Design study and full scale MBS-CFD simulation of the IDEOL floating offshore wind turbine foundation

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Abstract. A two MW floating offshore wind turbine is developed within the EU-FP7 project FLOATGEN. The focus of this paper is to perform design studies of the mooring foundation at the hull and to investigate the full scale floater concept in a coupled MBS-CFD environment at regular waves. Measurements from wave tank model tests are used for validation. The results show the potential of CFD methods to be used as virtual test bed during the design process.

1. Introduction
Floating offshore wind is an emerging technology with high potential for future industrialisation and market uptake [1], [2]. European research and demonstration projects have been launched to accelerate the maturity of the technology and to decrease the cost of energy. The FLOATGEN demo project will deploy a two MW floating offshore wind turbine at the SEM-REV test site, located twelve nautical miles from the French Atlantic coast and operated by École Centrale de Nantes.

Floating offshore wind turbines are operating in complex environmental conditions dominated by turbulent winds, stochastic waves and currents. The floating foundation is moored to the seabed but experiences 6-DOF motions. The state-of-the-art approach for numerical modeling of the hydrodynamics of offshore structures is based on semi-empiric Morison equation and/or potential flow theory. Especially non-slender and non-cylindrical floating foundations like IDEOLs ring-shaped concept require the consideration of wave diffraction, added-mass and radiation damping. However, reduced models do not include all effects as flow physics are non-linear and highly complex.

Only a limited number of researches have faced the challenge of analysing Floating Offshore Wind Turbine (FOWT) dynamics and flow physics using high-fidelity but complex and computational demanding Computational Fluid Dynamics (CFD) simulations. A detailed literature review is presented by the authors in [3]. Past CFD studies encompass modelling both aero- and hydrodynamics of a multi megawatt spar-buoy FOWT [4] and a comparison of hydrodynamics of a semi-submersible floater to a potential flow solver solution [5]. Recently, CFD has been used for derivation of the hydrodynamic drag coefficient of the OC4 DeepCwind semi-submersible [6].

The present study is a continuation from [3] in which a coupling between Multibody System (MBS) and CFD is successfully applied to the simulation of wave impact on the IDEOL floating
offshore wind turbine foundation at 1/32\textsuperscript{th} scale to gain high fidelity insight into predominant flow phenomena. Numerical simulations are compared to wave tank measurements for time series of floater kinematics, relative wave elevations, flow field visualisation and effects of upscaling. Results are presented for both model and full scale. Additional, the capability of CFD for performing design studies is demonstrated for variations of the mooring foundation at the hull of the floater.

### 2. Methodology

In this section both experimental and numerical modelling is described.

#### 2.1. Experimental measurements

Within the project FLOATGEN a model test campaign has been performed by OCEANIDE in its offshore basin BGO FIRST at La Seyne Sur Mer, France. The test campaign was performed to test the mooring system and the dynamic behaviour of the floater in extreme wave conditions and shallow depth. Froude similitude is applied and a mock-up of the floater at 1/32\textsuperscript{th} scale is tested. A lumped mass at the tower top connected to the foundation by means of a steel pipe represents mass and inertia effects of the wind turbine Rotor-Nacelle Assembly (RNA) and tower (figure 1).

![Figure 1: Test mock-up of the IDEOL floater at 1/32\textsuperscript{th} scale with instrumentation (source: IDEOL)](image)

#### 2.2. Numerical coupling methodology

Numerical simulations are conducted using a coupled MBS-CFD approach. Hydrodynamic loads on the floating foundation are calculated with the commercial CFD code ANSYS CFX. It uses the finite-volume method to solve the Reynolds-averaged Navier-stokes equations on structured and unstructured grids. The free surface is modelled by means of the volume of fluid method. The commercial MBS solver SIMPACK is applied for modeling of the structural properties and is coupled to CFD.

