Vortex-lattice-based nonlinear aeroservoelastic modelling and analysis of large floating wind turbines

ConFlex meeting
August 5^{th}, 2021

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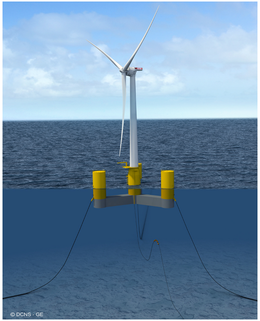
Introduction

Current wind energy challenges

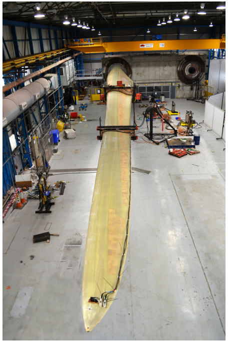
Future wind turbines



https://www.naval-group.com/en/episode/how-to-make-wind-float/

- Large highly-flexible blades
- Complex inflows
- Floating structures
- Expensive testing
- Difficult scaling

Future wind turbines



ORE Catapult https://www.sunwindenergy .com/wind-energy/conducting-flapwise-edgewise-fatigue-parallel

Computational methods that are **efficient and accurate** with the new designs are required

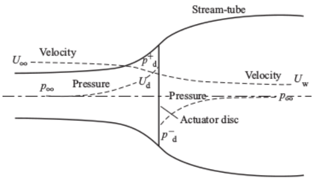
Project objectives

- **Propose improvements** for better trade-offs between cost and accuracy
  - Include viscous drag in UVLM
  - Reduce UVLM computational time
  - Include spanwise sections interaction in BEM
- Investigate different available **modelling fidelities** under real conditions
  - Uniform steady
  - Yaw inflow
  - Turbulent inflow
- Investigate influence of wind turbine **aeroelasticity**
- Include and investigate the influence of **floating dynamics**

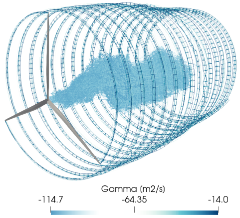
Methods

Imperial College London

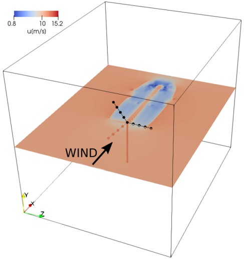
BEM



UVLM



LES-AL



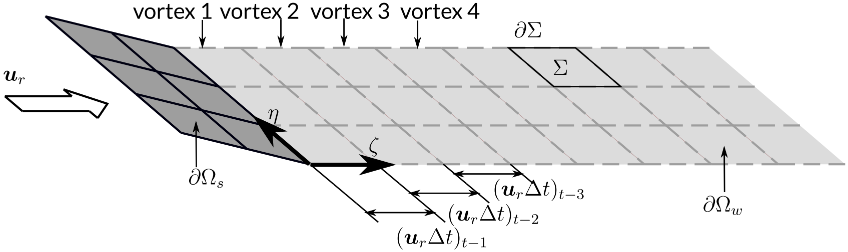
- Very accurate in **steady uniform** inflow
- Very **efficient**
- **Corrections** needed for yaw and turbulence

- Includes **unsteady and 3D** aerodynamic effects
- More computationally expensive than BEM
- No **viscous drag**

- Simulation of **wakes** (low velocity area behind a wind turbine)
- **Interactions** between turbines
- Computationally very **expensive**

UVLM wake convection equation

Solid surface $\partial\Omega_s$ and wake $\partial\Omega_w$ **discretisation** in UVLM:



Each point initially at $\boldsymbol{x}_0$ in the wake moves with the flow velocity $\boldsymbol{u}$

$$\boldsymbol{x}(t) = \boldsymbol{x}_0 + \int_0^t \boldsymbol{u}(\boldsymbol{x}(s), s)ds. \tag{1}$$

Form an **inertial** frame of reference and according to Helmholtz theorem, each closed curve $\partial\Sigma$ keeps its circulation Γ.

