Dynamic Responses of Jacket-Type Offshore Wind Turbines using Decoupled and Coupled Models

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Overview of Presentation

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- Description of the dynamic models
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  - SIMO-RIFLEX-AeroDyn (SRA)
  - Decoupled SIMO-RIFLEX-AeroDyn (SRA*)
- Environmental conditions
- Results and discussion of coupled nonlinear and decoupled linear models
  - Eigen-frequency analysis
  - Decay test
  - Wave-only simulations
  - Decoupling method
  - Computational efficiency
- Conclusion
Introduction

Types of Offshore Wind Turbines

- Bottom-fixed Wind Turbines:
  - Monopile
  - Tripod
  - Lattice

- Floating Wind Turbines:
  - TLP
  - Semi-submersible
  - Spar
Objectives

• The objective of this study is to evaluate the applicability of a computationally efficient linear decoupled model by comparing with results obtained from a nonlinear coupled model.

• The aerodynamic and hydrodynamic loads are calculated for several environmental conditions.

• The decoupled analysis was carried out using NIRWANA, whereas the coupled analysis was performed using SIMO-RIFLEX-AeroDyn. Both programs are based on time-domain FE methods.
Description of Dynamic Models

OC4 5 MW Jacket Wind Turbine

The turbine will be mimicked by equivalent point loads, point masses and a damper.

- Linear
- Hydroelastic
- Decoupled

- Non-linear
- Hydro-servo-aero-elastic
- Coupled

50m water depth, fixed bottom (no soil model)

NIRWANA

SIMO-RIFLEX-AeroDyn (SRA)
The turbine will be mimicked by equivalent point loads, point masses and a damper.

- Non-linear
- Hydroelastic
- Decoupled

Decoupled SIMO-RIFLEX-AeroDyn

SRA*
50m water depth, Hub Height = 90.55m

35m water depth, Hub Height = 87.4m
Long et al. (2012), Ong et al. (2017)
Environmental Conditions

<table>
<thead>
<tr>
<th>Index</th>
<th>Wind speed at the hub $V_{hub}$ (m/s)</th>
<th>Linear Random Waves</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$H_s$ (m)</td>
</tr>
<tr>
<td>EC1</td>
<td>7</td>
<td>0.63</td>
</tr>
<tr>
<td>EC2</td>
<td>11.4</td>
<td>1.69</td>
</tr>
<tr>
<td>EC3</td>
<td>15</td>
<td>2.85</td>
</tr>
<tr>
<td>EC4</td>
<td>20</td>
<td>4.67</td>
</tr>
</tbody>
</table>

The wave conditions were obtained using a wind-wave model proposed by Ong et al. (2013) based on the corresponding wind speeds.
Results and Discussion

1. Eigenfrequency analysis

2. Decay test

3. Wave-only simulations

4. Decoupling method 2 (Selected forces and moments from the isolated rotor + aerodynamic damper)

5. Computational efficiency
### 1) Eigenfrequency Analysis

<table>
<thead>
<tr>
<th>Items</th>
<th>Natural Periods (s)</th>
<th>NIRWANA</th>
<th>SIMO-RIFLEX-AERODYN</th>
<th>Popko et al. (2012)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Fore-Aft</td>
<td></td>
<td>3.31</td>
<td>3.34</td>
<td>3.13-3.34</td>
</tr>
<tr>
<td>1st Side-Side</td>
<td></td>
<td>3.33</td>
<td>3.35</td>
<td>3.13-3.33</td>
</tr>
<tr>
<td>2nd Fore-Aft</td>
<td></td>
<td>0.90</td>
<td>0.840</td>
<td>0.820-0.93</td>
</tr>
<tr>
<td>2nd Side-Side</td>
<td></td>
<td>0.88</td>
<td>0.82</td>
<td>0.76-0.90</td>
</tr>
<tr>
<td>1st Flapwise blade</td>
<td></td>
<td>-</td>
<td>1.60</td>
<td>1.43-1.75</td>
</tr>
<tr>
<td>1st Edgewise blade</td>
<td></td>
<td>-</td>
<td>0.94</td>
<td>0.90-1.06</td>
</tr>
</tbody>
</table>

![Diagram of initial and modified states](image)
2) Decay Test

1) Increase the load slowly to 900kN.
2) Hold the load for the static equilibrium, then remove the load.
3) Let the decay occur.