The MBS-CFD coupling has been developed in-house \cite{7} for the simulation of fluid-structure interaction. A validation based on submerged free-decay experiments of spring, gravity and bending pendulums in an aquarium filled with water is demonstrated in \cite{8}. The challenge of the coupling methodology is the transfer of loads and motion information between the CFD and MBS solver. A fully implicit iteration scheme is incorporated for transient simulations. Multiple coefficient loops are performed at each time step and coupling data is exchanged. Convergence is controlled by a moderator script (figure 2).
2.3. Structural modelling
The structural model is specified in the MBS tool by mass, centre of gravity and moments of inertia of the rigid floater, tower and RNA. Three dominant floater degrees of freedom are enabled - surge, heave and pitch. The mooring system is modelled by springs calibrated to the global linear stiffness of the mooring lines.

2.4. CFD modelling
The three-dimensional computational domain in model and full scale is discretized into a structured grid using ICEM CFD with 1.42 million hexahedra, tetrahedra and pyramid elements. In contrast to the preceding study [3] the tower at the aft of the floater and the mooring foundation at the fore are included. Three design variations of the mooring foundation are analysed in model and full scale. Mesh A (model scale) has no mooring foundation, mesh B (model scale) uses a simplified flat plate representation and mesh C (model scale) and D (full scale) includes the full mooring foundation (figure 3 to 6 and table 1).

An O-grid, where grid lines are arranged like an O shape to reduce skew, is used around the floater and the boundary layer is well resolved. The rigid floater is modelled using a no-slip
A numerical beach implemented by means of momentum source terms damps out waves behind the floater to avoid undesirable reflections. A first order backward Euler transient scheme is applied with first order turbulence numeric option using the SST turbulence model. The time step is fixed and set to $dt = 1/35^{th}$ of the wave period $T$. The implicit solver scheme is divided into four inner iterations. Air is modelled as compressible fluid and surface tension is disabled in the simulation.

Simulations are run in parallel to increase computational efficiency. Twelve partitions are manually specified in $x$-direction and weighting to increase robustness if a portion of a partition boundary is aligned with the free surface (figure 7). Using twelve solver processes the wall clock time on the simulation server is approximately 1.25 hours per wave period.

![Figure 7: Contour plot illustrating the user specified partitioning of the computational domain including partition numbers](image)

### 3. Results

The aforementioned CFD simulation environment is used for design studies of the floating foundation. First, the mooring foundation is simulated with increasing complexity and results are compared for global floater motion and flow characteristics. Second, the floater is simulated at full scale and compared to upscaled results of the model scale mock-up. Within the wave basin experiments described in section 2.1 wave conditions in the tank have been chosen with respect to predominant metocean conditions at the SEM-REV test site. In this paper only regular waves of wave height $H = 6$ m and period $T = 10$ s are selected as the measurements showed extreme values for green water load sensors and relative wave elevation sensors. Higher waves including irregular sea states have also been tested in the tank.
3.1. Mooring foundation design study

Three different design configurations of the mooring foundation are analysed, mesh A, B and C (see section 2.4 and table 1). The full configuration has been used in the experiment. Figure 8 illustrates the global floater motion in surge, heave and pitch for all mesh cases and the experimental results.

![Figure 8: Comparison of numerical (mesh A, B, C) and experimental results of floater motion over simulation time, top: surge x, middle: heave z, bottom: pitch β.](image)

In general a very good correlation between numerical and experimental results is achieved with a very good match of the period. The maximum surge response of the simulation is a little higher, though. Also the heave is not at the same phase as the experiment. The pitch shows the most interesting effects for the three different mesh cases. The offset in the pitch could not been confirmed in the measurements yet. The maximum pitch increases with increasing complexity of the mooring foundation and is found to be the highest for mesh C. An increase of $\Delta \beta = 0.8$ deg from mesh A to C is investigated. The reason is that the force of the incident waves acting on the floater increases for the simplified flat plate geometry and the full mooring foundation.

