INFLUENCE OF AERODYNAMIC MODEL FIDELITY ON ROTOR LOADS DURING FLOATING OFFSHORE WIND TURBINE MOTIONS

DENIS MATHA¹,²*, LEVIN KLEIN³, DIMITRIOS BEKIROPoulos³, PO WEN CHENG²

¹RAMBOLL WIND, GERMANY * (PREVIOUSLY WITH ²)
²STUTTGART WIND ENERGY, UNIVERSITY OF STUTTGART, GERMANY
³INSTITUTE OF AERODYNAMICS AND GAS DYNAMICS, UNIVERSITÄT STUTTGART, GERMANY
INTRODUCTION
**INTRODUCTION**

**Accuracy / Cost**
- full CFD-FEM FSI methods

**State-of-the-art**
- Aero-servo-hydro-elastic coupled analysis

**Design validation, optimization & certification**
- Frequency domain methods
- Semi-empirical methods (Morison)

**Efficiency / Speed**
- Reduced nonlinear coupled models

**Typical Application:**
- Component level / Detailed Design, validation
- Pre-design & Optimization

**Coupled / de-coupled**
INTRODUCTION

Probability of occurrence

Uncertainty
Design Risk
Optimization potential

Focus of this Work

Measurements

Advanced Tools

State-of-the-art tools

Loads

Signe Schløer, Bo Terp Paulsen, Henrik Bredmose, OMAE2014-24684, „APPLICATION OF CFD BASED WAVE LOADS IN AEROELASTIC CALCULATIONS“
INTRODUCTION

FOWT modelling research primarily focuses on hydrodynamics and mooring line dynamics

Leading Question for this Study

- What is the impact of Aerodynamic Model Fidelity on Rotor Loads during Floating Offshore Wind Turbine Motions?

Presented work is related to

- OFFWINDTECH Project within EU KIC Framework and associated PhD projects in Stuttgart
- Similar questions related to model fidelity are also investigated in ongoing EU project, e.g. LIFES50+
- (no results from LIFES50+ are presented)

Presented results were generated primarily at Stuttgart Wind Energy
INTRODUCTION

Aerodynamic effects on a floating offshore wind turbine

- **Blade motion**
  - Pitching
    - Blade torsion
    - Pitch control
  - Flapping
    - Blade bending

- **Inflow / Wake variation**
  - Periodic
    - Wind shear
      - Rotor tilt / yaw / cone
    - Tower shadow
  - Aperiodic
    - Wind turbulence
    - Wind gusts
    - Wake dynamics

- **Platform motion**
  - Rotation
    - BVI / wake interaction
  - Translation
    - BVI / wake interaction
    - Oblique inflow
    - Inflow velocity changes
    - Blade AoA variation
INTRODUCTION

- Complex 3d viscous & rotational effects
- Complex rotor interaction with
  - tower & nacelle
  - turbulent atmospheric boundary layer
  - (half) wake
  - Structure
- Wave & wind induced platform motion
  - unsteady aerodynamic effects

---

Percentage of aerodynamically unsteady \((k > 0.05)\) to total energy from \(\alpha\) PSDs:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Monopile</th>
<th>OC3Spar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below Rated</td>
<td>0.3 %</td>
<td>18.0 %</td>
</tr>
<tr>
<td>Rated</td>
<td>1.7 %</td>
<td>17.9 %</td>
</tr>
<tr>
<td>Above Rated</td>
<td>0.1 %</td>
<td>17.9 %</td>
</tr>
</tbody>
</table>

APPROACH
Modification of Blades & Controller:

- Recalculated airfoil tables
  - XFOIL (panel & BL code) generated to ensure comparability with new airfoils
  - Applied Viterna extrapolation, Snel 3D corrections & DS parameters for use in BEM

- Changed aerodynamic & structural twist angle
  - Goal: At rated wind speed, a lift coefficient close to today's high performance blade designs
  - $c_L > 1.1$ (from $c_L > 0.95$)

- Changed generator torque controller constant
  - Adjusted for blade modifications
**APPROACH**

**AERODYNAMIC MODELS**

**BEM: Blade Element Momentum Theory**
- State-of-the-art in aero-servo-hydro-elastic FOWT load simulation
- Basic idea: Balance of forces in axial (and tangential) directions from global momentum balance with Forces at the local blade element
- Encompasses various assumptions & semi-empirical correction models

**LLFVWM: Lifting Line Free Wake Vortex Method (Potential Flow)**
- Vorticity in the volume is lumped into vortex lines
  - Blade: Lifting Line (airfoil tables req.)
  - Wake: Free surface of shed vortices
- Dynamic wake effects and local blade aerodynamics are inherently represented

**CFD: (U)RANS (Unsteady Reynolds-Averaged Navier-Stokes)**
- State of the art for complex turbulent flow simulations (not yet in wind)
- Turbulence models are applied to solve the NSE
APPROACH
CFD MODEL

- Extended Block-structured Code
  FLOWER (DLR)
- 14 components
- CHIMERA overlapping mesh technique

