Structural Design of Wave Energy Converters


Part 2: Implementation and Results
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Structural Design of Wave Energy Converters


Part 2: Implementation and results

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1 Computational Fluid Dynamics for Floating WECs in waves

1.1 Introduction

Components of CFD\(^1\) methodologies required for accurately capturing the detailed motion of floating WECs\(^2\) in realistic irregular wave fields are the focus of the research. The motion of a floating WEC is prone to be affected by viscous damping effects caused by flow separation, as they are often designed to resonate and thereby produce large motion responses. To the author’s knowledge there is no CFD tool widely available which is validated thoroughly for numerical testing of surface-piercing, moored floater designs in more extreme sea conditions involving steep-sided and breaking waves or strong currents (Wu et al. 2014; Palm, 2014; Li & Lin, 2012; Review by Coe & Neary (2014); Yu & Li, 2013; Omidvar et. al., 2013; Bhinder et. al., 2011; Agamloh et al., 2007; Aliabadi et al., 2003). The latter papers including only sparse validation give evidence to this, as they represent largely the most recent papers\(^3\) on moored floating structure viscous wave response. The aim of the present report is to validate CFD codes for assessing floating WECs.

The work in deliverable 1.4-5 to the 5 year research project Structural Design of Wave Energy Devices (SDWED) funded by the Danish Strategic Research Council is submitted as a report consisting of two parts. The first part submitted in 2014 covers CFD methodologies and theory building on the OpenFOAM® platform, and reflecting on current state-of-the-art (Heilskov et al., 2014). The second and present part focusses on validation in the sense of comparing the strengths and weaknesses of OpenFOAM (Weller et al., 1998; Jasak 1996) against the code StarCCM+\(^4\) by measuring them against results of physical model tests. Validation and particularly mapping weaknesses is paramount before the CFD tool is used for simulating the hydrodynamic behaviour of a floating WEC with the aim of hydrodynamic optimization.

A TLP\(^5\) concept has been applied for validation, due to its simplicity from a CFD point of view at first sight (Heilskov and Petersen, 2013). A series of model tests was conducted at DHI laboratory, Hoersholm under HYDRALAB IV on a scaled model of a TLP floating wind turbine with four moorings (Tomasicchio et al., 2014; HYDRALAB IV, 2012). The TLP substructure used in the physical model tests is the object of the present investigation. The substructure consists of a vertical cylindrical structure (with a cylinder mounted on top of larger one), which in a pure form has been an object of extensive investigation in hydrodynamics; hence a foundation the present investigation can and will build upon. A resemblance to a floating point absorber WEC in an imagined survival condition may be drawn. During a storm passage, the point absorber’s survival system is envisaged to reduce its draught. As a result the line tension is significantly increased resembling the mooring of a TLP.

On the other hand, a real floating WEC, often of complex geometry, will give rise to sources of errors due to non-resolved complex fluid motions. The simple nature of the TLP substructure provides a measure to minimize the numerical sources of errors from a fluid modelling point of view, as it allows the computational mesh to be built in a regular

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1 Computational Fluid Dynamics; referring to solving the Navier-Stokes equations e.g. using the Finite Volume Method.
2 Wave Energy Converter.
3 Only the most recent paper of relevance from each author is cited.
4 StarCCM+ is the CFD code by CD-adapco™.
5 Tension Leg Platform.
structure, which is a demanded basis when we want to focus the CFD validation on floating body methodologies related issues. The wave impact motion response by a TLP is in nature small compared to a floating WEC, however, as a test case it provides a tightly bounded model needed when validating the flexible mesh approach, which is one of the central methodologies needed for accurately modelling the motion of a floater in OpenFOAM.

The HYDRALAB IV TLP validation test case furthermore provides an excellent platform for demonstration of the strength of CFD as a tool. It is from a hydrodynamic point of view highly complex, as the still water surface cuts right at the interface of the geometrical expansion, Figure 2.3, leaving room for complex viscous flow phenomena. Effects such as wave overtopping/breaking and wave run-up with significant impact on the motion of the TLP are likely to occur, which is also often an unavoidable part of the hydrodynamics of floating WECs designed to resonate. Moreover, capturing the effect of these kinds of highly non-linear phenomena is where potential codes such as WAMIT/WAMSIM⁶ by nature fall short.