UVLM wake convection equation

Using a **non-inertial** frame of reference moving with the solid surface $\partial\Omega_s$, an effective convection is established

$$\frac{\partial\Gamma}{\partial t} + u_r\frac{\partial\Gamma}{\partial\zeta} = 0. \tag{2}$$

The first order upwind discretisation is

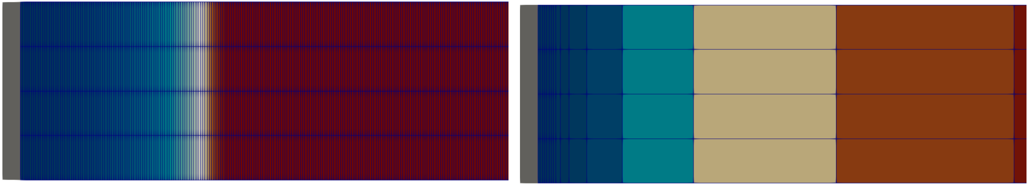
$$\Gamma_\zeta^{t+1} = \left(1 - \frac{u_r\Delta t}{\Delta\zeta}\right)\Gamma_\zeta^t + \frac{u_r\Delta t}{\Delta\zeta}\Gamma_{\zeta-1}^t = (1 - C)\cdot\Gamma_\zeta^t + C\cdot\Gamma_{\zeta-1}^t. \tag{3}$$

Traditionally, UVLM grids are generated such that $C = 1$. It is computationally very efficient because circulation is **shifted** one panel per time step:

$$\Gamma_\zeta^{t+1} = \Gamma_{\zeta-1}^t. \tag{4}$$

UVLM wake convection equation

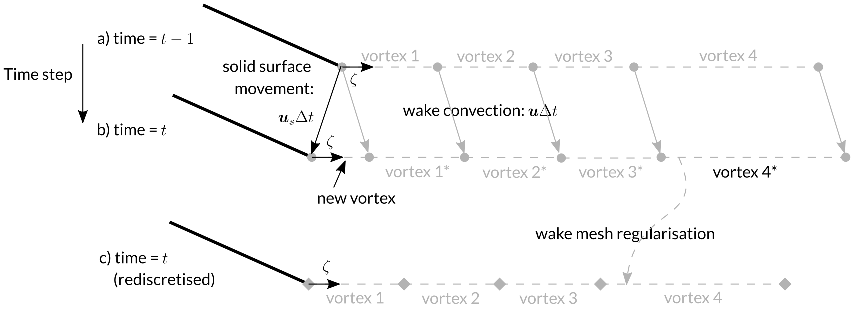
Computation cost grows as $\mathcal{O}(N_w^2)$ with N_w the number of vortices that discretise the wake geometry, thus, Using $C \neq 1$ allows the **coarsening** of panels far away from solid surfaces where their influence is smaller.



Top view of an airfoil and its wake. Traditional discretisation (left) and new discretisation (right)

UVLM wake convection equation

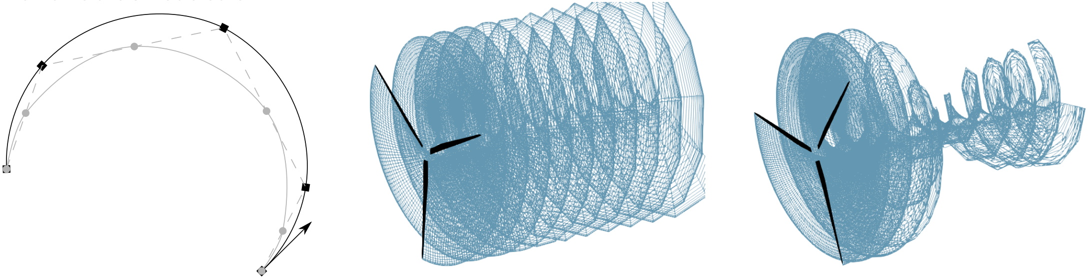
At each time step one panel is created (*new vortex*) and one removed (*vortex* 4^*):



To avoid wake shortening, a **rediscretisation** step is required.
Linear interpolation in Cartesian coordinates for flat airfoil wakes is accurate.

