Beyond OC5 – Further advances in floating wind turbine modelling using Bladed

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Abstract. Floating wind turbines offer the potential to harness the considerable wind energy resource located at deep water offshore locations. Accurate numerical modelling of floating wind turbines is of utmost importance given its prominence in the design process. DNV GL’s aero-hydro-servo-elastic modelling package ‘Bladed’ was one of the tools validated as part of the Offshore Code Comparison Collaboration Continuation with Correlation (OC5) project [1] and gave favourable results alongside the other participants. However, in common with all of the participants using a Boundary Element Method hydrodynamic approach, the majority of the loads were under-predicted (whilst over-predicted by Morison-only approaches). In particular, the low frequency excitation was not fully captured in the Bladed numerical simulations. This paper describes the implementation and results of new simulations in which additional modelling features are implemented in the DNV GL Bladed OC5 model. The results show that including instantaneous hydrostatics and Froude-Krylov forcing produces a better match with experimental spectral energy density for platform pitch and surge motion, which in turns leads to improvements in tower base shear force predictions.

1. Introduction
Accurate modelling of the complex coupled dynamics of floating wind turbines is a challenging task. The OC5 project [1] validated a wide range of aero- and hydro-elastic modelling tools against measured tank test data and although reasonable results for simulated fatigue and ultimate loads were obtained, the results also demonstrated that further advances in modelling are required to accurately characterise floating wind turbine performance. In particular, for wave-only cases, a ‘fairly consistent underestimation of wave-excitation forces outside the linear wave-excitation region’ [1] was reported for tower and upwind mooring line loads, particularly at the low frequencies associated with excitation of the platform pitch (~30s) and surge (~100s) natural frequencies. Uncertainties associated with the test conditions are likely to be part of the reason for this underprediction, and detailed work has been undertaken to quantify such uncertainties [2]. Another source of the underprediction could be modelling deficiencies. DNV GL have therefore implemented several modelling improvements in Bladed with the aim of achieving a closer match to the experimental measurements. This paper describes some key results.

2. Overview of tank test measurement arrangements in OC5 project
For the OC5 project, a 1/50th scale floating wind turbine on a semi-submersible platform was subjected to an extensive measurement campaign, conducted by the DeepCwind consortium at the MARIN offshore wind basin [3]. The system was tested under Froude-scaled wind and wave loads. Note that all input and output variable values in this paper are given as equivalent full-scale quantities, using Froude
scaling. Tests performed ranged from simple static displacement and free-decay tests to complex operating conditions with irregular sea states and dynamic winds. For a detailed description of the OC5 model properties and the tests performed, the reader is referred to Sections 2 and 3 of the OC5 report [1].

3. Bladed for floating wind turbine modelling

Bladed is a commercially available aero-hydro-servo-elastic multibody wind turbine modelling package, capable of fully coupled floating wind turbine simulation. Bladed has widespread use amongst wind turbine manufacturers, certification bodies, consultancies and universities around the world and so its performance in simulating floating wind turbines is of interest to a significant audience.

3.1. Bladed modelling features already implemented in OC5 study

The original submitted Bladed results for the OC5 project included the following features [1], whilst replicating measured environmental conditions:

- Time domain implementation of Boundary Element Method hydrodynamics using convolution integrals.
- Additional Morison hydrodynamics and global linear damping for better drag representation
- Second order wave excitation loads
- Dynamic mooring line model

3.2. Additional Bladed modelling features implemented for this work.

For the new simulations presented in this paper, additional features were implemented.

Model updates:

- Correction to the modelled overall 1st tower fore-aft and side-side frequencies. This adjustment was required to account for the additional flexibility identified in the model’s tower base load cell. The adjustment was achieved by reducing the modelled tower Young’s modulus value.

Hydrostatics and hydrodynamics updates:

- Small adjustments to the additional linear damping values for the floating structure, applied at the free surface on the tower centre line. The values were adjusted to achieve a better match to the free decay calibration simulations.
- Discretisation of floater geometry into a flat panel mesh of the whole platform, enabling the following enhanced hydrodynamic approaches to be implemented:
  - Instantaneous hydrostatics calculated based on the exact position and orientation of the floating platform at each time step
  - Instantaneous Froude-Krylov correction again based on exact position and orientation of the floating platform at each time step

Note that for the present results set, the free surface is taken to be the mean water level. There is also the option in Bladed to use the incident wave free surface but this was not used in the present analysis.