The influence of the surface capturing algorithm (VOF method) and the two-way coupling of the body motion solver and the hydrodynamic solver have been identified as the crucial components in CFD simulation of floating WECs. The accuracy of VOF on the wave kinematics in the top part of the waves is of particular impotence as the draft of a WEC is relatively small compared to depth.

1.2 Wave Kinematics

This section outlines the conclusions drawn from the investigation on wave kinematics in OpenFOAM presented by Dr Jacob V. Tornfeldt Sørensen, DHI, at the SDWED meeting, August 2012. The objective of the study was to investigate OpenFOAM’s limitations in simulating wave kinematics in the top part of the water column – hence the part that has a crucial effect on the operation of a floating WEC.

Using the Volume-of-Fluid (VOF) method, OpenFOAM solves the Navier-Stokes equations for two immiscible and incompressible fluids, as described in Part 1 (Heilskov et al., 2014). In OpenFOAM a variation of the VOF method is applied to capture the air-water interface (Berberovic et al., 2009; Rusche, 2002; Weller, 2002; Deshpande et al., 2012).

The VOF CFD code component plays an important role in view of accurately capturing the detailed motion of floating WECs, as it influences the computed wave kinematics in the vicinity of the free water surface. With the relatively small draft of a floating WEC, the corresponding forces on the floater are prone low fidelity, due to the velocity and pressure coupling (PISO⁷). Wave kinematics is therefore a main object of the study.

In order to show the ability to reproduce the kinematics of free surface water waves, a stream function wave was simulated and compared to the stream function theory. For this work OpenFOAM 1.6-ext was applied. Wave modelling was adopted by the wave generation framework waves2Foam. The development of this framework is described in Jacobsen et al. (2011).

A 2D numerical flume was set up with a flat bed, a total length of 2000 m and a water depth of 50 m. “Relaxation” zones were implemented at the inlet and at the outlet in order to generate and absorb the wave, respectively. For the test cases we were generating a regular wave using stream function theory with the following parameters: wave height

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⁶ Developed at DHI based on WAMIT® by MIT
⁷ Pressure Implicit with Splitting of Operators.
H = 6.0 m, wave period $T = 10$ s. The wave kinematics was extracted over a vertical line at a distance of 1000 m from the inlet relaxation zone of 200 m, i.e. the wave has travelled approximately 6.5 wave lengths. Adjustable time step was used in all cases with a Courant number limit of 0.25.

Figure 1.1 Contour plot of horizontal and vertical velocity centred around the point of data extraction (1200 m). The white line represents the free surface. The 2nd order upwind Gauss linear UpwindV cellMDLimited Gauss linear 1.0 scheme was applied for the velocity convection term in the Navier-Stokes equation.

Figure 1.1 shows the velocity field computed on a grid with uniform spacing of 0.5 m x 0.5 m, which gives a total of 560,000 computational cells. The two contour plots depict the magnitude of the horizontal and vertical velocity component, respectively, and both between 1100 m and 1300 m downstream. A fluctuating artefact of free shear layer characteristics is observed in the air phase just above the water surface in the vertical velocity field. Furthermore, a broad band of high velocity surrounding surface interface can clearly be seen. The high velocities appear both in the water and air phase, but are predominantly in the air phase. In order to rule out this phenomenon due to pure numerical artefacts, a comprehensive investigation was undertaken testing different mesh resolutions and numerical discretisation schemes\(^8\) used to solve the divergence terms in the governing equations. No turbulence model was used\(^9\). The numerical tests all show

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\(^8\) Some combinations of divergence schemes and pressure-velocity coupling algorithm - PISO or PIMPLE (a merge of the PISO and SIMPLE algorithms) lead to numerical instability. E.g. combination of MUSCL scheme and PISO. MUSCL (Monotone Upstream-centered Schemes for Conservation Laws) is particularly suitable for handling large gradients and discontinuities in the flow (Ferziger and Peric, 2002).