- Background mesh
  - 400m x 400 m x 520 m
  - $\Delta_{xyz} \approx 2 \text{ m}$
- Approx. 30 million cells
- 0.014s time-step size ($\equiv 1^\circ$)
- $k-\omega$ turbulence model
APPROACH
AERODYNAMIC ANALYSIS

1. Model Setup in 5 different aerodynamic codes, covering 3 methodologies using SIMPACK as structural WT model

2. Verification of baseline onshore loads

3. Selection of Floating Cases
   a) Extreme motions for CFD analyses for limited conditions
   b) IEC operating DLCs for inflow condition analysis

4. Performing load cases a) & b)

5. Analyzing extreme loads & inflow conditions
RESULTS
RESULTS
VERIFICATION OF ONSHORE LOADS

- Parametric correction model study performed to identify causes for large >12% torque deviations
- Significant influence from turbulent wake state (Glauert) correction observed due to high rotor induction level

\[ \alpha_c = 0.2 \]
RESULTS
TURBULENT WAKE STATE CORRECTION

- Turbulent wake state correction is an empirical modification for high induction factors, where the momentum equation breaks down and predicts multiple flow directions in the wake.

\[ \alpha_q = \frac{1}{1 + 4F \sin(\varphi)^2} \]

\[ a = \frac{4a_c^2F - CT}{(8a_c - 4)F} \]

\[ a > \frac{1}{3} \]
RESULTS
EXTREME MOTION ANALYSIS - THRUST

NRMSE \sim 17-19\% 

Dynamic Inflow identified as largest influence on thrust and torque differences of BEM and FVM/CFD loads
*additional pos. timeshifts
RESULTS
EXTREME MOTION ANALYSIS - TORQUE

NRMSE $\sim 24-29\%$

<table>
<thead>
<tr>
<th>Method</th>
<th>$NRMSE(T)$</th>
<th>$NRMSE(Q)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEM no DynIn</td>
<td>17-19%</td>
<td>24-29 %</td>
</tr>
<tr>
<td>AM BEM w. DynIn $a_c = 0.20 - 0.38$</td>
<td>$\sim 7%$</td>
<td>6-10 %</td>
</tr>
<tr>
<td>FVM</td>
<td>1-3%</td>
<td>2-6 %</td>
</tr>
</tbody>
</table>
RESULTS
EXTREME MOTION ANALYSIS – DYNAMIC INFLOW

- Simple model confirms influence of Dynamic Inflow during motions
- Sensitivity to model and time constants
- Particular relevance at specific wave periods

\[
L \cdot C_T = \tau \cdot \dot{a} + a
\]

\[
T_{DynInf} = \frac{D}{V_\infty} = \frac{126 \text{m}}{11.3 \text{m/s}} = 11.15 \text{s}
\]

\[
\tau_{GH} > \tau_{ECN} > \tau_{DTU} > \text{equil.}
\]
RESULTS
FLOW FIELD ANALYSIS

$T = 131 \text{s}$

FVM: Sensitive to vortex core models
CFD: Sensitive to $y^+$ and turbulence models

\[ \frac{k_i}{2|\vec{V}|} = \frac{\omega_{ptfm} c_i}{2\sqrt{U_\infty^2 + (r_i \Omega)^2}}. \]
RESULTS
FLOW FIELD ANALYSIS

Unsteady effects
Local blade load distrib. differences:
RESULTS

INFLOW CONDITIONS

Minor impact on design point: \( c_{l,\text{ref}}, M_{\text{a,ref}}, R_{\text{e,ref}} \)

Larger airfoil design range: \( \Delta c_l, \Delta M_{\text{a}}, \Delta R_{\text{e}} \)

IEC DLC 1.1 @ rated wind
CONCLUSION
CONCLUSION

- Study on aerodynamic model fidelity influence on FOWTs
- Models setup for BEM, FVM and CFD methods

Dynamic Inflow with important influence on thrust and torque loads and timeshifts for FOWTs

TWS correction is important for rotors operating at high induction levels, as likely for FOWTs

Other unsteady effects
Local blade loads influenced by flow separation & BVI

Inflow conditions
Design point not-influenced
Design range increased

- Use Dynamic Inflow models with appropriate time const.
- Critical assessment of local blade loads
CONCLUSION

Upcoming IEC 61400-3-2

“IEC 61400-3-1 clause 7.3.3 is generally applicable. The aerodynamic interaction between the airflow and the FOWT is of special importance due to their additional compliance and increased dynamic response. The interaction of potentially large translational and rotational motions of the floating sub-structure with the aerodynamic loading of the RNA and tower shall be considered, including aeroelastic effects and the associated global and local dynamic and unsteady aerodynamic effects (e.g. dynamic inflow, oblique inflow, skewed wake, unsteady airfoil aerodynamics including dynamic stall, blade-vortex interaction). Wind loads on the floating sub-structure shall also be considered, where relevant.”
THANK YOU