UVLM wake convection equation

Wind turbine **helicoidal wakes** require interpolation in **cylindrical** coordinates to avoid wake radius reduction



a) Scheme *b) t=0 s* *c) t=45 s*

Interpolation of helicoidal wakes in cartesian coordinates

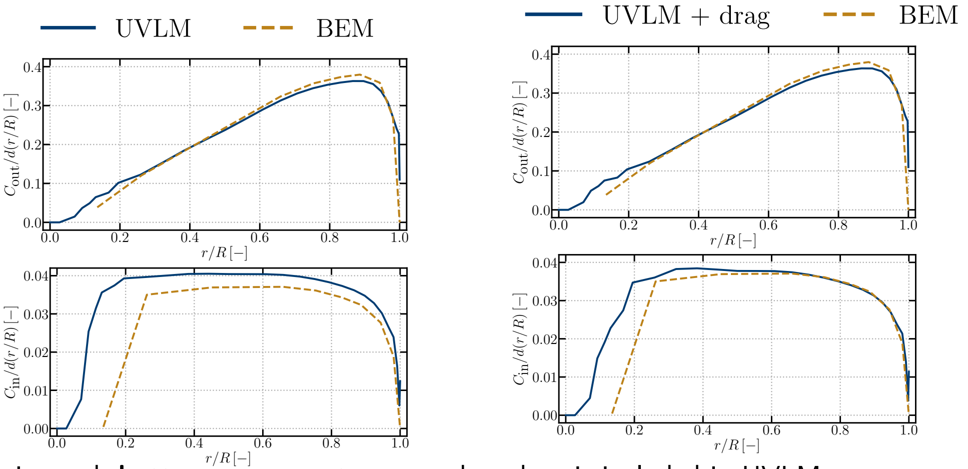
Uniform steady inflow

Include viscous drag in UVLM

Include drag in UVLM from the known **steady state** relationships between lift and drag

Structural loads

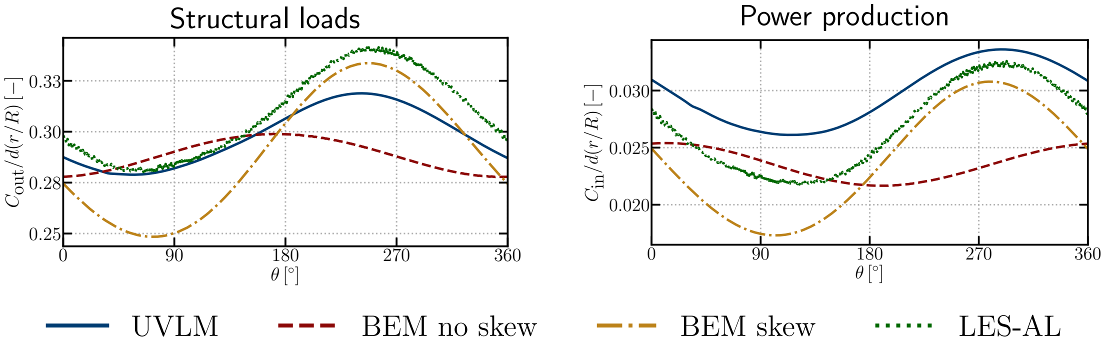
Power production



There is much **better agreement** on c_{in} when drag is included in UVLM

Yawed inflow

Structural loads and power production fluctuate when they are operated in yaw conditions during wind farm control

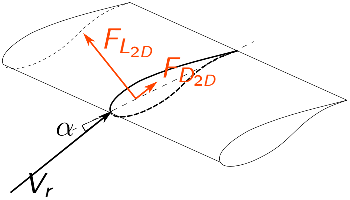


Maximum and minimum loading well captured by UVLM and LES-AL. Skew-wake corrections in BEM improve the results but still predict too large fluctuations

