A new framework for aeroelastic simulation of offshore wind turbine megastructures

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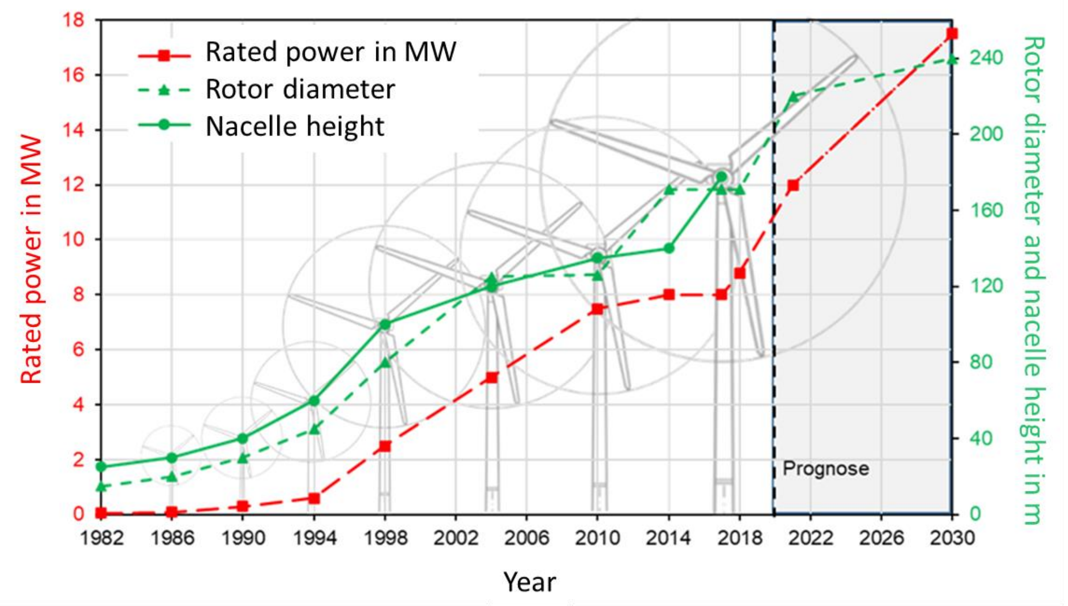
Motivation

CRC 1463
Offshore-
Megastructures

- Increasing structure sizes of future wind turbines due to the need for efficiently produced clean energy
- Instead of upscaling new designing methods are needed
- Developing a simulation tool to analyze the aeroelastic behavior including all nonlinear dynamic interactions, e.g.
  - Structural nonlinearities
  - Fluid-Structure-Interaction
  - Wind turbine control
- Simulation framework DeSiO
  - State of the art mid-fidelity methods
  - Computationally efficient yet sufficiently accurate



