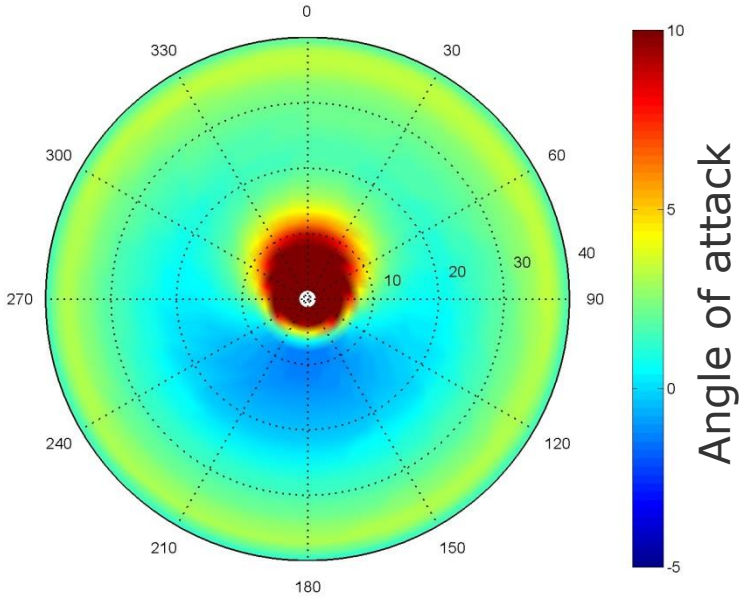




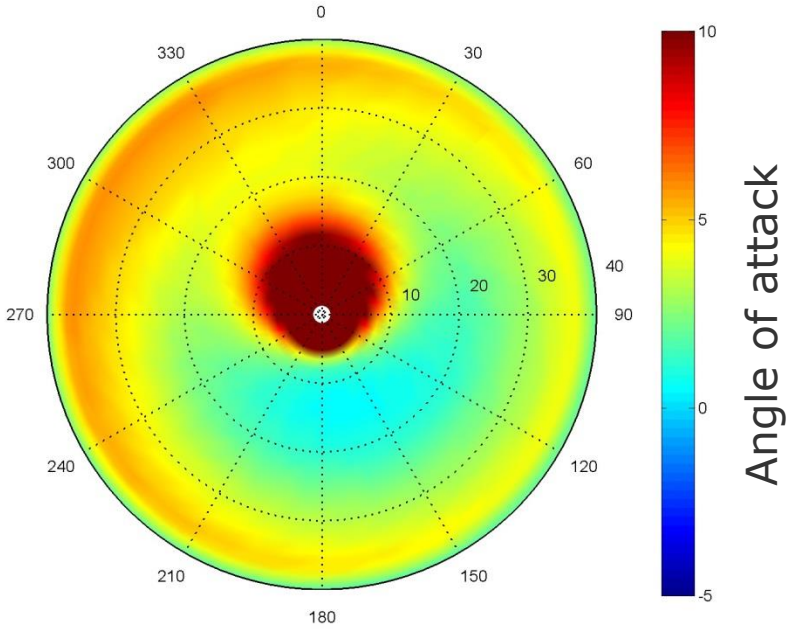
Skew Wake correction model – Verification (2)

- The distribution of angle of attack over the azimuth becomes significantly different.
- Again with a vortex line method, the skew wake model shows a good match

No skew wake 50°



skew wake 50°



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Dynamic stall model - Theory

- Three dynamic stall models are present in the new aerodynamics:
  - Incompressible Beddoes-Leishman
  - Compressible Beddoes-Leishman
  - Øye model
- The Beddoes Leishman models are based on a combination of work from Risø[1] and Leishman [2]
- The Øye model is in fact a reduction of the Leishman models only modelling dynamics of trailing edge separation

1 Hansen, M.H., Gaunaa, M., and Madsen, H.Aa., "A Beddoes-Leishman type dynamic stall model in state-space and indicial formulations". Technical report Risø-R-1354(EN), Risø National Laboratory, Roskilde, June 2004

2 G. Leishman, State-Space model of unsteady airfoil behaviour and dynamic stall, In Center for Rotorcraft Education and Research,1989

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Dynamic stall model – attached flow

- State-Space representation of the approximation of the Wagner function:
  - $\dot{x}_1 + \frac{\left(b_1 + \frac{c\dot{U}}{2U^2}\right)x_1}{T_u} = \frac{b_1 A_1 \alpha_{3/4}}{T_u}$
  - $\dot{x}_2 + \frac{\left(b_2 + \frac{c\dot{U}}{2U^2}\right)x_2}{T_u} = \frac{b_2 A_2 \alpha_{3/4}}{T_u}$
  - $T_u = \frac{c}{2U(t)}$

