TG2-1, Turbine and Wind Load

Development of Vortex Filament Method for Aerodynamic Loads on Rotor Blades

PhD Candidate

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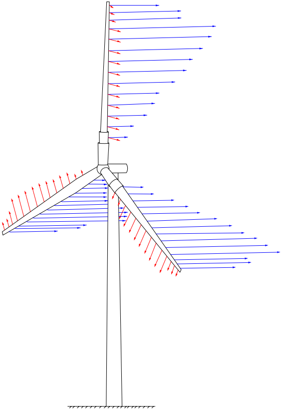
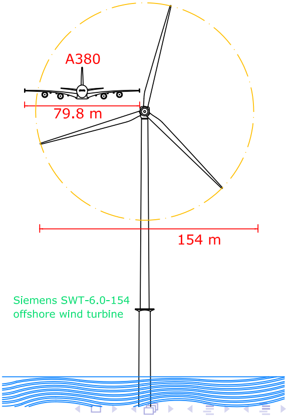
OUTLINE

Motivation

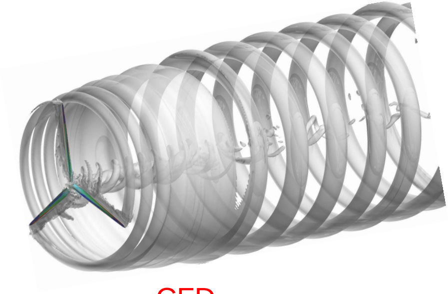
- Aerodynamic load as the largest loads acting on wind turbine blades.
- Acquiring an accurate-fast method to predict aerodynamic loads.
- Preparing input data for the aeroelastic and drive train system.
- Decreasing the operating and maintenance costs.



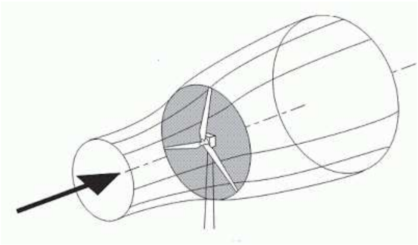


PROBLEM

- Traditional Method, Blade Element Momentum (BEM): Unable to predict the unsteady (transient) load, valid only for limited operating condition.
- Advanced Method, Computational Fluid Dynamics (CFD): Being too expensive (computational time), making it impractical engineering method.



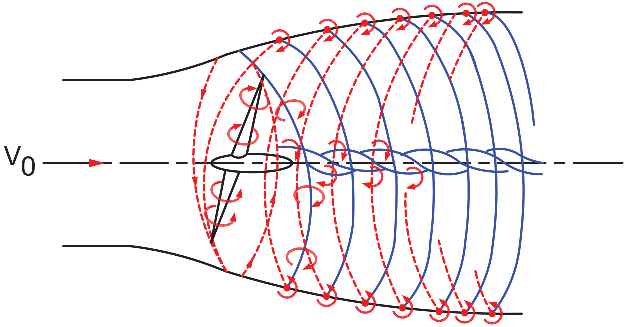
CFD



BEM

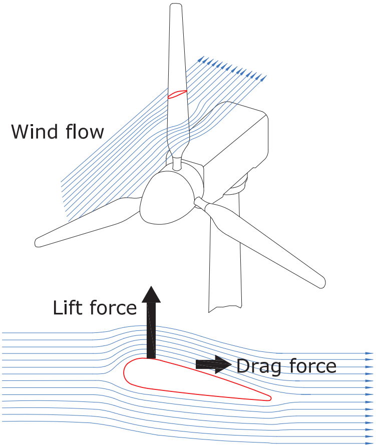
GOAL

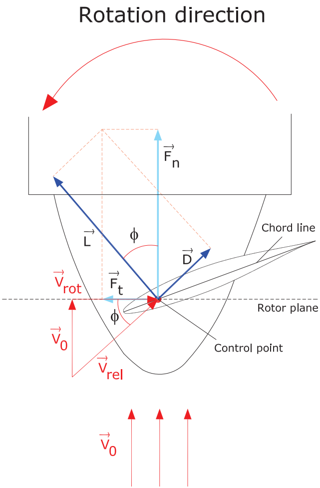
- Preparing an Accurate & Fast design tool to predict unsteady aerodynamic loads.
- Developing Vortex Method instead of BEM and CFD.



