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Multibody Modelling of Floating Offshore Wind Turbine Foundation for Global Loads Analysis

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ABSTRACT

This paper presents a methodology for the calculation of internal loads, induced by wind and waves, on a floating offshore wind turbine. The ring shaped hull is divided in separated compartments on which diffraction radiation is calculated and then used in a time-domain dynamic analysis of the floater, also including wind turbine and mooring system. In addition to reproducing the dynamic behavior of a rigid body, the multibody modelling provides information of loads transmission inside the hull.

KEY WORDS: Floating offshore wind turbine, time-domain hydrodynamics, global loads analysis.

INTRODUCTION

Several ways of modelling floating wind turbines and accessing loads exerted in the hull can be considered. The most suitable model is usually chosen on the basis of the hydrodynamic and aeroelastic properties of the wind turbine. Several techniques were presented whereby the floating foundation was modelled on the basis of simple hydrodynamic models like in Utsunomiya et al. (2013) for a spar platform or Le Cunff et al. (2013) for a three floater semi-submersible platform, or where the full 3D pressure field of the waves was directly calculated at each time-step in time domain simulations and then mapped to finite element models as proposed by Cermelli et al. (2010).
The floating foundation considered in the present paper is a large volume structure for which it is necessary to account for diffraction and radiation, but for which part of the wave loads are caused by viscous vortex-shedding effects. Both techniques mentioned above have been tried, but the technique proposed by Utsunomiya et al. (2013) and Le Cunff et al. (2013) could not effectively be used due to the limited accuracy of Morison's equation for the ring floater, while the latter technique used by Cermelli et al. (2010) is more adapted when most of the loads come from perfect fluid phenomena. In addition, the computation time of the structural analysis using direct pressure field application made the latter method difficult to handle in the detailed design of a floating foundation where a large number of load cases need to be considered.
This made the authors search for an alternative method described here, which would provide accurate hydrodynamic modelling of the foundation and direct information on the loads governing the structural design of the hull: tower loads, accelerations, but also bending, shears and torque of the caissons constituting the hull.

FLOATING WIND TURBINE CHARACTERISTICS

The wind turbine is a 130m rotor diameter wind turbine weighing 450 tons. It is a regular variable speed, pitch-regulated wind turbine.
The floater is a square ring fitted with a large opening at centre. The hull is 45m in breadth with a depth of 11m and an opening 27 m x 27 m wide. The skirt placed all around the hull increases floater wave frequency damping. The floating turbine draft is 7 m. The hull is composed of 16 compartments, some of them are filled with sea water ballast in order to equilibrate the floating wind turbine.
The floating foundation also includes a transition piece which connects the tower to the hull and ensure a smooth transition of wind and inertial loads within the hull. Its mooring lines are grouped in three clusters of two catenary mooring lines, each spurring at 120° from each other. More information on the concept is provided in Choisnet et al. (2014).

ENVIRONMENT DATA

For this design, the offshore site has a 55 m depth and the following waves and wind conditions.

Waves

Waves are modelled by irregular waves without directional spreading. The wave spectrum is the Pierson Moskowitz / ISSC spectrum. It is a two-parameter spectrum mostly relevant for locally-generated sea-states. The power spectrum density as a function of wave frequency is given by the Eq. 1.

$$S_{\eta\eta}(f) = \frac{0.3125 \, . H_s{}^2 \, . f_p{}^4}{f^5} e^{-1.25(f_p/f)^4} \tag{1}$$

where:

η is the wave elevation (m),
$S\eta\eta$ is the wave elevation power spectrum (m².s²),
f is the frequency under consideration (Hz),
f_p is the peak frequency of the power spectrum ($f_p = 1/T_p$, in Hz),
H_s is the significant wave height (m).

For this study, the critical condition considered consists of a maximum significant wave height H_s of 10 m with a significant peak period T_p in the range of 12 s to 15 s.

