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Advanced wind turbine aerodynamics modelling with a GPU-based vortex solver

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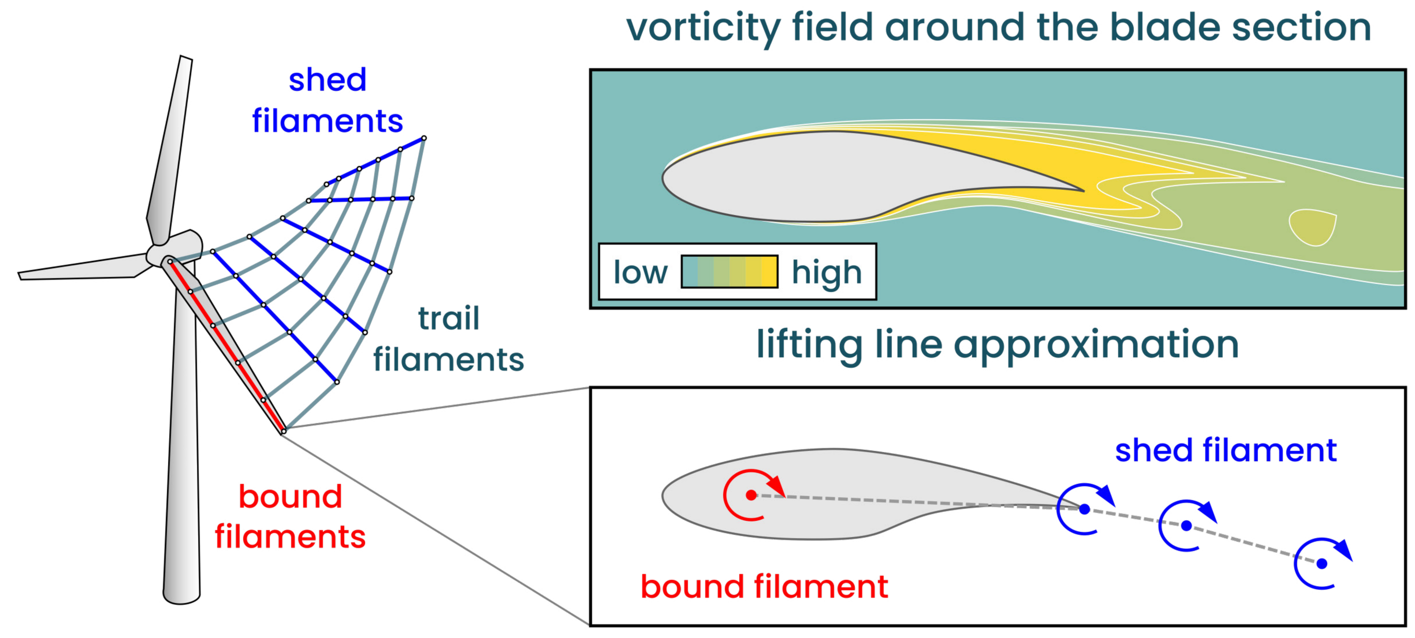
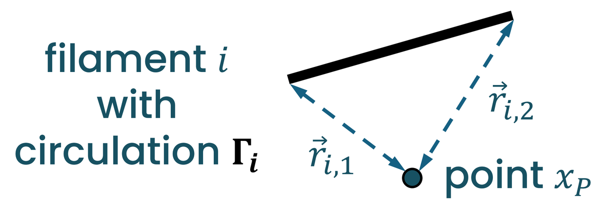
Context

- Industry's standard solver for wind turbines aerodynamics, BEM (**B**lade **E**lement **M**omentum), is based on several approximations and requires numerous corrections (non-planar rotor, unsteady inflow, etc...).
- More complex geometries and flow conditions found in modern turbines demand more accurate modelling.
- The latest increases in GPU's (**G**raphics **P**rocessing **U**nit) performance allow the use of advanced algorithms with affordable computational times.