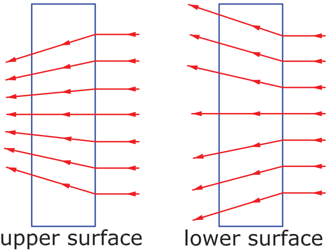
Flow Over the Wind Turbine Blade

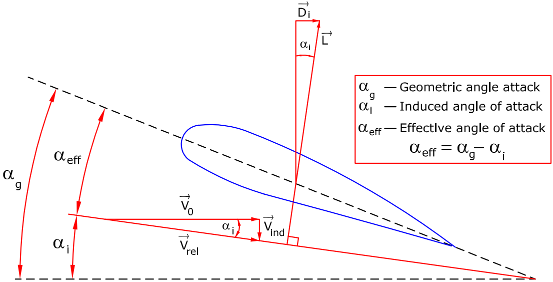
- **Lift and Drag Forces**
  - Lift & Drag forces as the source of generated Power and Thrust.





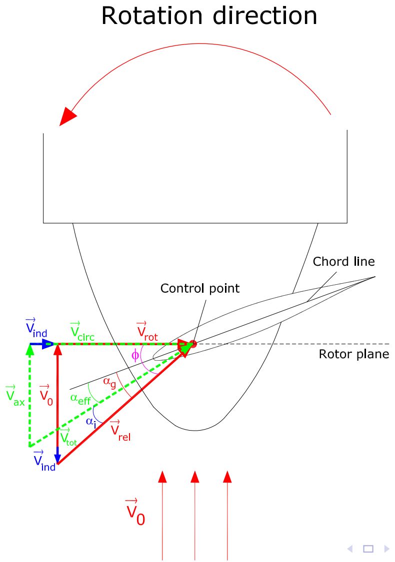
- **The Effect of Pressure Imbalance**
  - Air leakage at the tip resulting in the flow deflection.
  - Reducing the angle of attack seen by each section (Downwash effect).





Flow Over the Wind Turbine Blade

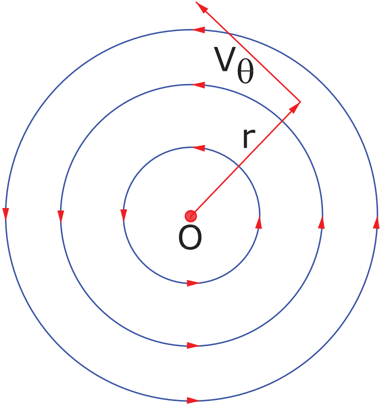
- **Induced velocity effect**



Vortex Flow, Definition

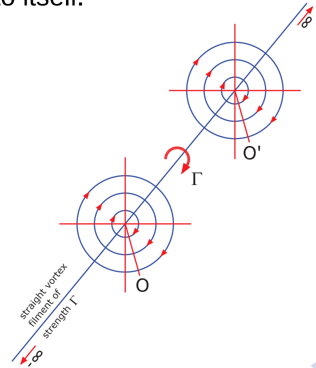
- The vortex flow including vortices produces finite lift.
- It is modeled as streamlines which are concentric circles about a given point with a constant velocity along any circular streamline.
- Vortex strength Γ