  Where:
  - $\dot{x}_n$ attached flow state (rate)
  - A_n, b_n Coefficients and exponents of indicial functions
  - U Local wind speed (including induction, and structural motion)
  - $\alpha_{3/4}$ angle of attack at quarter chord position
- With the attached flow states an effective angle of attack is determined:

$$\alpha_E = \alpha_{3/4}(1 - A_1 - A_2) + x_1 + \ x_2$$

- The attached normal force coefficient is then found as:
- $C_N^{Circ_att} = Cn_\alpha(\alpha_E - \alpha_0)$

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Dynamic stall model – attached flow verification

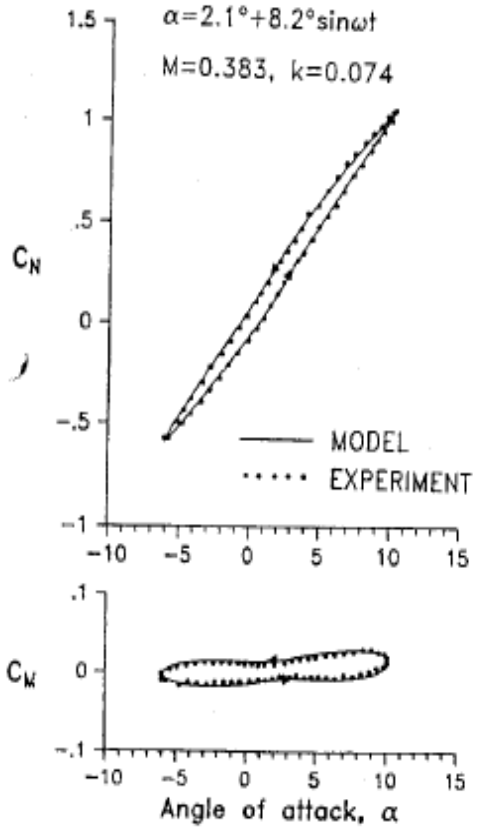
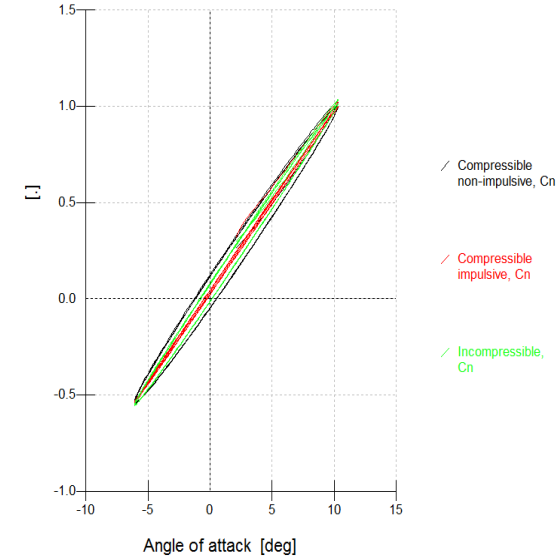
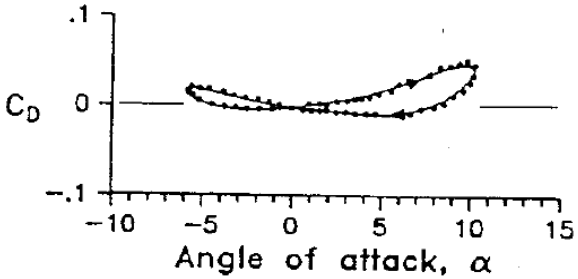
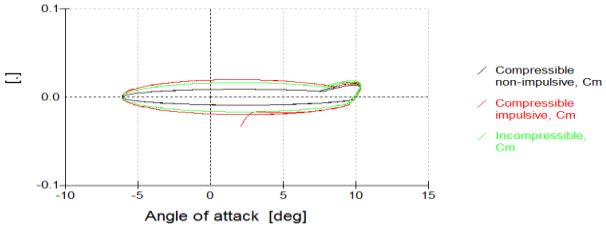
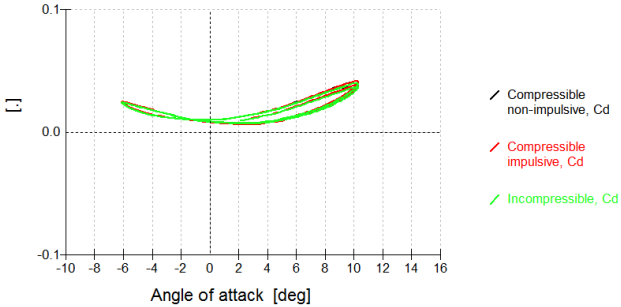


Fig. 5 Prediction of normal force and pitching moment under attached flow conditions at M = 0.4.