Wind

Wind profile is modelled by an exponential law (Eq. 2).

$$V(z) = V_{hub} \cdot (z/z_{hub})^{\alpha} \quad \text{if } z>10 \text{ m}$$
$$V(z) = V(10\text{ m}) \quad \text{if } z<10 \text{ m} \qquad (2)$$

where:

V_{hub} is the wind speed at hub,
z is vertical pointing upward,
z_{hub} is the hub height,
α is a parameter equal to 0.14 for normal wind profile, 0.11 for extreme wind profile.

For structure moored at sea with a low frequency resonant periods of motion, it is of great concern to model the power density of the wind spectrum in this range realistically. The wind spectrum is obtained by the Norwegian Petroleum Directorate (NPD, 1995) and is formulated as Eq. 3.

$$S_{NPD}(f) = \frac{320 \cdot (\frac{U}{10})^2}{(1+\bar{f}^n)^{5/3n}}$$
$$\bar{f} = 172 f \cdot (\frac{U}{10})^{-3/4}$$
$$n = 0.468 \qquad (3)$$

For this floating wind turbine, the hub height is 92 m and extreme wind associated is 50 m/s.

The forward end of the floater is opposite to the turbine, the aft end is at the turbine end. The reference frame is defined as follows: Z is vertical, positive upwards; X is in the symmetry plan of the floater, directed forward; Y is positive to portside, perpendicular to the 2 other axes. The origin of the floater reference frame is located in the symmetry plan of the floater; on the lower side of the bottom of the floater; at the aft-most point of the hull in the symmetry plan of the floater, excluding skirt and appurtenances (Fig. 1).

HYDRODYNAMIC ANALYSIS

To get internal loads inside the hull, the hull is split in 16 compartments, based on the geometry of the physical compartments. Hydrodynamic data base is then computed with this multibody approach and finally used in time domain global analysis.

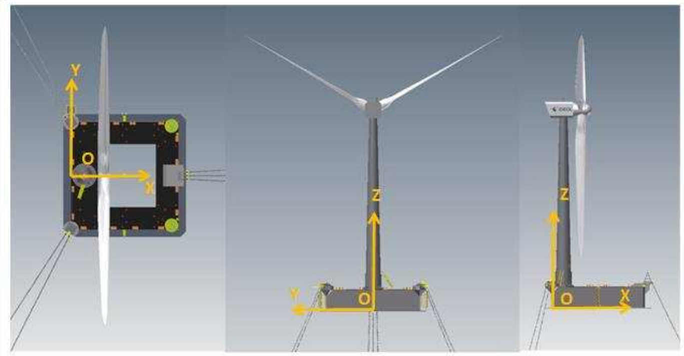

Fig. 1. Position of reference frame

Hydrodynamic Databases and Hydrostatic Stiffness

Hydrodynamics database of the floater is calculated with Aqwa™ software release 15.0, developed by Ansys®. It provides an integrated facility for developing primary hydrodynamics parameters coming from wave potential theory, required to undertake complex motions and response analysis. The following modelling approach is adopted.
An Aqwa model is built in order to compute potential theory loads for each compartment and include hydrodynamics interactions between each other.

First, with Aqwa, each compartment is modelled as a rigid body on which diffraction and radiation loads are computed. Each compartment is drawn as the outer surface in contact with water. Compartments are closed on their sides and separated by a gap of 0.1 m in order to avoid divergence of calculation. The hull is meshed with defeaturing tolerance of 0.1 m and maximum element size of 2 m (Fig. 2). Mass and inertia properties are applied to each compartment. Environmental parameters are set to their corresponding values (water depth, water density, gravity).

An external lid has been placed on the moonpool to avoid standing waves as presented by Cheetham et al. (2007). The lid damping factor is 5% and the gap for lid is the width of the moonpool.

To solve hydrodynamic diffraction, waves are coming from -180° to 180° with an interval of 22.5° and periods from 2.5s to 70s.

Hydrodynamic databases include hydrostatic stiffness and first order wave loads acting on each compartment. Added mass and radiation damping coefficients are calculated for each compartment, along with the contribution of the other compartments.

Comparison of Hydrodynamic Databases

The multibody approach is validated by comparing hydrodynamic loads with those obtained with a rigid single body.

Hydrostatic stiffness depend on the displacement of the rigid body. Since compartments are cut in order to create a gap between them, a correction is applied so that the global stiffness of multibody model stays consistent with the one of the rigid body.