$$v_\theta = \frac{\Gamma}{2\pi r}$$



Vortex Flow, Properties

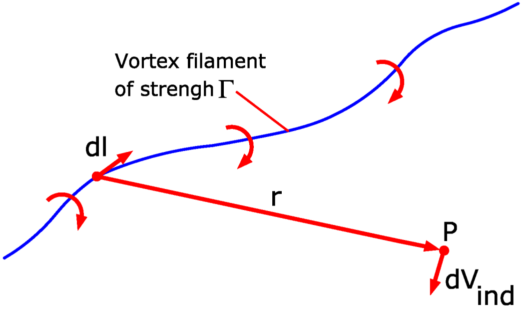
- **Vortex Flow Properties**
  - Incompressible flow ($\nabla.\mathbf{V} = 0$) at every point.
  - Irrotational flow ($\nabla \times \mathbf{V} = 0$) at every point except at the origin where the velocity is infinite.
- **Vortex Filament**
  - A straight line of strength $\boldsymbol{\Gamma}$ inducing the flow in any plane perpendicular to itself.



VORTEX FLOW, KEY EQUATION

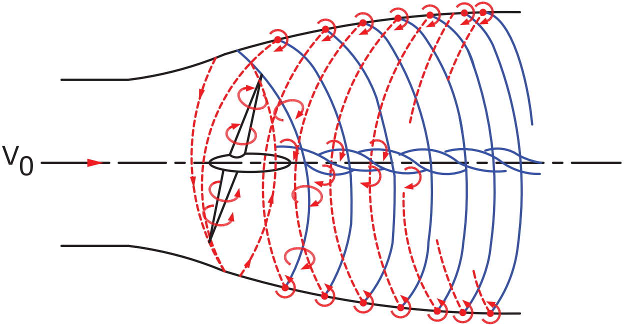
- **Biot-Savart Law**
  - Inducing a flow field in the surrounding space by a vortex filament of strength Γ.

$$d\vec{V}_{ind} = \frac{\Gamma}{4\pi}\frac{d\vec{l} \times \vec{r}}{|\vec{r}|^3}$$



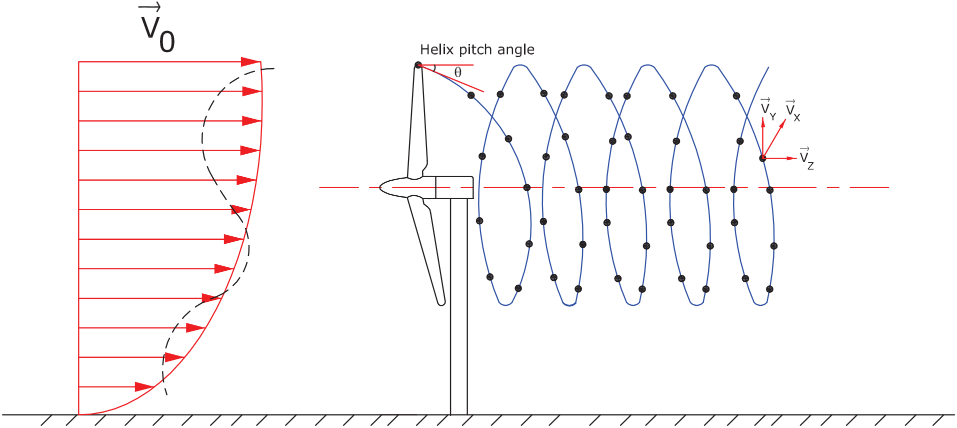
Vortex Flow, Wake Construction

- Modeling the wake behind the rotor by the vortex filament elements.
- Calculating the induced velocity field generated by the trailing vortices.