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Dynamic stall – separated flow

- Time lagged interpolation between fully attached and fully separated flow

$$\dot{x}_3 + \frac{x_3}{T_p T_u} = \frac{Cn_\alpha(\alpha_e - \alpha_0) + \pi T_u \dot{\alpha}}{T_p T_u}$$

$$\dot{x}_4 + \frac{x_4}{T_f T_u} = f^{st}\left(\frac{x_3}{Cl_\alpha + \alpha_0}\right)$$

- Where:
  - T_p Pressure lag constant (user input in Bladed)
  - T_f Separation position constant (user input in old & new aerodynamics)
- The dynamic normal force coefficient then is expressed as:

$$Cn^{dyn} = Cn_\alpha(\alpha_E - \alpha_0)x_4 + Cn^{fs}(\alpha_E)(1 - x_4) + \pi T_u \dot{\alpha}$$

- Where:
  - Cn^{fs} Normal force coefficient for fully separated flow

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Dynamic stall – miscellaneous modifications

- A vortex lift term is added, which only kicks in in case there is a rapid ramp to stall
- The model is expressed in Cn,Cc rather than Cl,Cd but for the drag coefficient the Cd is calculated explicitly
- Impulsive lift/moment states are available for the compressible model. However these are high frequency -> slower simulations

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Dynamic stall – separated flow verification

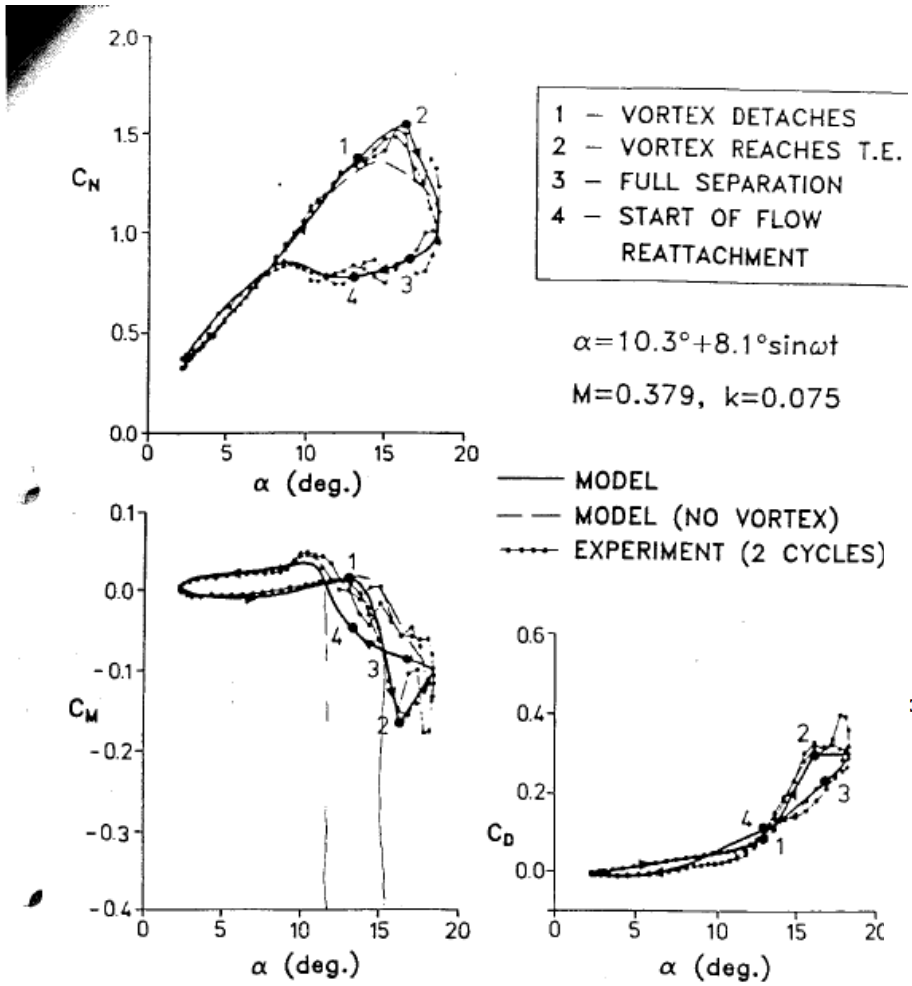
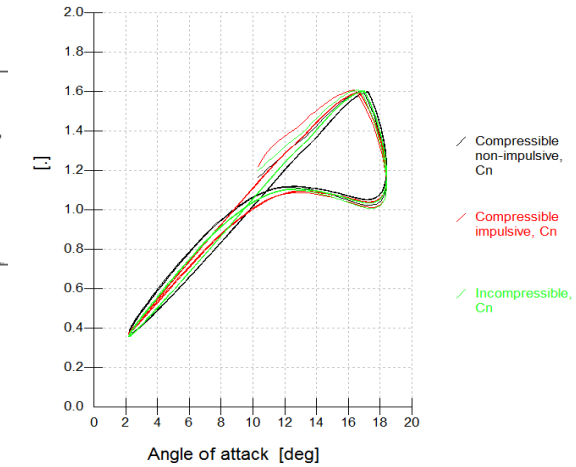
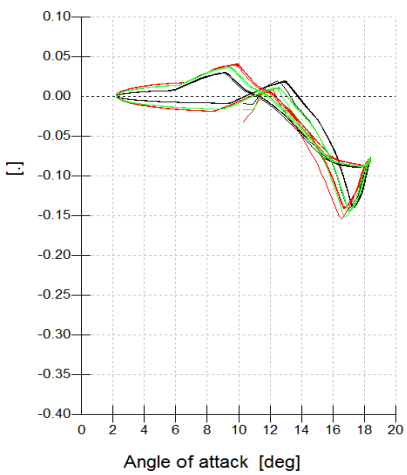
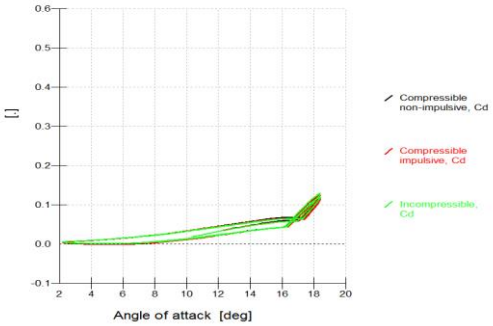