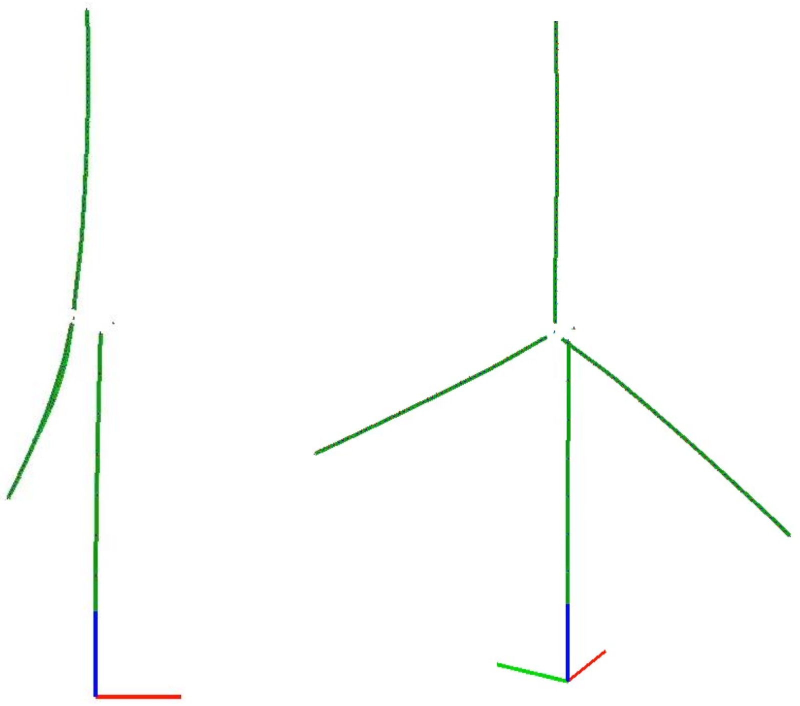
Structural Model

- Multibody system for rigid and flexible structures
- Governing equation derived using Hamilton's principle
- Total Lagrangian Description
- Director-based kinematics
- Holonomic and non-holonomic constraints
- Energy-conserving/dissipative, momentum-conserving time integration method
- Several analyses: nonlinear static, nonlinear dynamic, buckling and modal analyses

$$\mathcal{S} = \int_{t_1}^{t_2} \Big(\mathcal{K}(\boldsymbol{v};t) - [\mathcal{W}(\boldsymbol{x};t) - \mathcal{P}(\boldsymbol{x};t)] + \boldsymbol{\lambda}(t) \cdot \boldsymbol{h}(\boldsymbol{x};t) + \boldsymbol{v}(t) \cdot [\boldsymbol{l}(\boldsymbol{v};t) - \boldsymbol{l}(\dot{\boldsymbol{x}};t)] \Big) \, \mathrm{d}t$$

kinetic energy; strain energy; external work; constraints; momentum

$$\delta \mathcal{S} = 0$$



Left: Modal analysis, first eigenmode
Right: Transient simulation
NREL 15 MW turbine

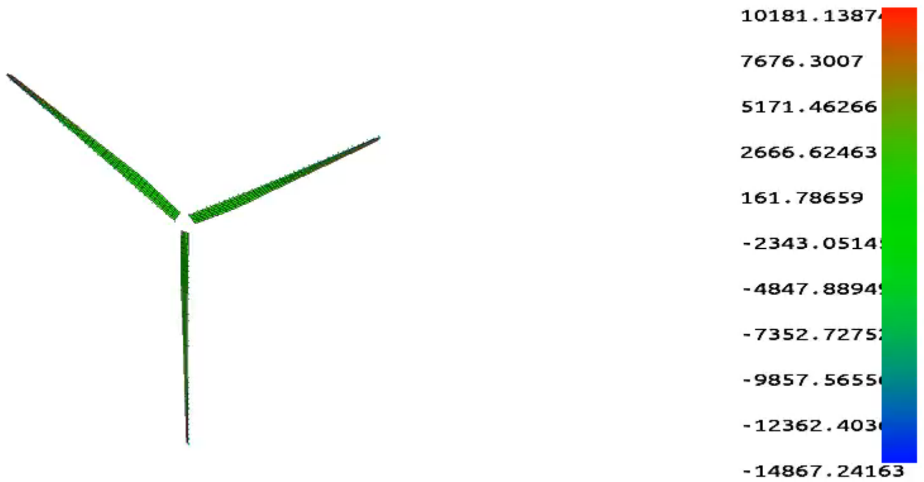
Aerodynamic Model

- We use the Unsteady Vortex Lattice Method (UVLM)
- Computationally fast yet sufficiently accurate
- Advantages of this method are e.g., (compared with the Blade Element momentum theory):
  - More accurate realization of aerodynamic response
  - Full free wake, unsteady effects
  - Considering aeroelastic stability effects
  - No restriction of camber and/or angle of attack
- Assumptions
  - Incompressibility of the fluid
  - Neglecting viscous phenomena like turbulences

Non penetration condition: $\boldsymbol{v} \cdot \boldsymbol{n} = 0$

$$\boldsymbol{v} = \underbrace{\boldsymbol{v}_\infty}_{\text{free field}} + \overbrace{\boldsymbol{v}_s}^{\text{surface}} + \underbrace{\boldsymbol{v}_{v,surf}}_{\text{vortex-induced surface}} + \overbrace{\boldsymbol{v}_{v,wake}}^{\text{vortex-induced wake}}$$