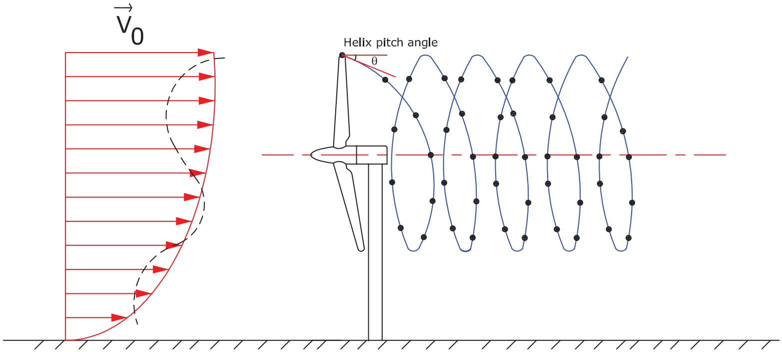
Vortex Method, Wake Modeling

- Prescribed Vortex Wake (forced wake geometry)
- Free Vortex Wake (self-development wake geometry)



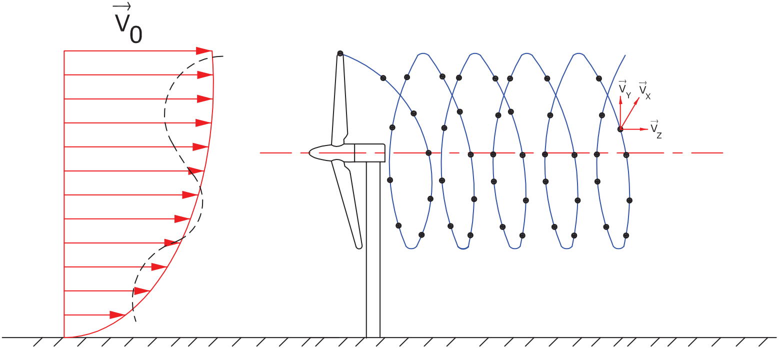
Prescribed Vortex Wake

- **Advantage**
  - More efficient (computational time) than free wake model.
  - Suitable for steady-state inflow condition.
- **Disadvantage**
  - Not suitable for unsteady conditions such as yaw misalignment, turbulent inflow, etc.



Free Vortex Wake

- **Advantage**
  - Applicable for a broad range of wind turbine operating condition such as yaw condition, atmospheric turbulence, ground boundary layer effects and etc.
  - Suitable for unsteady and transient condition.
- **Disadvantage**
  - Computationally expensive than prescribed vortex wake.



Free Vortex Wake, Governing Equation

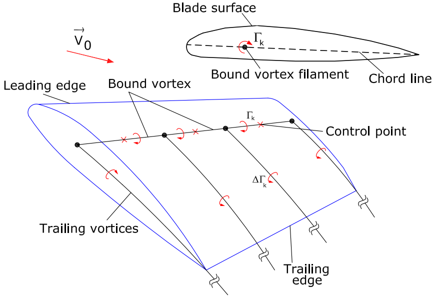
$$\frac{d\mathbf{r}}{dt} = \mathbf{V}(\mathbf{r}, t) \qquad \mathbf{r}(t=0) = \mathbf{r_0}$$

r, position vector of a Lagrangian marker
t, time
V, the total velocity field

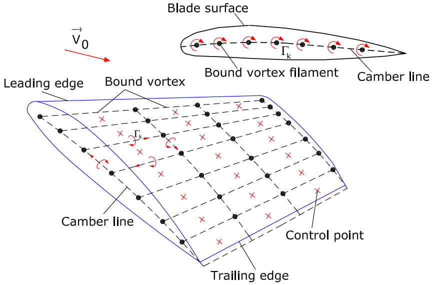
$$\mathbf{V} = \mathbf{V}_\infty + \mathbf{V}_{ind,blade} + \mathbf{V}_{ind,wake}$$

Vortex Method, Blade Modeling

- Lifting line (Replacing the blade with varying strength vortex filament)
- Lifting surface (Replacing the blade surface with vortex panels)