Fig. 8 Prediction of forces and moments during strong dynamic stall at M = 0.4.







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Aerodynamics control – new settings

Submodel	Default setting in Beta aerodynamics	Default setting in pre-4.7 aerodynamics
Drag induction	On	On*
Momentum theory	Glauert momentum theory	Axial momentum theory*
Dynamic wake base	Dynamic wake on blade element	Dynamic wake on blade element*
Dynamic wake model	Øye dynamic wake	Dynamic inflow
Dynamic tangential induction	On	N/A
Skew wake correction model	Glauert skew wake model	No skew wake model
No inflow below TSR	1	0
Full inflow above TSR	2	0
Tip loss correction	On	On
Hub loss correction	Off	Off
Dynamic stall model	Incompressible Beddoes-Leishman	Compressible Beddoes-Leishman
Dynamic pitching moment coefficient	On	On*
Include impulsive lift and moment contributions	Off	On*
Starting radius for dynamic stall	25	0
Ending radius for dynamic stall	95	100*
Separation time constant	3.0	3.0
Pressure lag constant	1.7	1.7*
Vortex lift constant	6.0	6.0*

(*) Not a user input

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Expected differences with old aerodynamics

- DNV GL has carried out comparison studies with several multi MW wind turbines.
- Main trends are:
  - General good agreement in fatigue loads
  - Extreme wind shear/ yaw angle cases become generally more driving (skew wake correction model increases loads in yaw)
  - In parked cases instabilities occur more frequently. Requires increase in modal damping.

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New VortexLine aerodynamics

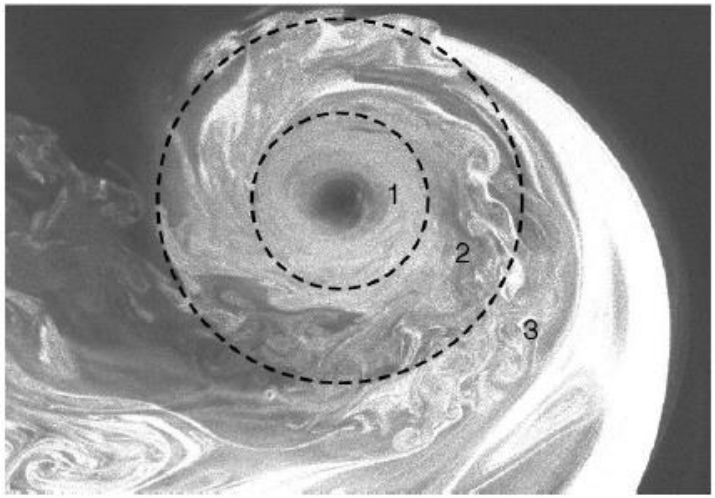
Aim of the work

- Provide an alternative aerodynamics module for more detailed aerodynamics investigations:
  - Yawed flow conditions
  - Individual pitch control
  - Sweep/prebent blades
  - Floating turbines
- Implemented against same API as new BEM aerodynamics.