For added mass and radiation damping coefficients, results are calculated for each compartment along with the contribution of the other compartments. As an example, the added mass at 12 s of rigid body and multibody model (sum of all compartments contributions) show good agreement: surge and sway added mass are overestimated in the multibody by 1% and 4% respectively. Heave added mass is underestimated by 13%. This can come partially from the gap created between the compartments. However the gap volume is only of around 2.3% of the total hull displacement. This difference is an issue still to investigate.

(a)

(b)

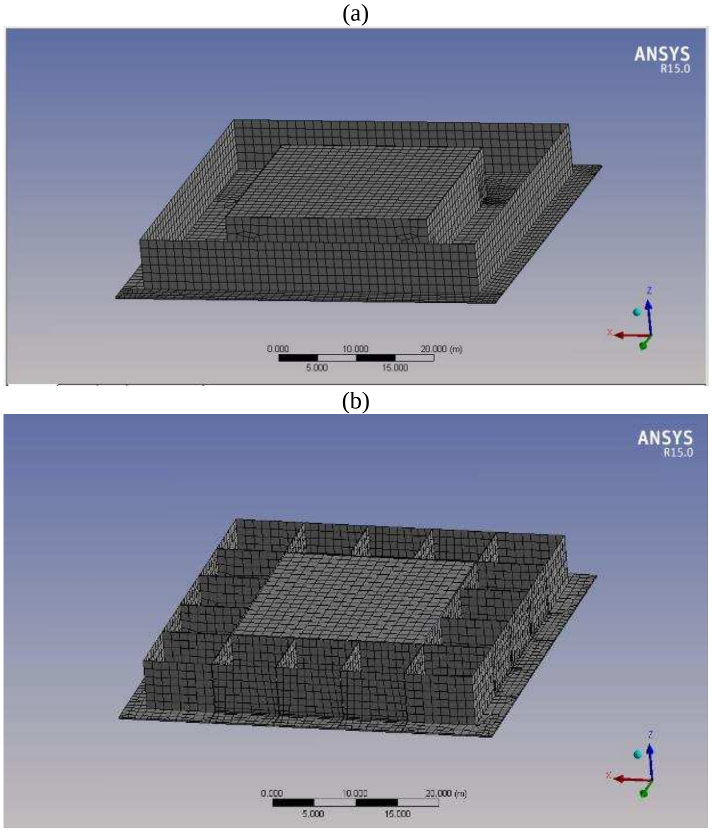

Fig. 2. View of the meshed floater as rigid body (a) and multibody (b)

It has also been checked that heave loads Response Amplitude Operator (RAO) of rigid body model and the sum of each compartment heave load RAO show good agreement between both models (Fig. 3).

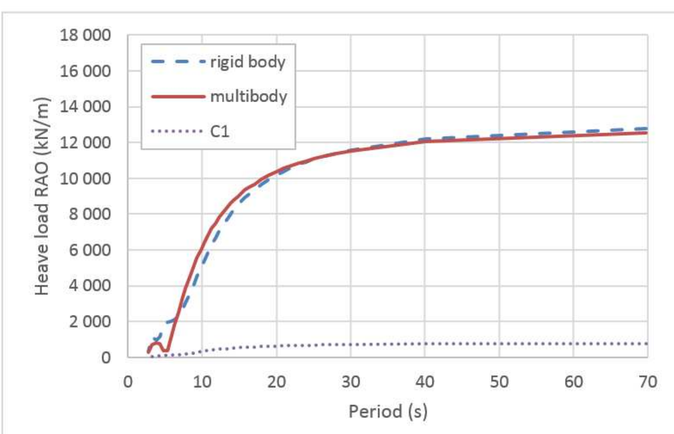

Fig. 3. Heave Response Amplitude Operator for rigid body model, C1 compartment (below the tower) and multibody model (sum of all compartments contributions).