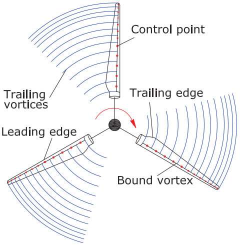
Lifting line



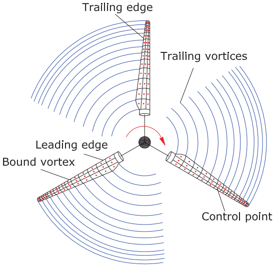
Lifting surface

Different Approaches

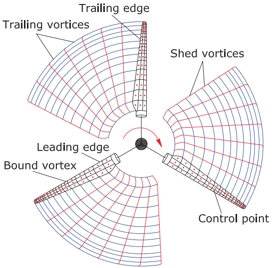
- Lifting Line Prescribed Wake (LLPW)
- Vortex Lattice Prescribed Wake (VLPW)
- Vortex Lattice Free Wake (VLFW)



LLPW



VLPW

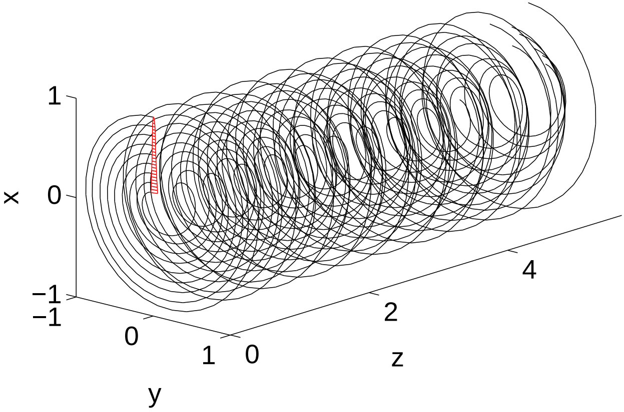


VLFW

RESULTS

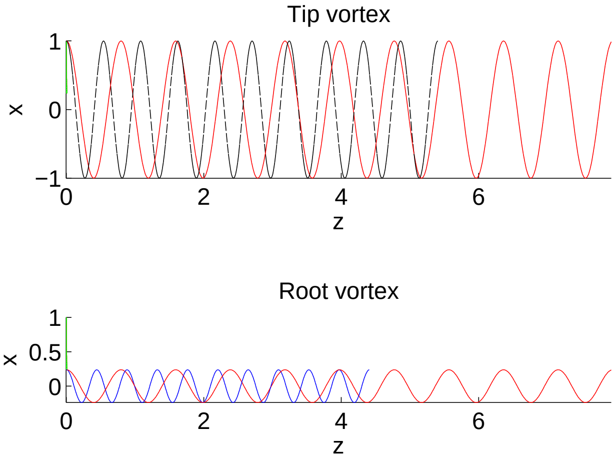
NREL 5-MW Reference Wind Turbine	
Rating	5 [MW]
Rotor Orientation, Configuration	Upwind, 3 Blades
Rotor, Hub Diameter	126 m, 3 m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Rotor Mass	110,000 kg

RESULTS



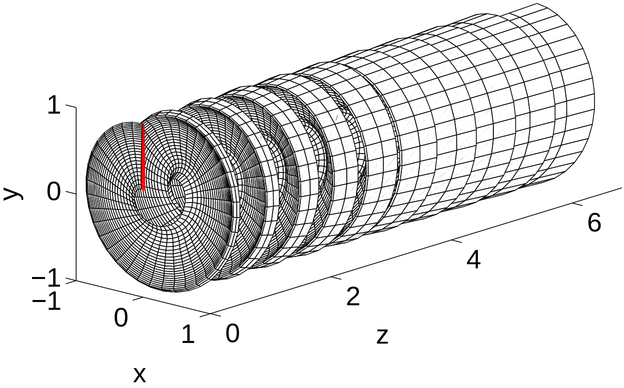
Lifting line prescribed wake (LLPW)