\(^9\) Laminar viscous flow considered only.
the same sign of a high velocity band surrounding the interface between air and water; however, some cases were more pronounced than others, see Figure 1.2.

Figure 1.2 Contour plot of horizontal velocity centred around the point of data extraction (1200 m). The white line represents the free surface. Top: divergence scheme: SFCDV. Bottom: divergence scheme: Gauss linearUpwindV cellMDLimited Gauss linear 1.0. Mesh of 1 mill cells in both cases.

Figure 1.3 presents the velocity profiles compared to stream function theory for the model with refinement of the aforementioned base mesh around the free surface. The refinement has been found to be a mean to limit the band size of high velocity surrounding interface between air and water, and has increased the mesh size to 1 million cells with a maximum aspect ratio of 4.5. The profiles are presented with a spacing of 0.5 s. Since stream function wave theory is inherently irrotational, we do not expect the results of the viscous Navier-Stokes solution to match perfectly. In most parts of the water column, the numerical model captures the kinematics of the stream function. However, near the surface the numerical results start to deviate considerably. Contrary to the expected behaviour of the viscous solution, the velocities are not damped but overestimated close to the surface. If we were to remove the viscosity in the CFD simulation, the deviation observed in the top part of the water column would most likely be amplified.

Results using two different divergence schemes are presented in the figure, where the Gauss linearUpwindV cellMDLimited Gauss linear 1.0 scheme is seen superior in terms of accuracy. When observing the corresponding surface elevation, Figure 1.3, almost no discrepancy between theory and numerical results is seen. Several divergence schemes
in relation to the velocity convection term in the Navier-Stokes or the divergence term in the phase fraction equation for the volume fraction variable have been tested. The investigation also included different combinations of the schemes including the interface compression scheme\textsuperscript{10} for the artificial compression term in the VOF formulation (Rusche, 2002). However, with no significant improvement in most cases or no improvement compared to the results presented in Figure 1.3.

Some improvement in the kinematics was obtained by further refinement of the mesh, however, only with the cost of a large increase in computational time. With increasing refinement of the mesh around the free surface, the model deviates from the theory at a point slightly closer to the free surface.

Figure 1.3 Comparison of horizontal velocity profile when changing the numerical scheme for the velocity convection term in the Navier-Stokes equation from Gauss linearUpwindV cellMDLimited Gauss linear 1.0 scheme to limitedLinearV. The results are plotted against streamfunction. The profiles are presented with a spacing of 0.5 s. Left: Crest half period. Right: Trough half period. Bottom: Surface elevation at the time of measurement.

\textsuperscript{10} E.g. the scheme Gauss interfaceCompression.
In order to test whether the high velocities near the surface are evident in a 3D model, the mesh was extended to have a thickness of 1m with a discretization of 5 elements. Similarly, a probe at 1200 m downstream was used to compare velocity results to the results of the corresponding 2D simulation. Figure 1.4 shows that no difference can be observed between the 2D and 3D model.

With the band of high velocity surrounding the surface interface and the deficiency in OpenFOAM to accurately simulate the wave kinematics in the top part of the waves in mind, it is evident that the high velocities surrounding the air/water interface are an artefact of spurious nature. The artificially high velocities in the air phase just above the free surface are likely to affect the kinematics of the top part of the waves, hence contaminating the hydrodynamic velocity field. In order to maintain balance in the physical system, the velocities in the top part of the waves will have to assume a size which from a momentum point of view counterbalances the spurious velocities which arise in the air phase. The high velocities close to the surface seen in Figure 1.3 and Figure 1.4 can in other words be viewed as a counteraction to the artificial velocities arising in the air phase just above the free surface.

Consequently, the velocity artefact parallel to the water surface can only be ascribed to the current VOF implementation suffering from a physical incorrect interpolation routine for the computational cells where the free surface intersects. Hence, emergence of spurious velocities in the air phase is an inherent part of the VOF method implemented in OpenFOAM.