Bladed incorporates a default quasi-linear hydrodynamics formulation based on boundary element method (BEM), potential flow solver derived properties. The force calculation is an augmented, multi-body arrangement of the well-known Cummins equation

Bladed also includes more advanced hydrodynamics options to allow the Froude-Krylov component of the wave exciting force and the hydrostatic force to be computed directly using the instantaneous wetted profile of a body. In this case, the Froude-Krylov pressure, \( p \) at any given point in the flow field may be calculated for each wave frequency constituent \( \omega \) as:

\[
p(\omega, t) = -\rho A Re[j\omega \Phi_{FK}e^{j\omega t}] \tag{1}
\]
where $t$ is time, $\rho$ is water density, $A$ is wave amplitude, $j$ is the imaginary number, $\Phi_{FK}$ is the complex velocity potential amplitude:

$$
\Phi_{FK}(\omega) = -\frac{g}{\omega} \frac{\cosh k(z + h)}{\cosh kh} j \omega \exp(jk(dx))
$$

in which $g$ is acceleration due to gravity, $h$ is the water depth, $k$ is wavenumber and $d$ is a vector representing the horizontal wave direction. The pressure on each panel is integrated over the wetted body profile, $S$ to directly yield the applied force and moment:

$$
F_{FK}(\omega, t) = \int_S p(n \times r) dS
$$

where $n$ is a unit vector pointing in to the body and $r$ is a vector describing the position of a panel with elemental area $dS$.

The hydrostatic pressure is integrated in a similar manner and is given by:

$$
p(t) = \rho g z(t)
$$

where $z$ denotes the vertical panel displacement from the reference height. Bladed allows the wetted body profile to be defined either as the instantaneous body surface below the mean waterline or the instantaneous body profile below the instantaneous incident water surface elevation, neglecting diffraction and radiation effects. The latter option introduces a greater level of nonlinearity.

More information about these methods can be found in [4] and [5].

It should be noted that some of the nonlinearities arising from the use of the instantaneous hydrostatics and Froude-Krylov forces are theoretically already accounted for in the second order excitation force which is also included in the model. For this work, exactly the same second order flow solver data was used both with and without the new features and so double accounting is present. Furthermore, accounting for some but not all nonlinearities when modelling a dynamic system can lead to greater errors than not including any since the model becomes theoretically inconsistent. However, it is the aim of this work primarily to assess the influence of including a more detailed description of some phenomena on the results, given that the above mentioned potential shortcomings may in practice have a negligible effect on results.

4. Methodology

The study focusses on two load cases from the original OC5 study. These are both 3-hour simulations with unidirectional irregular seas (JONSWAP spectrum), and no wind:

LC3.3 – Operational wave : $H_s = 7.1m$ ; $T_p = 12.1s$ ; $\gamma = 2.2$

LC3.4 - Design Wave : $H_s = 10.5m$ ; $T_p = 14.3s$ ; $\gamma = 3.0$

Wave only load cases were selected in order to highlight the effect of the implemented changes on the hydrodynamic modelling fidelity. By removing the influence of wind, uncertainties associated with the reproduction of characteristic scaled wind conditions, and the model-scale turbine’s response to those conditions, was eliminated.

The data channels for analysis were selected to best illustrate the effects of the modelling changes on hydrodynamic modelling accuracy. Available channels included platform motion, structural loads and mooring line loads (fairlead tension). From these, global platform motion was identified as the primary
metric for comparison of hydrostatic and hydrodynamic modelling capability in wave only load cases, as uncertainties associated with the as-built model-scale tower definition can be considered to have only a minor influence. In addition, tower base shear force was also analysed, bearing in mind the aforementioned uncertainties.

The experimental results presented below were generated directly from the measured OC5 LC33 and LC34 3-hour time series.

Output channels were processed into peak exceedance plots, autospectra and damage equivalent loads (DELs). Damage equivalent loads were calculated based on the same process as the original OC5 results (1Hz reference frequency, Wohler coefficient = 5, Goodman adjustment).