TIME DOMAIN GLOBAL ANALYSIS

Time domain global analysis is performed by a finite element model developed in OrcaFlex. The hull is modelled with all its relevant parts to study the global loads:

- Hydrodynamics loads are taken into account through the ".lis" file that contains radiation diffraction results;
- Compartments are linked to each other thanks to beam finite elements reproducing the hull structural stiffness and therefore its global structural dynamics;
- The tower is modelled with beam finite elements in order to account for its dynamic behaviour;
- The Rotor-Nacelle Assembly (RNA) is modelled as a rigid body with mass, inertia and a drag element for the wind loads;
- The mooring lines are modelled with beam finite elements.

OrcaFlex software version 9.7d, developed by Orcina, is coupled to Aqwa thanks to its output ".lis" file. OrcaFlex is a fully 3D non-linear time domain finite element program. The simulations are 1-hour long with an additional 500 s of transient. The simulation time origin is specified for each sea state in order to correctly model maximal wave height. OrcaFlex uses an implicit integration method. The constant time step is equal to 0.025s. Since currents loads and second order wave loads have mainly an impact on the mooring system design, they are not taken into account in this study. Primary motion is treated as wave frequency dependent.

Additional Damping

Viscous flow separations that cannot be modelled in diffraction radiation calculations were modelled by additional damping. This additional damping was calibrated according to basin model tests as presented in Choisnet et al. (2014). The calibration methodology is similar to the one presented in Ricbourg et al. (2006) on Deepwater CALM buoys.

Beams

Beams are linking the geometrical centre of adjacent compartments. They have the mechanical properties of the corresponding hull sections.

Wind Load Modelling

The RNA is represented by an OrcaFlex element with appropriate mass, centre of mass and mass moments of inertia. In order to calibrate turbine loads, a wing element has been added. This feature allows to define a global drag coefficient for all rotor nacelle assembly. Rotor thrust can be expressed as $F = \frac{1}{2}\rho C_d U^2$, with ρ the air density, S the area exposed to wind, Cd the drag coefficient and U the wind velocity. To reproduce a rotor thrust estimated at 400kN in critical environment at a wind speed of 50m/s, the wing drag element is set to 1m² and the drag coefficient to 253.

MODEL VALIDATION

This multibody model is compared with the reference rigid body model of the floater based on decay tests, motion RAO and irregular waves.

Static Validation

The hydrostatic properties of the multibody global loads model are verified against the reference rigid body model of the floater. As seen in Table 1, the agreement found is good. Decay tests will now allow to check the added mass of the floating wind turbine.

Table 1. Comparison of platform displacement for both models under applied load.

Applied load		Floating wind turbine displacement
Direction	Amplitude	Difference between multibody and rigid body model
Heave force	980 kN	-1.47%
Pitch moment	50 000 kN.m	1.73%
Roll moment	50 000 kN.m	0.78%

Decay Tests

The natural periods of the system are checked to confirm the mass properties of the FWT (both added mass from hydrodynamic database and mass of the OrcaFlex model). This verification is done on the basis of decay tests (see Figure 4). The natural periods are found with a very good agreement for both models (Table 2). Multibody model has a heave period 3.7% smaller than the rigid body model. This is consistent with the underestimated heave added mass in multibody model.

With decay tests, the dynamic behaviour of the FWT is only checked at the natural period of the system. But the incoming wave spectrum peak periods vary over a different period range. In order to verify the dynamic behaviour of the hull over the incoming wave period range, RAO are calculated.

Response Amplitude Operator

RAO are calculated with incident Airy waves. The sea heading is 180° for surge, heave and pitch and 90° for roll degree of freedom. The RAO are presented in Figure 5. Results show good agreement between rigid body and multibody RAO. Roll and pitch RAO of the global load model remain on the conservative side.

Table 2. Natural period for rigid body and multibody model calculated from free decay tests.