RESULTS



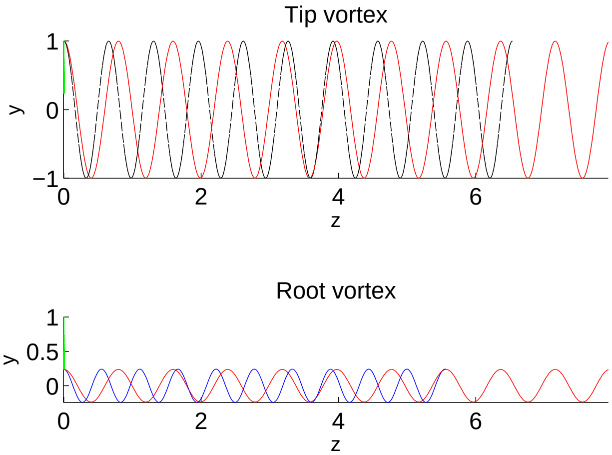
Lifting line prescribed wake (LLPW)

RESULTS



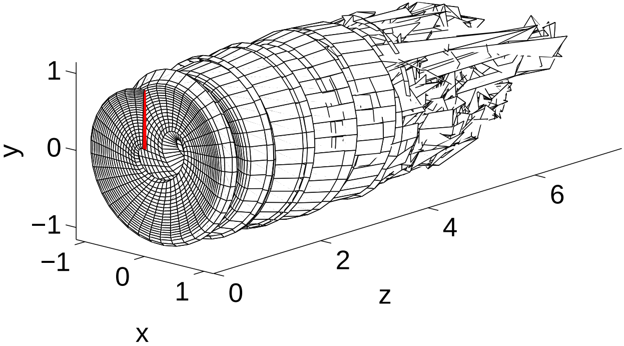
Vortex lattice prescribed wake (VLPW)

Results



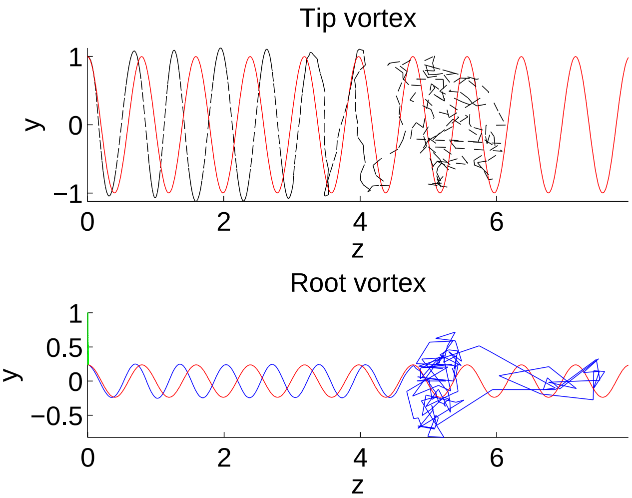
Vortex lattice prescribed wake (VLPW)

RESULTS

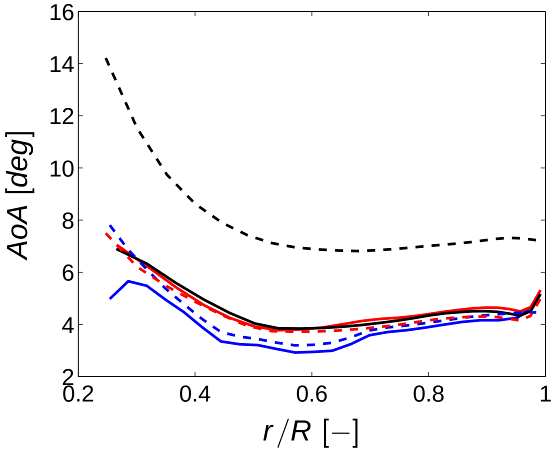


Vortex lattice free wake (VLFW)