5. Results
Three versions of load cases LC33 and LC34 are compared:
1. Original 3-hour experimental data
2. Originally submitted Bladed OC5 simulation
3. New updated Bladed simulation with additional modelling features

![FIGURE 1: LC33 Global x- position (surge) spectral energy density](image-url)
The left-hand peak in Figures 1 & 2 corresponds to the surge resonant frequency of the platform. The updated simulations show clear increases in low frequency surge response and are closer to the experimental results, with a particularly clear improvement seen for the LC3.4 simulation. The second peak at around 0.07-0.08Hz (surge response at incident wave frequencies) shows a good match for the LC3.3 simulation, but a slight overprediction for the LC3.4 extreme wave case.
Figures 3 & 4 show a close match between the original and updated Bladed simulations for global heave motion spectral density. Both signals are also in good agreement with experimental results. The expected difference in amplitude response between the two cases is clear, especially for the lower frequency peak corresponding to the platform heave natural frequency at 0.05 – 0.06Hz. The good match shows that heave motion is not greatly affected by instantaneous hydrostatics / Froude-Krylov forces, as expected given the floater geometry. This can be explained by the fact that the horizontal projection of the mean wetted surface is very close to that of the instantaneous position of the platform, assuming small pitch motions.
Figures 5 & 6 are very similar. The large peak on the left of both figures corresponds to the platform pitch resonant frequency, and shows the significant underprediction of pitch resonance in the original results. The second peak corresponds to the response at the incident wave energy spectrum frequencies. In both figures, the updated Bladed simulations display improved pitch excitation although the LC3.4 simulation slightly overestimates the first order pitch response.
FIGURE 7: LC33 Tower base fore-aft shear force (Fx) spectral energy density

FIGURE 8: LC34 Tower base fore-aft shear force (Fx) spectral energy density

Tower base shear force is driven largely by pitch and surge motion, and Figures 7 & 8 reflect the improved spectral response of platform pitch shown in Figures 5 & 6. The additional peak in the LC34 plot corresponding to $T_p=14.3$ (0.07Hz) is clearly visible. The sharp peak on the right of both plots corresponds to the tower frequency, with the updated results showing an overestimate in loads. However, uncertainty in tower damping in the constructed physical model reduces the confidence with which this tower frequency response comparison can be made.
Figures 9 & 10 show good agreement between Bladed and the experimental results for tower base Fx (shear force) exceedance probability. There is a particularly good match for the updated LC34 Bladed simulation. However, it should be noted with reference to Figure 7 & 8 that this could partly be due to the fact that there is both some over-prediction and some under-prediction of large loads at different frequencies.

Damage equivalent loads (DELs) were calculated based on the same process as for the original OC5 results (1Hz reference frequency, Wohler coefficient = 5, Goodman adjustment).

Figures 11 & 12 show an improved correspondence with the experimental results for tower base Fx DELs for the updated Bladed simulations.
6. Conclusions
Inclusion of instantaneous Froude-Krylov and hydrostatics provides a clear improvement in modelling low frequency pitch and surge dynamics of the floating platform. Prediction of tower base shear force, a signal driven strongly by pitch, also shows a better match to the measured tank test data. This can be understood in terms of the instantaneous hydrostatics and Froude-Krylov force more accurately capturing the nonlinear transfer of incident wave energy to other frequencies, such as the platform surge and pitch resonant frequencies.

The instantaneous hydrostatics correction has not had a significant impact on simulated heave motion. However, given the geometry of the DeepCWind floating structure, this result was expected, and agreement with experiment was already strong. For structures in which platform motion leads to a more nonlinear variation in vertical hydrostatic forces (for example structures including vertical members of varying diameter near the free surface), instantaneous hydrostatic correction may yet prove to be significant. For the present results, the free water surface is taken to be the mean water level. A possible avenue for further work would be to repeat the analysis using the incident wave free surface.

The change to the simulated tower structural definition has improved the match to the experimental tower frequency, however the updated Bladed simulations now overestimate the tower base shear force response at the tower frequency. Uncertainties in the mass distribution and structural damping values for the tower mean that it is not possible to draw definitive conclusions from this, however.

These results suggest that improvements in floating wind turbine modelling fidelity can be achieved by implementation of the enhanced modelling approaches described in this paper. It is noted that the use of a suitable surface discretization mesh is required to implement the modelling improvements considered in this paper.

Modelling improvements such as these could help reduce risk in the design process, enabling more optimised and cost effective designs to be realised. This in turn would lead to a reduction in the cost of energy and would increase the viability of floating wind as a commercial technology.

References
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