Vortex Line - Theory

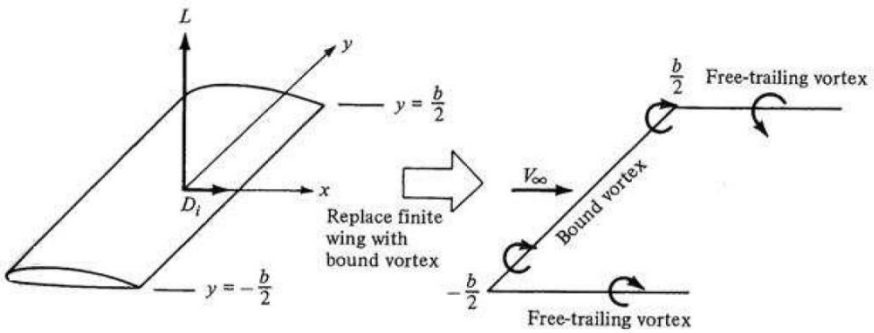
Near wake structure behind a rotor

- Downstream of a wind turbine a helical vortex wake
- Potential flow methods are populair to describe the near wake behind wind turbines is present
- Building blocks of potential flow codes are vortices, sources and doublets

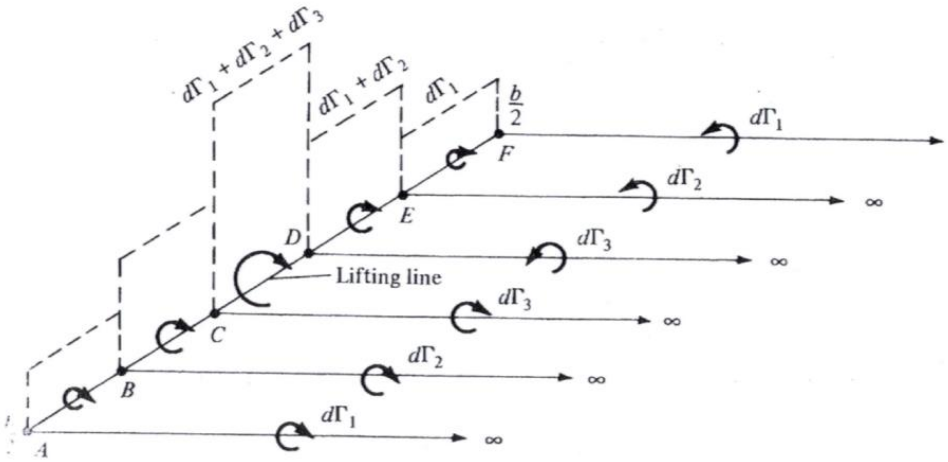


Vortex Line - theory

Single bound vortex



Distributed bound vortex



- Single bound vortex

$$L = \Gamma V_\infty \rho b$$

- Distributed bound vortex

$$L = \int_0^b \Gamma(y) V_\infty \rho dy$$