The flow around the floater is demonstrated for all three mesh configurations in figure 9 with highlighting of vortices via the q-criterion, which is based on the computation of the second invariant of the velocity gradient tensor. The wave is running over the fore floater deck resulting in green water. The mooring foundation acts as an obstacle and somehow wave breaker. The fore of mesh A and B are fully under water and large vortices are shed by the skirt of the floater. However during one wave period, the full mooring foundation of mesh C experiences a compression and decompression of entrapped air in the resulting chamber. Thus, the simulation is run with compressible air. When the floater has its maximum heave position the mooring foundation is above sea level leading to exchange of air between the freestream and the chamber. Even when the wave runs over the floater the air bubbles are present in the chamber leading to increased buoyancy.
The compression and decompression of entrapped air at the mooring foundation during one wave period is demonstrated in figure 10 for mesh C. The plane visualising the density of the fluid is clipped to only show regions of air. A dark blue colour refers to the density of air at 20 degree Celsius $\rho_{\text{air}} = 1.25 \text{ kg/m}^3$ and red refers to 40 times of this value.

3.2. Floater simulation at full scale

Within the FLOATGEN project a two MW floating foundation is designed and installed for thorough testing. So far only numerical and experimental results at model scale are analysed by upscaling results using Froude similitude. To investigate floater behaviour before deployment of the two MW prototype numerical simulations at full scale are performed and compared to the upscaled model scale results. This analysis does not focus on validating the well known and often applied Froude scaling but rather wants to highlight possible differences due to changes in flow characteristics.

Figure 11 illustrates the global floater motion in surge, heave and pitch for mesh cases C and D (see section 2.4 and table 1) and the experimental results. As for the previous design study in section 3.1 a very good correlation between numerical and experimental results is achieved with a very good match of the period. The surge response of the full scale simulation is even closer to the upscaled measurements. The heave and pitch motion show no significant deviations between model and full scale simulation.

This trend is also seen for the relative wave elevation sensors WP4-8 that are positioned around the floater (see figure 1) as shown schematically in figure 12 and 13.
of these sensors is presented in figure 14 together with the reference wave probe $W_{\text{ref}}$ that is located next to the floater for measurement of the incident wave field. The water level inside the pool (WP4 and WP7) is predicted to be lower in the simulation compared to the experiment. This can be confirmed when looking at video footage of the wave basin test. The relative wave height before and behind the pool is, however, predicted with good agreement. Differences in global motion between experiment and model and full scale simulation may be explained by not perfectly matched incident wave field $W_{\text{ref}}$. Tuning the wave height is an iterative process done in 2D to increase efficiency. One could directly load the wave field of the wave basin into the inlet boundary condition of the numerical wave tank but this is not done here.

As global floater motion and relative wave elevation sensors show a good agreement between model and full scale it is expected that vortex shedding at the floater that mostly induces heave
damping behaves similar. This effect is illustrated in figure 15 showing a visual comparison for the vortex shedding between model and full scale for one time step.

Figure 15: Illustration of vortex shedding using q-criterion for $t = 601$ s and mesh C and D

4. Conclusions
Within this study a coupling between MBS and CFD is successfully applied to the simulation of wave impact on a floating offshore wind turbine foundation. A wave tank test of the floater model at $1/32$ scale and full scale has been performed within the EU-FP7 project FLOATGEN. A numerical wave tank is setup in CFD. A regular wave test case with extreme values for green water loads and relative wave elevation is selected.
The CFD simulation environment is applied for detailed design studies. First, the mooring foundation is simulated with increasing complexity and results are compared for global floater motion and flow characteristics. Second, the floater is simulated at full scale and compared to upscaled results of the model scale mock-up.

Floater motion in surge, heave and pitch and relative wave elevation sensors show a very good correlation between numerical and experimental results. Increasing complexity of the mooring foundation results in higher pitch response. Air is entrapped in a chamber in the full mooring foundation and is de-/compressed during a wave period. The full scale simulation shows a good accordance to model scale results indicating good agreement with Froude similitude. The presented methodology provides very satisfactory results for load assessment and design optimisation of various types of offshore structures.

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