If the grid resolution is rather coarse, the free surface will be more diffuse depending on the size of the cells at the surface, which means that artificial air velocity will have a large effect on the fluid phase in these cells. This effect will decrease for refinement of the grid. Based on the results for stream function waves, it is concluded that the model will provide a good representation of the wave kinematics in the majority of the water column, but the presence of the high velocity makes the current model unsuitable for modelling near-surface wave kinematics. Hence care should be taken when interpreting near surface velocities. Furthermore, the investigation indicates that an examination of the surface elevation is an insufficient measure when assessing accuracy and quality of simulated waves.
Following the validation of the capabilities of the model to reproduce the kinematics of free surface water waves, it was afterwards demonstrated how the kinematics of an irregular wave condition can be generated with similar accuracy. In Figure 1.5 results of a Pierson-Moskowitz spectrum for significant wave height $H_s = 6$ m, peak wave period $T_p = 10$ s and water depth, $h = 50$ m are compared to numerical results obtained with OpenFOAM 1.6-ext on the afore-mentioned regular base mesh. An acceptable coherence is obtained in view of the coarse mesh used.

The following investigations will as an intrinsic part have focus on reducing the impact of the spurious velocities in the air phase on the wave kinematics, hence impact on the forces of the floating WEC. It should be mentioned here that several studies done with OpenFOAM on fixed structures that pierce the water surface show excellent agreement with measurements when assessing the loads on the structure (e.g. Paulsen et al., 2014).

![Simulation of irregular waves imposing a wave boundary condition mimicking the sea environment given by a Pierson-Moskowitz spectrum with 6 m significant wave height and 10 s peak wave period. The wave spectrum is extracted over a vertical line at a distance of 400 m and 1200 m downstream the inlet.](image)

Finally, in a new research project (funded by the Danish Council for Independent Research) DHI is investing heavily in eliminating these problems by improving the VOF algorithm and its implementation in OpenFOAM. However, with the current VOF implementation, it is recommended to use a very regular mesh near the free surface, as the solution otherwise is likely to become unstable and inaccurate.
2 Floating Body Complexities in CFD

Two different codes are objects of this study, namely the open source code OpenFOAM 2.2\(^{11}\) with a flexible mesh approach and the commercial CFD code StarCCM+ with the overset mesh method. The focus of the investigation is on validation in the sense of comparing the strengths and weaknesses of OpenFOAM against the commercial code StarCCM+ by measuring them against results of physical model tests. The governing methodologies needed for accurately capturing hydrodynamic impact on floating WECs lie in the surface capturing algorithm and the two-way coupling between the body motion algorithm and the hydrodynamic solver of the Navier-Stokes equation. The implication of the surface capturing method has been assessed in the previous section. The latter involves not only the coupling between the Navier-Stokes equation and the linear 6-DOF (Six Degrees of Freedom) solver, but also a “re-meshing” technique is needed to follow the movement of the floating WEC. Between the two solvers, information is transferred through a so-called FSI (Fluid Structure Interaction) interface, the surface of the structure being the common object of force transfer. Structural deformations are ignored as focus is on the rigid body motion.

The 6-DOF model is used to simulate the motion of a rigid body in response to pressure and shear force exerted by the fluid, as well as to additional forces defined by the user, e.g. mooring line force. The model calculates the resultant force and moment acting on the body due to all influences, and solves the governing equations of rigid body motion to find the new position of the rigid body. The impact of this motion is transferred to the computational mesh.

Hence at each time step of the solution algorithm, the fluid-structure boundary surface is displaced and reoriented in accordance with the total hydrodynamic plus external forces and torques on the structure. In OpenFOAM an algorithm to redistribute mesh points inside the fluid domain is activated at each time step to ensure the mesh quality. On the fluid-structure interface a moving wall boundary condition is applied for the fluid velocity field in order to ensure the no-slip condition. However, in StarCCM+ the displacement of the body inside the mesh is contrary to OpenFOAM handled in a non-flexible mesh fashion.