Degree of freedom	Natural period
	Difference between multibody and rigid body model
Surge	-0.2%
Heave	-3.7%
Roll	-0.5%
Pitch	0.4%

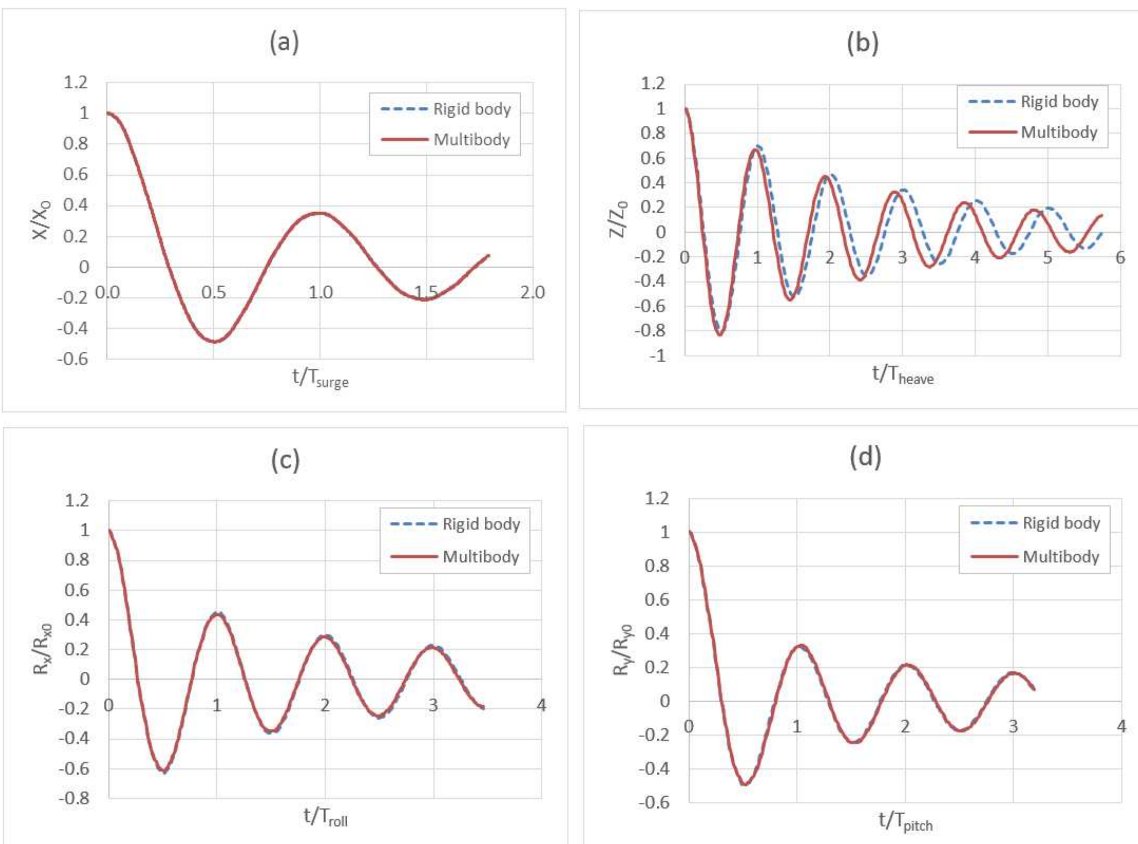

Fig. 4. Dimensionless decay tests in (a) Surge; (b) Heave; (c) Roll and (d) Pitch for multibody and rigid body models. Time is divided by rigid body natural period and displacement by initial amplitude of movement.