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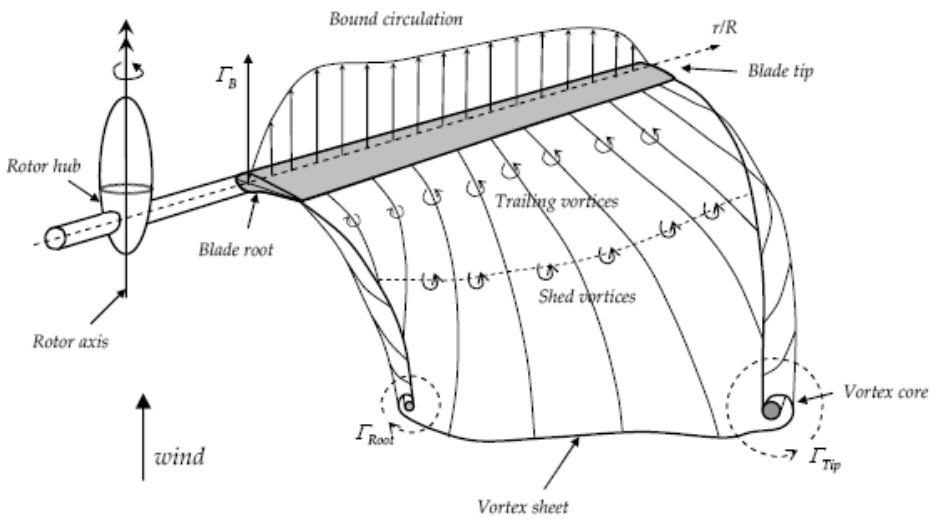
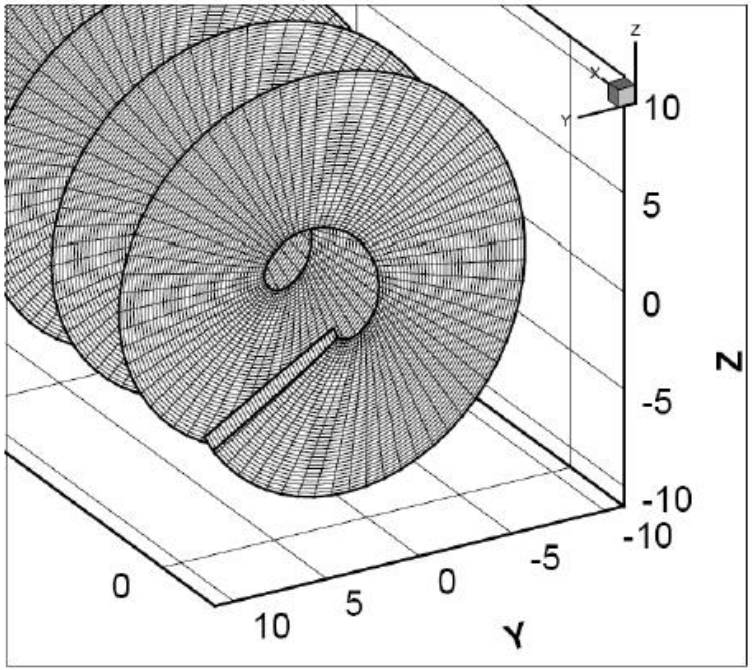
Vortex Line - Theory

- Horseshoe vortices represent a helical vortex sheet with distribution bound circulation
- Vortex sheet represents the wake of the rotor





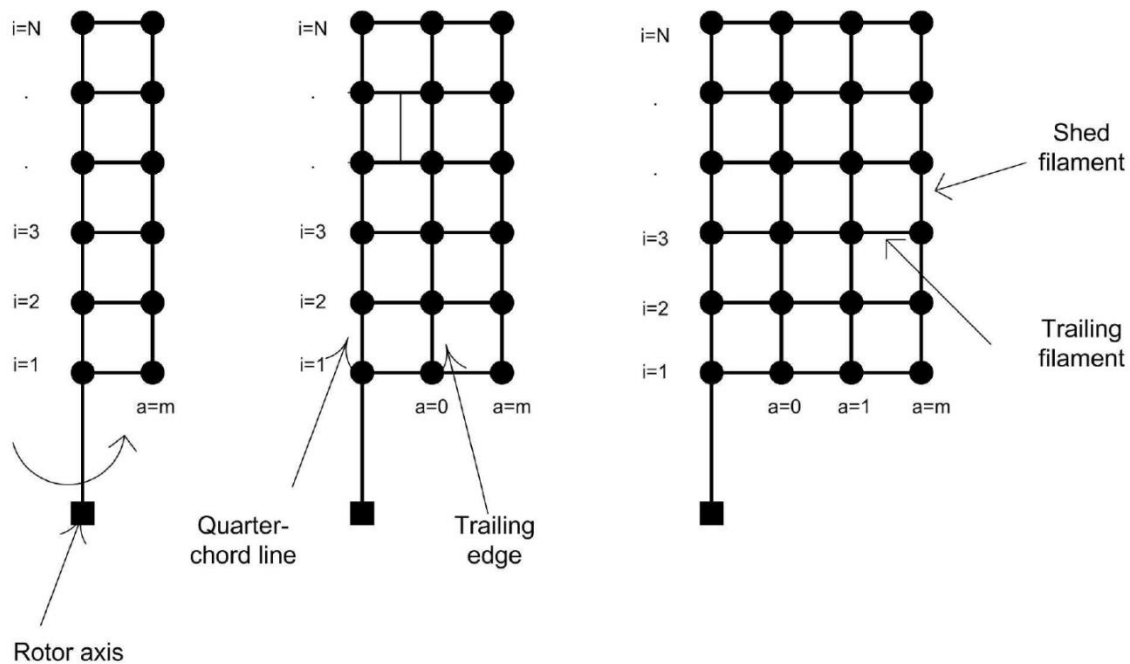
Vortex Line – Theory

- Discretization of the wake in number of trailing and shed vortex elements.
- Each time step the number of elements is increased
- The vortex strength of trailing (Γt) and shed elements (Γs) found by applying Kelvin's theorem