Geometry is instead decomposed into a system of geometrically simple overlapping grids, and boundary information is exchanged between these grids via interpolation of the flow variables, hence many grid points may not be used in the solution (Atta and Vadyak, 1983). This solution technique is known as Overset grid method in StarCCM+ (Chimera grid system), with the major advantage that the grid quality is not affected by body motion. This implies that walls of the floater are modelled with standard no-slip wall boundary condition.

For the floating body two meshes are built. One is the background region containing the far-field flow domain. Another is created in a defined region surrounding the body of interest with a minimum of four layers of complete cells between bodies and the overset boundaries. The mesh regions do not need to be conformally linked. Flow-field information is passed between the two regions at the overset boundary and the

\(^{11}\) OpenFOAM 2.3 was released during the present study, but it has intentionally not been applied, due to reported problems (and not solved) in the pressure solution algorithm for two-phased flows (http://www.openfoam.org/mantisbt/view.php?id=1354). During the present study, it was found that the flexible mesh algorithm in OpenFOAM 2.2 often resulted in low quality mesh and corresponding low quality flow solution (Heilskov et al., 2014). It is worth mentioning that the algorithm in sixDoFRigidBodyMotion has been re-written in OpenFOAM 2.3 to remedy degrade mesh resulting from even modest rotations by introducing spherical linear interpolation. sixDoFRigidBodyMotion can now be specified as a mesh morphing solver. This improvement speaks in favour of OpenFOAM 2.3, however, it does not resolve the strong FSI coupling issue. Furthermore in the case of body constraints, an explicit correction of the motion to obey constraints has been introduced to avoid possible high-frequency force fluctuations induced by the old way of force correction. Thus the old force adjustment has been replaced.
background through acceptor cells. In other words, information passes from the active cells of one mesh to the active cells of another through the acceptor cells. Acceptor cells accept values from the other region via interpolation of donor cells, hence the numerical link between the two meshes. For each acceptor cell, donor cells must be found on the other mesh. The set of donor cells depends on the number of active cells in the donor region around the acceptor cell centroid. In the overlapping zone, it is recommended that cells are of comparable size in both meshes to minimize interpolation errors. The solution is computed on all grids simultaneously; hence the two grids are implicitly coupled through a linear equation system matrix.

Figure 2.1  Implicit coupling scheme in StarCCM+ (STAR Korean Conference 2012, presentation by Perić et al.).

The time integration of the 6-DOF body motion ordinary differential equations (ODE) is performed using a special symplectic integrator (Dullweber et al., 1997) in OpenFOAM, which is characterized as a leapfrog time integration method. This ensures the correct two-way coupling between the body motion and the transient solution of the flow equations.

In StarCCM+ equations of motion for the body with 6 degrees of freedom are solved using 2nd order discretization and implicit coupling with flow equations. The implicit coupling scheme updates both flow-induced forces on body and body position and grid in flow domain after each outer iteration. The method is outlined in Figure 2.1.

The standard FSI implementation in OpenFOAM is based on a leapfrog methodology which has resulted in a weak coupling algorithm between the body motion and the hydrodynamics (Campbell and Paterson, 2011). The implementation is explicit and applying a partitioned scheme, where the fluid solver and rigid body motion solver are

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12 Computational cells where the governing equations are solved. In each region active cells are separated from passive cells (no equations are solved) by the acceptor cells.
working alternately. The partitioned scheme is constructed such that the information is transferred once in every time step\textsuperscript{13}.

As we shall learn in Section 2.2, this approach is not sufficient in our case, when motion of the body is strongly coupled to the solution of the hydrodynamics (a stiff system). Including external forcing on the body in terms of mooring has only amplified the need of a numerical scheme that enforces a strong FSI coupling. In addition to floating structures moving due to wave excitation being extremely challenging for traditional dynamic deforming meshing techniques, a consequence of weak two-way coupling applied on floating WECs has been identified as the main source leading to frequent failure or poor performance.