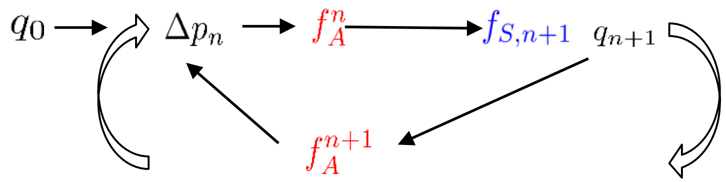
$$\boldsymbol{v}_v(\boldsymbol{r};t) = \frac{\Gamma}{4\pi} \frac{(r_1 + r_2)\boldsymbol{r}_1 \times \boldsymbol{r}_2}{r_1 r_2 (r_1 r_2 + \boldsymbol{r}_1 \cdot \boldsymbol{r}_2) + r_c^2}$$



Fluid-Structure-Interaction

- A weak coupling between the structural and aerodynamic models leads to a slow convergence towards the exact solution
  - Weak coupling: Structural and aerodynamic contributions are calculated at different time steps: f_A^n , f_S^{n+1}
- A strong coupling between the structural and aerodynamic models leads to a faster convergence towards the exact solution
  - Strong coupling: Structural and aerodynamic contributions are calculated at the same time step: f_A^{n+1}, f_S^{n+1}
- The nonlinear governing equation is solved using Newton's method: Therefore the aerodynamic load needs to be linearized along the strong coupling

Schematic structure of a weak coupling



Governing equation for the weak coupling

$$\boldsymbol{g}^{weak}_{n+\frac{1}{2}} = \begin{bmatrix} \boldsymbol{f}_d^{int}(\boldsymbol{q}_{n+1}, \boldsymbol{q}_n, \boldsymbol{s}_{n+1}, \boldsymbol{s}_n) - \boldsymbol{f}_d^{ext}(\boldsymbol{q}_{n+1}, \boldsymbol{q}_n) + \dot{\boldsymbol{l}}_d(\boldsymbol{s}_{n+1}, \boldsymbol{s}_n) + \boldsymbol{H}_d^T(\boldsymbol{q}_{n+1}, \boldsymbol{q}_n) \cdot \boldsymbol{\lambda}_{n+1} - \boldsymbol{f}_A(\boldsymbol{q}_n, \boldsymbol{s}_n) \\ \boldsymbol{h}_d(\boldsymbol{q}_{n+1}, \boldsymbol{q}_n) \\ \boldsymbol{l}_d(\boldsymbol{s}_{n+1}, \boldsymbol{s}_n) - \boldsymbol{l}_d(\boldsymbol{q}_{n+1}, \boldsymbol{q}_n) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

Schematic structure of a strong coupling

Governing equation for the strong coupling

$$\boldsymbol{g}^{strong}_{n+\frac{1}{2}} = \begin{bmatrix} \boldsymbol{f}_d^{int}(\boldsymbol{q}_{n+1}, \boldsymbol{q}_n, \boldsymbol{s}_{n+1}, \boldsymbol{s}_n) - \boldsymbol{f}_d^{ext}(\boldsymbol{q}_{n+1}, \boldsymbol{q}_n) + \dot{\boldsymbol{l}}_d(\boldsymbol{s}_{n+1}, \boldsymbol{s}_n) + \boldsymbol{H}_d^T(\boldsymbol{q}_{n+1}, \boldsymbol{q}_n) \cdot \boldsymbol{\lambda}_{n+1} - \boldsymbol{f}_A(\boldsymbol{q}_{n+1}, \boldsymbol{q}_n, \boldsymbol{s}_{n+1}, \boldsymbol{s}_n) \\ \boldsymbol{h}_d(\boldsymbol{q}_{n+1}, \boldsymbol{q}_n) \\ \boldsymbol{l}_d(\boldsymbol{s}_{n+1}, \boldsymbol{s}_n) - \boldsymbol{l}_d(\boldsymbol{q}_{n+1}, \boldsymbol{q}_n) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$