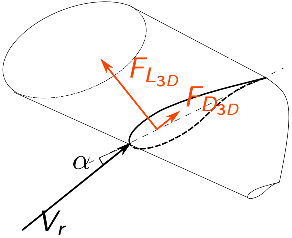
Turbulent inflow

Spanwise-varying loads filter

Wind tunnel experiments



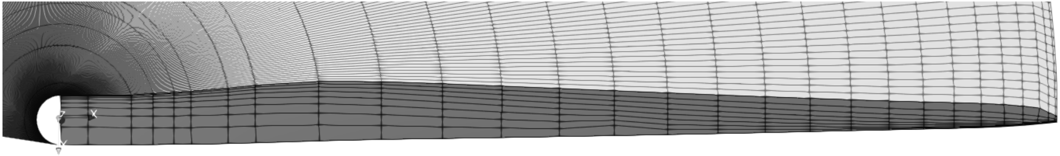
BEM approximation



- Obtain forces as a function of the angle of attack
  - Lift $F_{L_{2D}}(\alpha)$
  - Drag $F_{D_{2D}}(\alpha)$
- **No 3D effects**

- **Assume** $F_{L_{2D}}(\alpha) = F_{L_{3D}}(\alpha)$ and $F_{D_{2D}}(\alpha) = F_{D_{3D}}(\alpha)$
- Except at blade root and tip (Prandtl correction)
- **Fails** if V_r changes along the span: turbulent flows

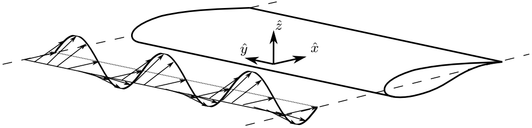
UVLM discretises the **full blade** geometry:



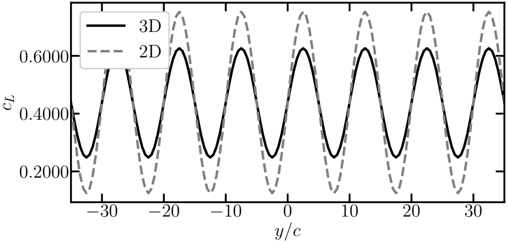
- UVLM accounts for **3D effects** in lift $F_{L_{3D}}(\alpha)$
- Drag $F_{D_{2D}}(\alpha)$ estimation is not accurate
- More **expensive**

Use UVLM to analyse the effects of spanwise-varying flow

Spanwise-varying flow on an airfoil with constant wavelenght



$$\boldsymbol{V}_r = V_x^{\infty}\hat{x} + \left(V_z^{\infty} + \Delta V_z^{\infty}\sin(2\pi y/\Lambda)\right)\hat{z}. \quad (5)$$

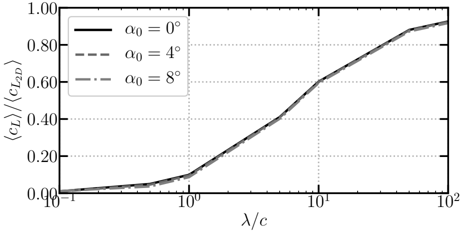


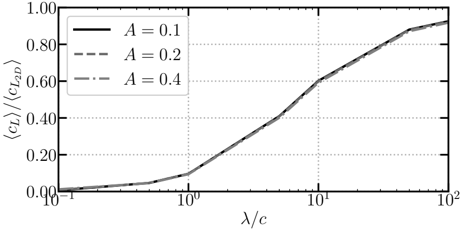
UVLM (3D) and 2D approximations are significantly different. Same average value and different peak-to-peak values.

Turbulent inflow

Spanwise-varying loads filter

Compute the **peak-to-peak** 2D and 3D lift coefficient for different **wavelengths**





2D and 3D ratio is not influenced by the initial angle of attack of the gust intensity. We have created a filter to apply to BEM loads:

$$H_c(\lambda^{-1}) = \mathfrak{c}_L(\lambda^{-1}) / \mathfrak{c}_{L_{2D}}(\lambda^{-1}). \quad (6) \qquad \tilde{c}_L(y) = \mathcal{F}^{-1}\left\{H_c(\cdot)\mathcal{F}\{c_{L_{2D}}\}(\cdot)\right\}(y). \quad (7)$$

with $\mathcal{F}$ the Fourier transform, H_c the filter function and $\tilde{c}_L$ the filterred lift coefficient distribution