A monolithic strong FSI coupling is implicit, which implies solving the flow equations and the rigid body equation simultaneously. The governing equation for fluid flow is discretized and rearranged to yield a matrix equation. A simultaneous solution of both fluid flow and rigid body motion will, however, require that the structural problem is embedded directly into the matrix equation for the fluid flow resulting in a coupled matrix equation, which is not straightforward to set up.

Figure 2.2 Flowchart of the FSI strong coupling scheme (Seng, 2012).

However, a strong FSI coupling may also be obtained by constructing a partitioned scheme using an iteration technique combined with predictor-corrector scheme for solving the rigid body motion. The method is outlined in Figure 2.2, and implies that the symplectic integrator in OpenFOAM used in the time integration of the 6-DOF body motions ODE needs to be replaced due to its leapfrog nature. Following Seng (2012), a partitioned scheme resulting in a strong coupling can be achieved by replacing the symplectic algorithm with an Adams-Bashforth-Moulton method, to solve the governing equations for the body motion. The procedure does, however, not take into account implications of mooring constraints. The instability issue arising from the weak two-way coupling in OpenFOAM will not be pursued further in this context. Hence only a limited set of OpenFOAM results are presented, demonstrating limitations due to the weak two-way coupling. DHI will use the present research as a firm basis to pursue the instability issues further in other ongoing research projects including a Ph.D. project.

\textsuperscript{13} A tighter FSI coupling would have been achieved if the partitioned scheme was constructed in a way that information was transferred several times in an iterative manner. OpenFOAM 2.3 offers a new option that when looping more than one time over the PISO algorithm within one time step it updates the body position at every PISO loop. This is not done in an iterative manner, but it allows for some under-relaxation between these loops. The position sub-step update is switch on by use of moveMeshOuterCorrectors, however, version 2.3 has not been applied due to reasons stated in footnote 11. Moreover, a similar stability result can presumably be achieved by reducing the time step.
2.1 TLP in Waves

Two validation cases have been objects of this study, namely a TLP substructure in regular waves and in irregular waves. The CFD simulations are compared to data from the physical model tests performed at DHI’s offshore wave basin within the European Union-Hydralab IV Integrated Infrastructure Initiative, in October 2012 (Tomasicchio et al., 2014). The measurement campaign involved regular and irregular wave attacks on a 1:40 scaled model of a floating TLP wind turbine with and without steady wind loads. Only the TLP substructure, Figure 2.3, in waves only is considered in this study. Two wave climates have been studied: regular waves with wave height $H = 0.15$ m, wave period $T = 1.8$ s, and irregular waves represented by a JONSWAP spectrum with a peak enhancement parameter of 3.3, significant wave height $H_s = 0.15$ m and peak wave period $T_p = 1.6$ s. All measures are in model scale.

![Figure 2.3 TLP substructure model used in the physical lab test at DHI (Tomasicchio et al., 2014).](image)

The TLP structural design is very simple with a height $h = 1.497$ m, consisting of a small cylinder mounted on top of a larger one with a diameter of 0.1625 m and 0.45 m, respectively. The cylindrical TLP has a mass of 141.73 kg and a design draft $T = 1.1973$ in water of density $\rho = 1000$ kg/m$^3$. The basin still water depth was 5 m. Its roll and pitch inertia about the centre of mass is 5.4459 kgm$^2$.

At the bottom of the TLP, a steel plate connects four mooring legs, Figure 2.4, to the structure each with a radius to fairleads of 0.675 m in a cross formation. The line tension in each of the four vertical tethered moorings was 12.1456 kg and is modelled with a linear spring. The un-stretched length is 3.7925 m and spring is set to coefficient $k = 11000$ N/m in the model. The hydrodynamic forces on the mooring lines and four fairleads have no significant influence on the motion of the TLP and are neglected in the models. The mooring lines of a TLP are orthogonal to the seabed, with the restoring force mainly generated by the change in buoyancy of the topside structure. The position of the TLP is such that looking in the wave direction you will see the upstream tension leg in front of the downstream tension leg, see Figure 2.4.
Initially, the floater is at rest in the centre of the computational domain with a centre of mass position at [3.0; 3.0; 3.9847] m, see Figure 2.5. The computational domain extends in the x-direction [0; 6] m, y-direction [0; 6] m and z-direction [0; 6.0] m with the still water level being at $z = 5.0$ m.
In StarCCM+ the domain needed to be extended in the horizontal plane for wave absorption reasons, which results in centre of mass position in \([x, y] = [10,10]\) m.