Methodology

- Vortex methods [1]: Lagrangian representation of the flow field by vortex elements based on the Euler equation and airfoil aerodynamics.
- Vortex filaments are emitted by the blade and advected into the wake. The induced velocity of each filament on a point is calculated using the Biot-Savart law:



$$\mathbf{\Gamma_i} = \frac{1}{2}|\vec{u}|cC_L \qquad \vec{u}_{\Gamma_i}(x_p) = \frac{\mathbf{\Gamma_i}}{4\pi}\frac{(\vec{r}_{i,1} - \vec{r}_{i,2})}{|\vec{r}_{i,1} - \vec{r}_{i,2}|}$$

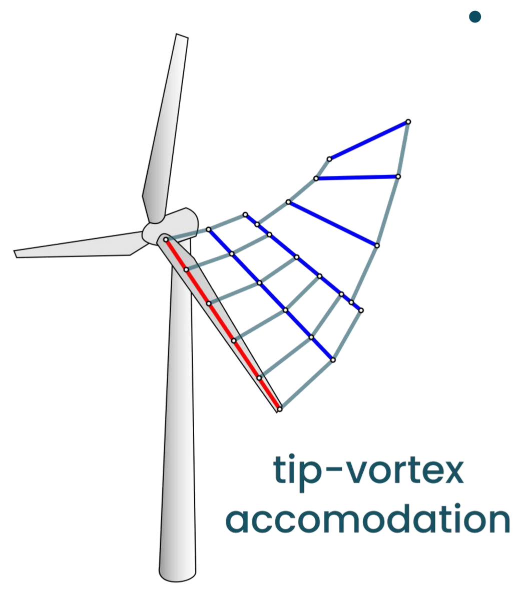
- Each filament has an influence on all others: **N**-body problem that scales with **N**^{2}, more fitted for GPU computations. For **N** filaments:

$$\vec{u} = \vec{U}_\infty + \sum_{i=1}^{N} \vec{u}_{\Gamma_i}$$

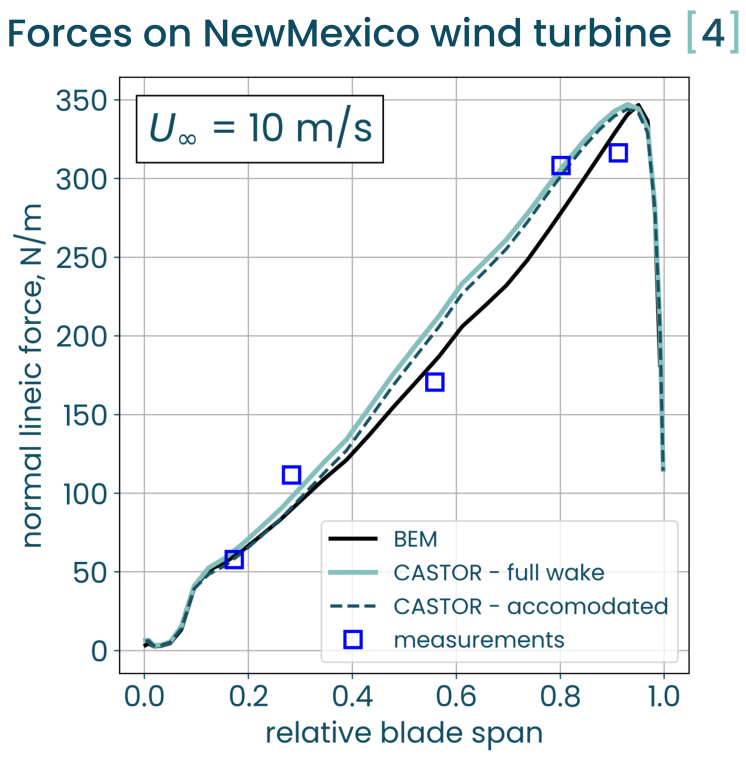
- **CASTOR** - *Code **A**érodynamique pour la **S**imulation de **T**urbines **O**ffsho**R**e*
  - Wake representation with filament and/or particles
  - CUDA (GPU) implementation
  - Advanced wake accommodation [2]: shed-merging, trail-merging, tip-vortex [3]
  - Coupled with hydro-servo-aero-elastic solver **DeepLines**™ principia-group.com/blog/product/deeplines-wind/

Results & Performance

- Validated for different test cases, good results obtained even under complex conditions: yaw, unsteady inflow.
- Almost real-time response when combined to accommodation techniques.