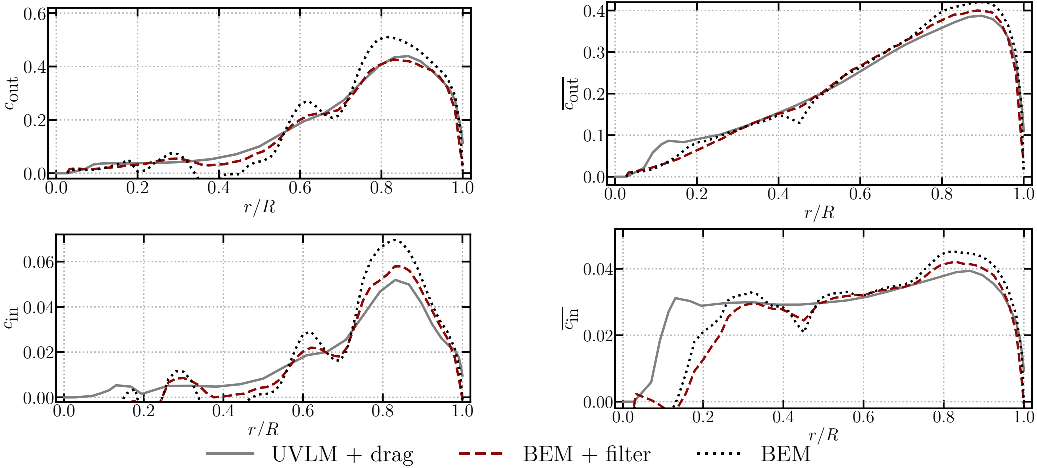
Turbulent inflow

Spanwise-varying loads filter

Loads at a specific time instant | Average loads along a revolution

Struct. loads

Power gen.



BEM + filter in better agreement with UVLM than standard BEM

Main reference: Jonkman, J. M. *Dynamics of offshore floating wind turbines-model development and verification*. Wind Energy, Wiley, 2009, 12, 459-492

Quasisteady mooring: Mooring forces can be defined from the instantaneous location of the mooring fairleads

Hydrostatics: Linearisation around equilibrium position

$$\boldsymbol{F}_{HS} = C\boldsymbol{q}$$

Potential hydrodynamics:

Radiation: Added mass and damping matrices

$$F_{HD} = \left[B(\omega) + \left(A(\infty) - A(\omega)\right) i\omega\right] \dot{\boldsymbol{q}}(\omega)$$

Diffraction: Wave forces

$$F_W(t, \beta) = \mathcal{F}^{-1}\{W(\omega)J(\omega)X(\omega, \beta)\}$$

Viscous drag From Morison's equation

$$F_{HD} = \rho_w C_m V \dot{u} + \frac{1}{2}\boldsymbol{\rho_w C_d A u}|\boldsymbol{u}|,$$

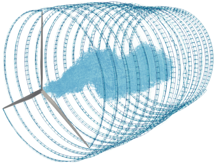
Floating wind turbine

Aeroelastic coupling

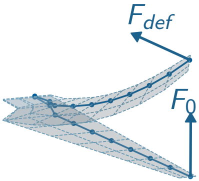
SHARPy: A dynamic aeroelastic simulation toolbox for very flexible aircraft and wind turbines. del Carre, A; Muñoz-Simón, A; Goizueta, N & Palacios, R. Journal of Open Source Software, 2019. `https://github.com/ImperialCollegeLondon/sharpy`

- Changes in **aeroelastic surface** due to deformation
- Include **floating** dynamics
- Modelling of **multibody joints** with Lagrange Multipliers

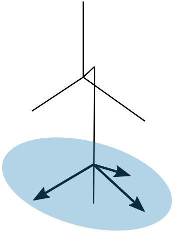
Aerodynamics (UVLM)



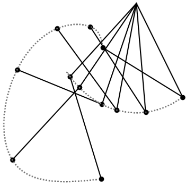
Structure (GEBK)