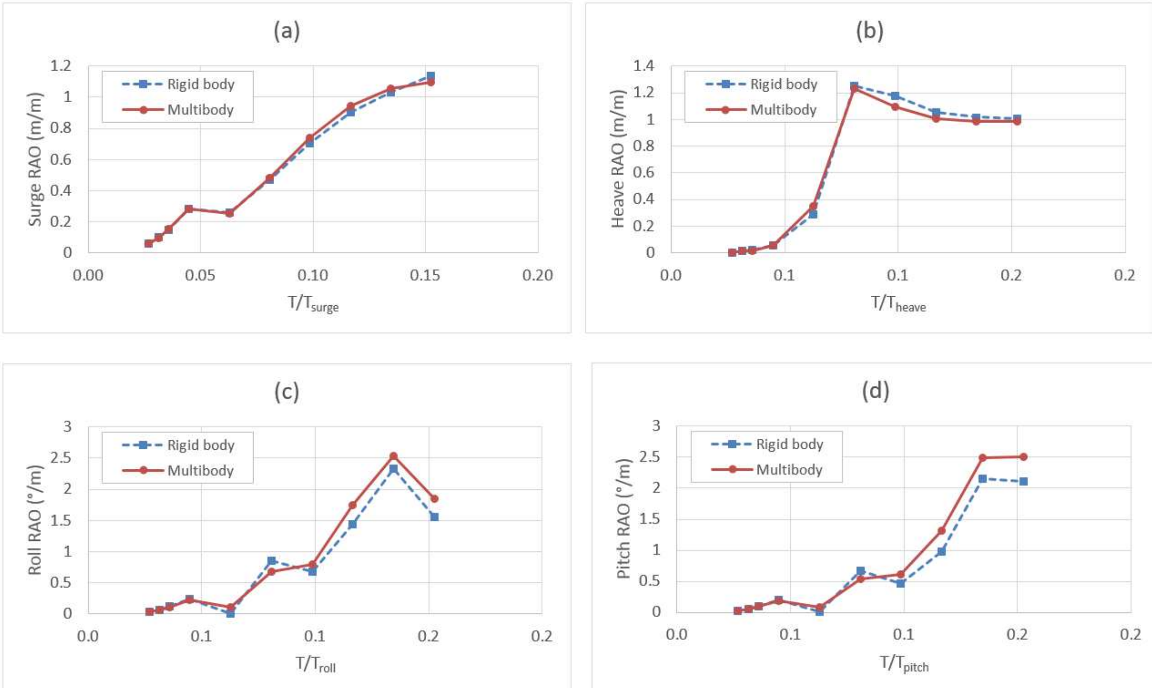

Fig. 5. Response Amplitude Operator for rigid body and multibody models for four degrees of freedom: (a) surge, (b) heave, (c) roll and (d) pitch. Incident wave period is divided by rigid body natural period. The Airy waves heading is 180° for surge, heave and pitch and 90° for roll degree of freedom. RAO are calculated at floater centre of gravity.

Time Domain Comparison

Time domain simulations are run with OrcaFlex. The multibody approach needs an increased computation time by a factor around 15.

Motions and tower base moment obtained with multibody global loads model are consistent with those obtained with reference model (Table 3).

Table 3. Statistical analysis of 1 hour simulation with collinear waves and wind for idling case in extreme environment.

Waves and wind collinear headings		90°	135°	180°
Heave	Max	-2.1%	-2.6%	-1.4%
	Standard deviation	-5.3%	-4.5%	-4.1%
Pitch	Max	-	20.2%	14.7%
	Standard deviation	-	17.0%	16.1%
Tower Bending Moment	Max	5.5%	3.1%	-3.0%
	Standard deviation	10.6%	11.2%	13.1%

UTILISATION OF MULTIBODY MODEL

Structural Dynamic of the Hull

The OrcaFlex model allows to perform the modal analysis of the floating wind turbine. For the sake of conciseness, only the first two hull modes are presented in Fig. 6.

Load Cases Definition

Required simulations are run under varying environmental conditions (waves and wind intensity and orientation) and wind turbine mode (operation or idling with and without fault). Based on this simulations, 132 most critical loads are identified including maximum bending moment, shear forces and torsion for each beam element, maximum tower bending moments and tower top accelerations but also maximum FWT motions and accelerations.
The local axis of the beam are presented in Fig. 7.

A most critical case obtained with idling turbine, wind coming for the aft of the floater and waves from the front is presented in Fig. 8. For this load case, we can visualize the moments on the beam linking compartments (Fig. 9). The bold black lines stand for the beams linking the compartments. Tower and mooring lines are also represented. Data are plotted with the beam axis as abscissae axis. The ordinates are positive outside the floater and negative inside. X-bending moment (horizontal) (a), Y-bending moment (vertical) (b), Z torque (c) and Effective tension in the beam axis (d) are presented. Unit values correspond to maximum value for this case. (a) scaling is 2.7 time smaller than (b) or (c).
Our model allows us to show compression induced in the portside and starboard sides of the floater (Fig. 9d). Loads from the turbine induce X-bending moment and Y-bending moment at the tower basis (Fig. 9a-b).