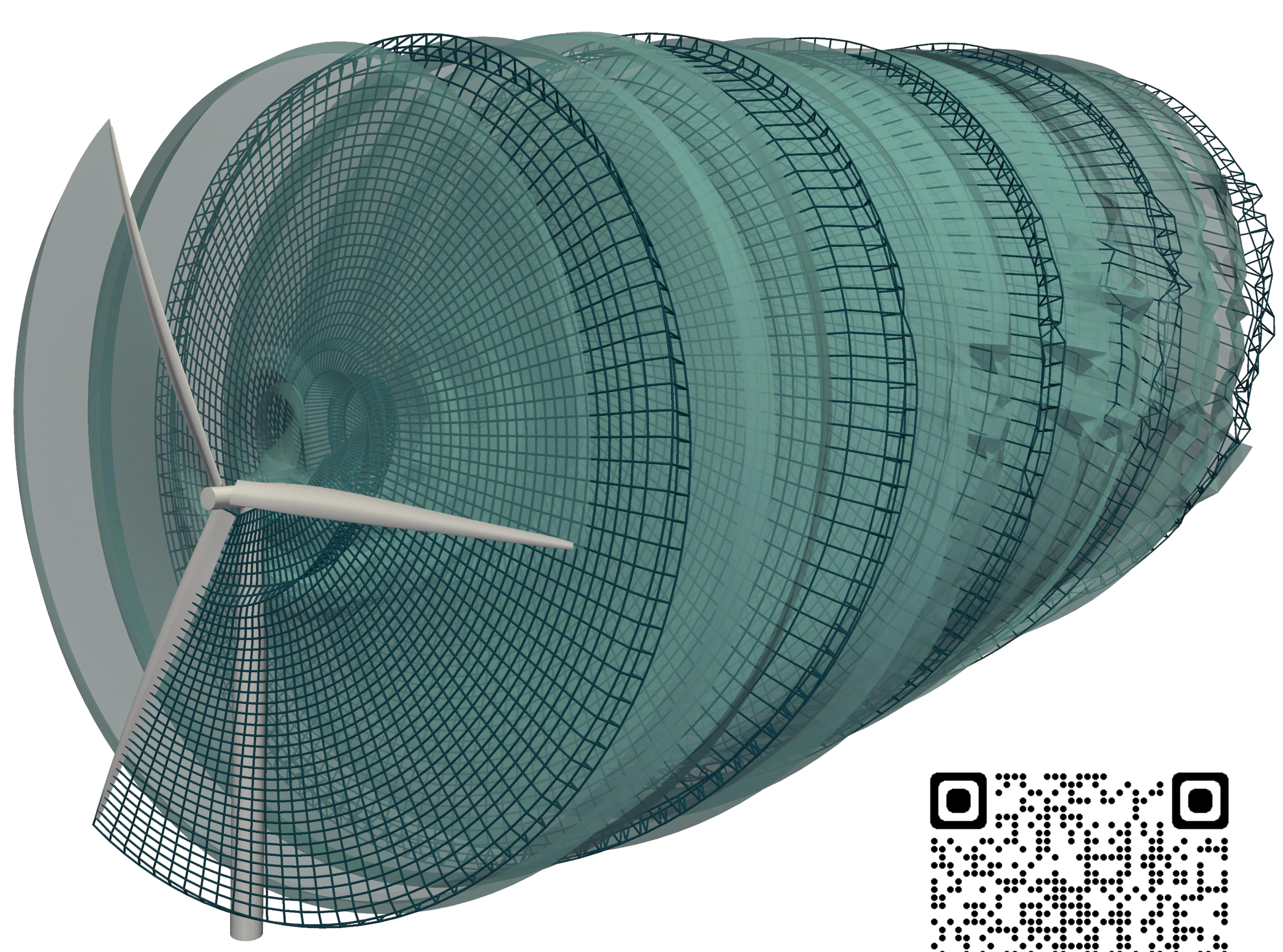
Forces on NewMexico wind turbine [4]



Aero-hydro-servo elastic simulations of the NREL 5 MW on a semi submersible floater (hydro 3p2 case [5]), from [2]

performance	BEM (CPU)	CASTOR (GPU)	
		full-wake	tip-vortex*
computational time, s	2029	73319	5747
ratio to real-time	0.56	20.36	1.59

*: tip-vortex accommodation applied after the first rotation



Conclusions & perspectives

- Vortex methods are strong candidates to replace BEM solver in state-of-the-art wind turbine design in complex scenarios.
- They are adapted to large offshore wind turbines, and, thanks to GPU acceleration combined with wake accommodation techniques, almost real-time response is obtained.
- On-going developments and investigations:
  - vortex core models and automated wake accommodation parametrization
  - modelling of viscosity decay and incoming turbulence
  - algorithm optimization and multipole methods

References: [1] Cottet & Koumoutsakos, *Vortex Methods: Theory and Practice* 2000; [2] Blondel et al., *Towards vortex-based wind turbine design using GPUs and wake accommodation* TORQUE 2024 [3] B. Montgomery, FOI Swedish Defense Research Agency report, 2004. [4] K. Boorsma et al., *Final report of IEA Wind Task 29 Mexnext (Phase 3)*, 2018 [5] A. Robertson et al., *OC4 Within IEA Wind Task 30: Phase II*, OMAE 2014.