Stiffness-proportional damping is applied.

<table>
<thead>
<tr>
<th></th>
<th>Observed structural damping $\lambda$ (% critical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIRWANA</td>
<td>0.36</td>
</tr>
<tr>
<td>SIMO-RIFLEX</td>
<td>0.38</td>
</tr>
</tbody>
</table>

![Chart showing observed structural damping for NIRWANA and SIMO-RIFLEX.]
Locations for decoupled and coupled model result comparisons

Tower top (0,0,88.15)

Tower base (0,0,20.15)

Element 1
3) Wave-only simulations

Point mass/inertia (5 MW Wind turbine)
EC4 Largest Waves

<table>
<thead>
<tr>
<th>Index</th>
<th>Mean (kN)</th>
<th>Standard Deviation (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NIRWANA</td>
<td>SIMO-RIFLEX-AeroDyn</td>
</tr>
<tr>
<td>EC3</td>
<td>$-3.91 \times 10^3$</td>
<td>$-3.86 \times 10^3$</td>
</tr>
<tr>
<td>EC4</td>
<td>$-3.91 \times 10^3$</td>
<td>$-3.86 \times 10^3$</td>
</tr>
</tbody>
</table>
4) Decoupling method (NIRWANA)

Thrust and torque from an isolated rotor model (AeroDyn) including the upwind tower influence

Damper to account for Aerodynamic damping ~ C U_{\text{hub}}

\[ C = \frac{dF_T}{dV_{\text{hub}}} \]

\( F_T \) = Thrust force
\( V_{\text{hub}} \) = Wind speed at hub height

See Bachynski (2014) and Salzman and Tempel (2005)
EC2 Largest Thrust

Time-Series Plots

Tower top (0,0.88.15)

Tower base (0,0,20.15)

Element 1 (6, 6, -50)
Spectral Analysis

- Tower top displacement $m^2/s$
- Tower base bending moment $(kNm)^2/s$
- Element 1 axial force $(kN)/s$

- Wind
- Wave
- 1st fore-aft

Tower top $(0, 0.8815)$
Tower base $(0, 0.2015)$
Element 1 $(6, 6, -50)$
Summary

<table>
<thead>
<tr>
<th>Index</th>
<th>Mean (kN)</th>
<th>Standard Deviation (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NIRWANA</td>
<td>SIMO-RIFLEX-AeroDyn</td>
</tr>
<tr>
<td>EC2</td>
<td>-6.79 × 10³</td>
<td>-7.39 × 10³</td>
</tr>
<tr>
<td>EC4</td>
<td>-5.27 × 10³</td>
<td>-5.80 × 10³</td>
</tr>
</tbody>
</table>

The results of the decoupling method 2 (NIRWANA) and the coupled model (SIMO-RIFLEX-AeroDyn) are generally in good agreement.

Slight under-prediction of Standard Deviation due to the limited accuracy in modelling the actual aerodynamic damping (linear damper)
5) Computational Efficiency (Decoupling Method 2)

Number of elements: 137
Number of nodes : 74

Computer CPU : Intel i7CPU 1.73GHz
RAM : 16GB

Number of total simulated time steps : 8192

Actual dynamic simulation time required:
NIRWANA (Linear Model) : 8.2s
SIMO-RIFLEX (Nonlinear Model) : 64.5s

If the nonlinear response of the investigated structure is not significant, NIRWANA can be a good engineering tool for dynamic analyses.
Conclusion

• Coupled and decoupled models of jacket-type wind turbines were developed and compared for several environmental conditions.

• Applying the thrust force from an isolated rotor model in combination with a linear aerodynamic damping gives reasonable mean and standard deviation results compared to fully-coupled simulation for environmental conditions where wind force is dominating.

• If the nonlinear behavior of the investigated structure is not significant, a linear model can be used to save computational time.