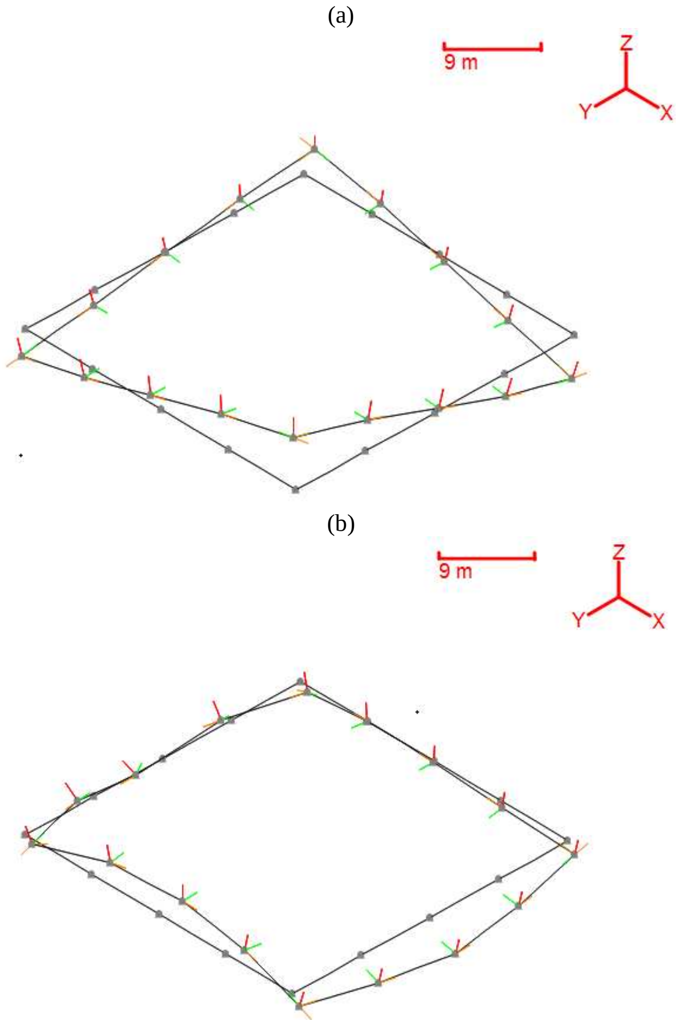

Fig. 6. First vertical hull bending moment (a) and first horizontal bending moment (b) floater deformation mode computed by OrcaFlex at respectively 0.213s and 0.201s. Only the beams linking the compartments and their local axis are drawn.

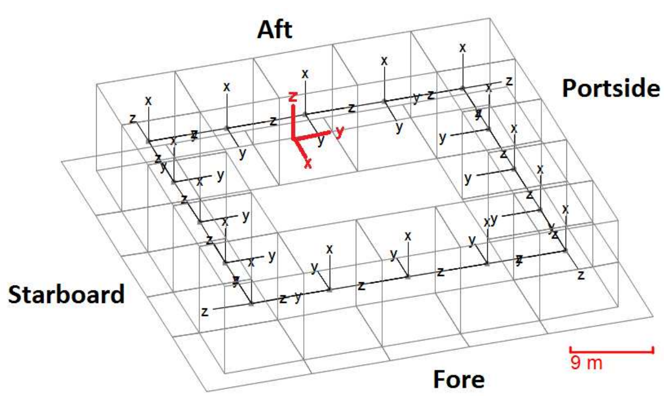

Fig. 7. Global axis of the floater (in bold red) and local axis of the beams (in thin black).