Floating



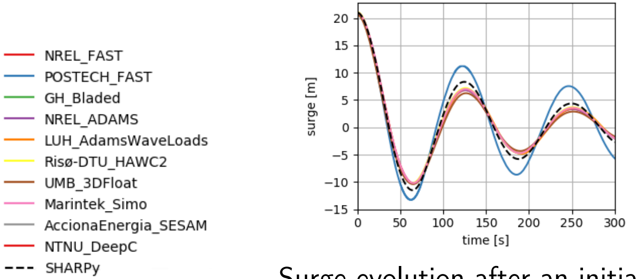
Multibody



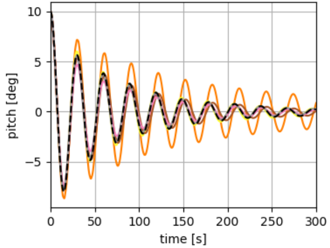
Floating wind turbine

Validation: free decay tests

Test description: The NREL5MW-OC3 is **displaced from the equilibrium** position in each one of the degrees of freedom independently and let evolve (No aerodynamics) The **main movement** of the platform correspond to the degree of freedom that have been initially perturbed. **Good agreement** with the previous literature review with slightly less dissipation

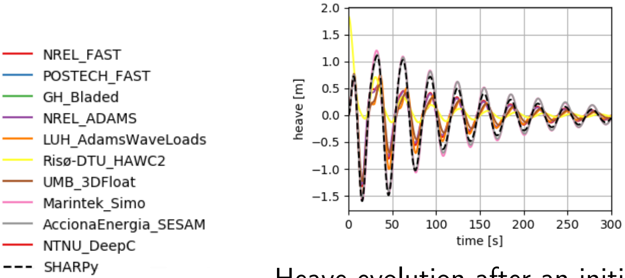


Surge evolution after an initial surge displacement

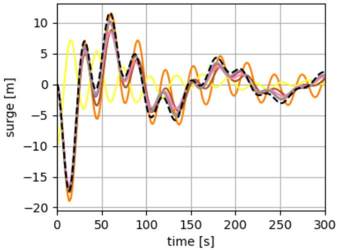


Pitch evolution after an initial pitch displacement

Secondary movements are induced in the platform due to couplings. We have good agreement with the literature results.



Heave evolution after an initial pitch displacement



Surge evolution after an initial pitch displacement

Reference: Jonkman, J. Musial, W. *Offshore Code Comparison Collaboration (OC3) for IEA Wind Task 23 Offshore Wind Technology and Deployment Office of Scientific and Technical Information (OSTI)*, 2010

Conclusions

- Important **unsteady and three-dimensional aerodynamics** in wind turbine rotor aerodynamics
- Proposition of **numerical improvements**
  - Viscous **drag** in UVLM from steady-state look-up tables
  - New **wake convection** equation discretisation in UVLM
  - **Spanwise**-varying loads **filter** for BEM
- Influence of aeroelasticity and floating dynamics on the system

Publications

Conference papers

- Muñoz-Simón, A; Wynn, A & Palacios, R. *Unsteady and three-dimensional aerodynamic effects on wind turbine rotor loads*. AIAA Scitech 2020 Forum, American Institute of Aeronautics and Astronautics, 2020
- Muñoz-Simón, A; Palacios, R & Wynn, A. *Benchmarking different fidelities in wind turbine aerodynamics under yaw*. Journal of physics, conference series, TORQUE2020, 2020.
- Muñoz-Simón, A; Maraniello, S; Palacios, R & Wynn, A. *Efficient aeroelastic modelling of highly-flexible wind turbines*. Wind Energy Science Conference (WESC), 2019.
- Wang, C; Muñoz-Simón, A; Deskos, G; Laizet, S; Palacios, R; Campagnolo, F & Bottasso, C L *Code-to-code-to-experiment validation of LES-ALM wind farm simulators*. Journal of physics, conference series, TORQUE2020, 2020.

Publications

Journal papers

- del Carre, A.; Muñoz-Simón, A.; Goizueta, N. & Palacios, R. *SHARPy: A dynamic aeroelastic simulation toolbox for very flexible aircraft and wind turbines.* Journal of Open Source Software, 2019
- Muñoz-Simón, A; Palacios, R & Wynn, A. *Some modelling improvements for prediction of wind turbine rotor loads in turbulent wind.* Wind Energy (accepted for publication)

PhD status

- Currently in writing up phase
- Thesis submission deadline: September, 30^{th}, 2021
- Thesis examination before end of 2021

Future plans

- Wind energy industry as aeroelasticity engineer
- Research: continue with wind turbine floating dynamics and control

ConFlex

Imperial College London

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