RESULTS

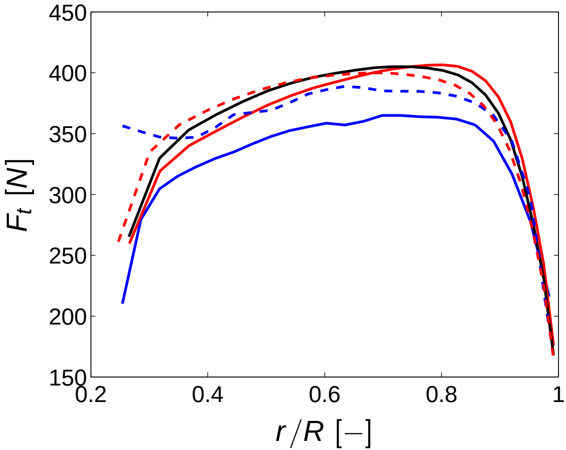


Vortex lattice free wake (VLFW)



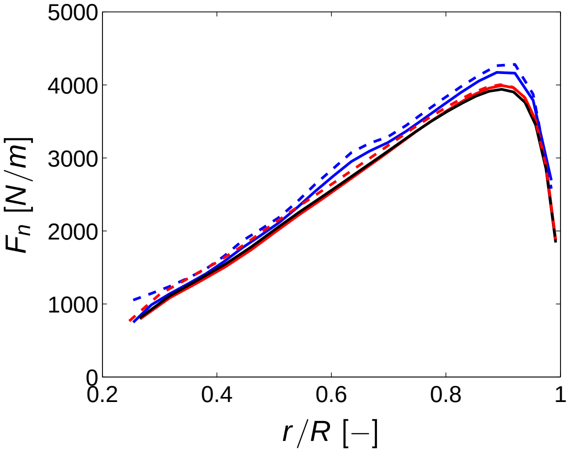
Distribution of the angle of attack along the blade, ——: *LLPW*, ——: *VLPW*, ——: *VLFW*, - - - - - -: *BEM*, - - - - - -: *GENUVP*, - - - - - -: *Geometric*

RESULTS



Distribution of the tangential force along the blade, ——: *LLPW*, ——: *VLPW*, ——: *VLFW*, - - - -: *BEM*, - - - -: *GENUVP*

RESULTS



Distribution of the normal force along the blade, ——: *LLPW*, ——: *VLPW*, ——: *VLFW*, - - - - -: *BEM*, - - - - -: *GENUVP*

RESULTS

Model	**Power** [MW]	**error** [%]	**Thrust** [kN]	**error** [%]
Lifting line prescribed wake	1.819	9.14	379.228	3.79
Vortex lattice prescribed wake	2.002	0.00	359.793	1.52
Vortex lattice free wake	2.002	0.00	360.651	1.28
BEM	1.949	2.64	387.042	5.93
GENUVP	2.002	——	365.360	——

[1]GENUVP is an unsteady flow solver based on vortex blob approximations developed for rotor systems by National Technical University of Athens (NTUA).

Future Outlook

- Developing the free wake code for different operating conditions such as turbulent inflow, yaw condition, separated flow and the blade elastic deformation.
- Ongoing cooperation with Scandinavian Wind AB through the project, Hönö turbine properties and thrust vector at yaw misalignment.
- Coupling the free wake code to the aeroelastic solver called FreeDyn in cooperation with Teknikgruppen.
- Cooperation with the project Fatigue Loads in Forest Regions (TG2-2) through the Swedish Wind Power Technology Centre (SWPTC).

ACKNOWLEDGMENTS

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- The Swedish Wind Power Technology Centre (SWPTC) is a research centre for design of wind turbines. The purpose of the Centre is to support Swedish industry with knowledge of design techniques as well as maintenance in the field of wind power. The research in the Centre is carried out in six theme groups that represent design and operation of wind turbines; Power and Control Systems, Turbine and Wind loads, Mechanical Power Transmission and System Optimisation, Structure and Foundation, Maintenance and Reliability as well as Cold Climate. This project is part of Theme group 2.
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Thanks for your attention

Världens Starkaste Björn (”The World’s Strongest Bear”)