$$\frac{D\Gamma}{Dt} = 0 \quad \text{Kelvin's Theorem}$$

$$\Gamma_t = \Gamma_{b,i} - \Gamma_{b,i+1}$$

$$\Gamma_s = \Gamma_{b,t-1} - \Gamma_{b,t}$$



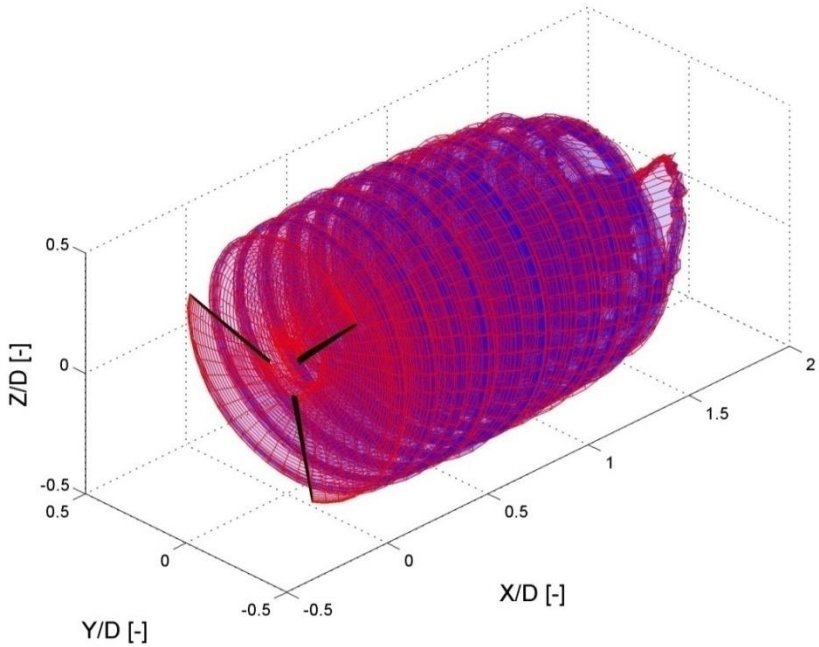
Vortex Line - Theory

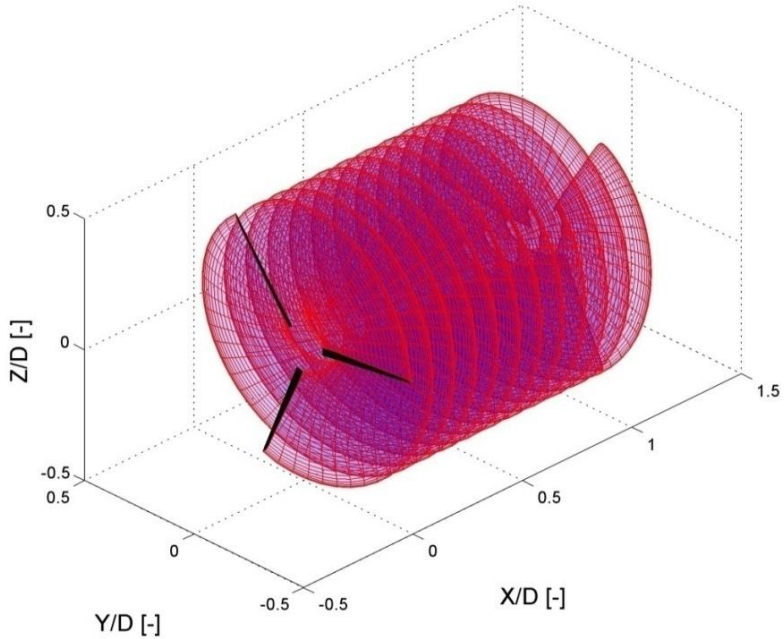
Free wake:

- Let the wake evolve every time step
- Physically more correct
- Computational much more intensive

Fixed wake:

- Prescribe the geometry of the wake
- No roll up of tip vortex
- Computational less intensive