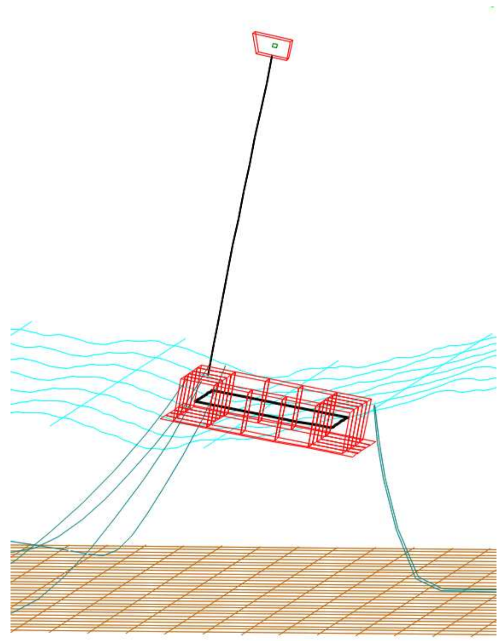

Fig. 8. View of the OrcaFlex model of the floater in one of the critical case. The turbine is idling, wind is coming from the aft of the floater and waves are coming from the front. The platform presents a 10.7° pitch angle.

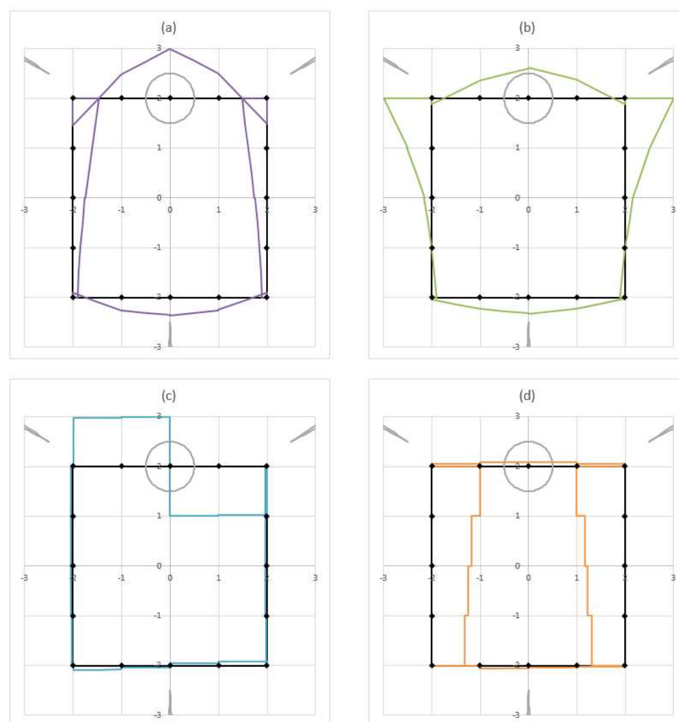

Fig. 9. Loads on the beams in one critical conditions.

Inputs for Structural Team

All the load situations are provided as an input for structural analysis of the hull and transition piece. The final structural analysis is made using a detailed finite element model. The static case deformation of the floater after equilibrating the structural finite element model is presented in Fig. 10.

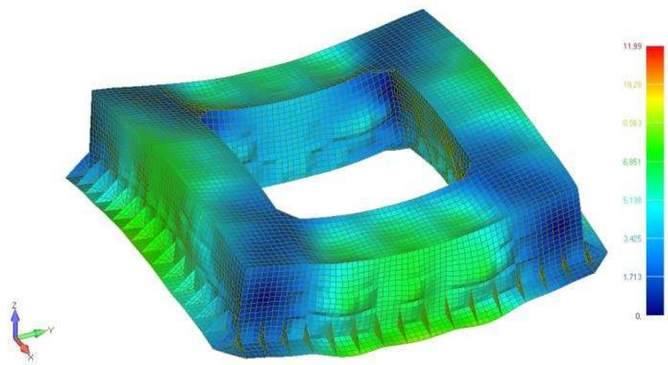

Fig. 10. Floater finite element model as used for the structural analysis. Local deformation is presented for the static case.

CONCLUSIONS

The methodology used for the global load analysis of a floating wind turbine is presented here. It has been validated by comparison with the results obtained from a classical rigid body floater model. This methodology can be refined regarding the heave added mass computed in radiation diffraction. Complex environmental loads including both waves and wind are accounted for. In addition, the methodology takes into account the structural dynamic of the floater. It allows to get access to the hull global loads inside a ring shaped floater for a reasonable increase of computation time. Internal loads can be used for a detailed structural analysis of the hull.

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