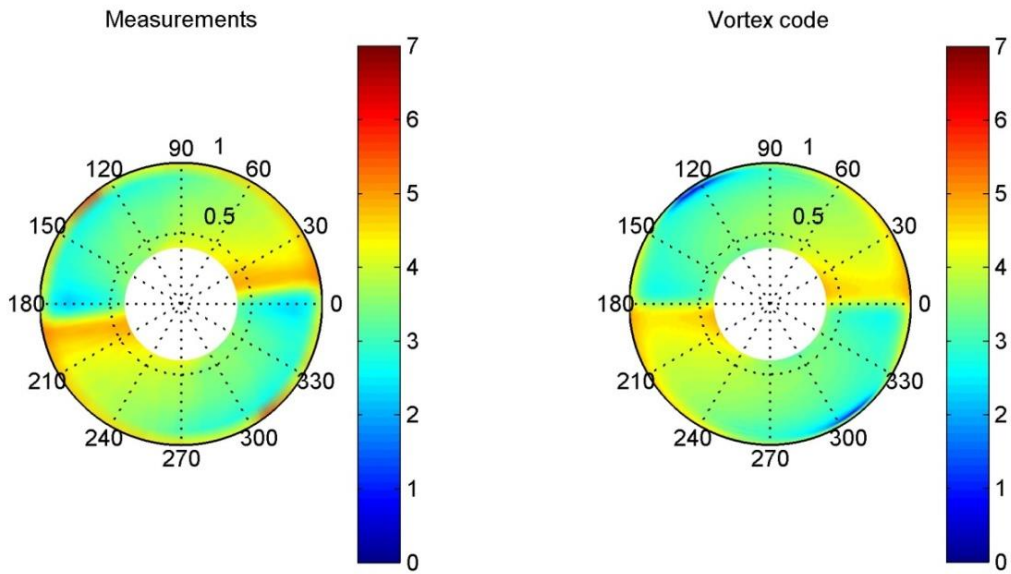




Vortex Line - Validation

Validation close to the rotor:

Comparison of hot-film velocity measurements against vortex code prediction

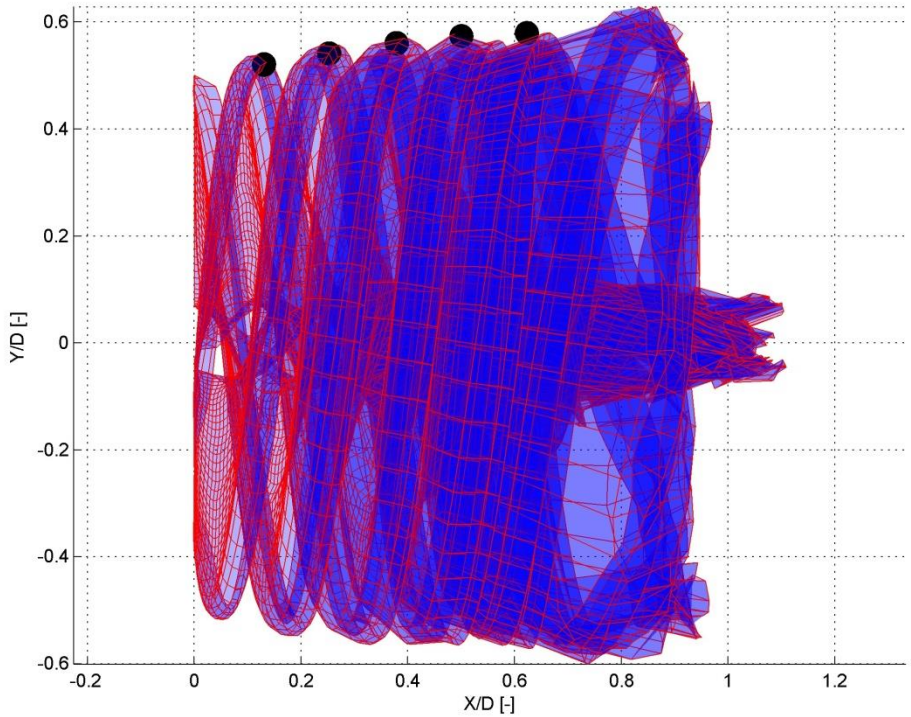


Velocities at 6.5 cm behind the rotor

Vortex Line - Validation

Wake expansion:

Measured tip vortex positions



Vortex model captures the **expansion** of the wake quite well.

Vortex Line – Differences with BEM

Lifting Line	BEM
Inherently unsteady	Inherently steady
Cl, Cd lookup tables	Cl, Cd lookup tables
Requires dynamic stall model	Requires dynamic stall model
Inherently models dynamic wake	Requires dynamic wake model
No tip loss factor required	Needs Prandtl tip loss factor
Automatically captures skew wake, bent blades, sweep etc.	Theory assumes, straight blades, steady axial flow, requires corrections
Computationally expensive	Fast!

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Vortex Line – Time line

- Improving speed:
  - Simplified equation for Biot Savart in far field
  - Fast Multipole Algorithm
  - Parallel evaluation of Biot-Savart
- Further testing and verification
- Jan 2016: Beta- release
- Will be available as additional module in Bladed

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www.dnvgl.com

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