### 2.1.1 Numerical Model and Boundary Conditions

In this section, both OpenFOAM 2.2 and the CFD code StarCCM+ are validated. The two codes are both based on the finite volume method and solving the unsteady incompressible Reynolds-averaged Navier-Stokes equations. As in OpenFOAM, the surface capturing algorithm for two-phase flows is solved using the VOF method in StarCCM+.

The boundary conditions in StarCCM+ were set up to match OpenFOAM as closely as possible. However, StarCCM+ does not use a flexible mesh algorithm, but instead the dynamic motion of the floater is computed with the use of overset grid technology. The flexible mesh algorithm implies that the walls of the TLP have to be set with a moving wall boundary condition in OpenFOAM in order to maintain the wanted no-slip condition.

Turbulent fluid flow is modelled with a \(k-\omega\) SST model in combination with standard wall functions (Wilcox, 2010) for modelling the wall boundary effect on the TLP. The wall function method on no-slip walls uses empirical formulae that impose suitable conditions near the wall without resolving the boundary layer. Hence, by placing the near-wall cell at a distance \(30 < y^+ < 100\), the flow in this cell may then be described by wall function. In OpenFOAM a standard wall function was used, while StarCCM+ offers the choice of an all-\(y^+\) wall treatment. The all-\(y^+\) wall function is a hybrid that combines wall functions depending on the value of \(y^+\) (Reynolds number). The mesh at the wall boundary was in both models created with the intention of running the standard wall function within its range of function in most parts, however, since the flow field is of oscillation nature the benefits of the all-\(y^+\) wall treatment is evident. The SST (Shear Stress Transport) model of (Menter, 1994) is an eddy-viscosity model, which in general has merit for its good behaviour in adverse pressure gradients and separating flow.

With wave periods of \(T = 1.8\) s and \(T_p = 1.6\) s, desktop calculations of the orbital motion show that the surface waves will not ‘feel’ the bottom, hence the seabed is assumed not to influence the waves. We therefore used a deep water approximation for the bottom and applied an inlet condition at the bottom boundary, which resembled a far-field condition. On the top boundary of the computational domain, an atmospheric boundary condition is imposed, with inlet/outlet character.

In OpenFOAM, the active absorption boundary condition by Higueras et al. (2013) is imposed on all vertical boundaries of the computational domain, hence removing the demand of extending the domain, which was necessary in StarCCM+ where a relaxation zone technique is used as wave damping boundary at the outlet boundaries. Wave damping in StarCCM+ is accomplished by a vertical momentum sink applied at the free surface following the work by Choi and Yoon (2009).

In OpenFOAM, the pressure-velocity coupling is solved using the PISO algorithm while StarCCM+ uses the SIMPLE\(^{15}\) algorithm. In both StarCCM+ and OpenFOAM, 2\(^{nd}\) order numerical convections schemes are applied.

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\(^{14}\) The normalized distance \(y^+\) originates from the law of the wall and accounts for the actual flow condition in the vicinity of the wall (Wilcox, 2010).

\(^{15}\) Semi-Implicit Method for Pressure Linked Equations (Ferziger and Peric, 2002).
2.2 OpenFOAM

Prior to the study of floaters subjected to waves, a series of hydro-static validation tests was performed. The results were presented at the 2nd SDWED April 26th, 2012 symposium and validated the hydrostatic capabilities of OpenFOAM including decay tests (Heilskov and Sørensen, 2012).

OpenFOAM 2.2 is applied in the following. Wave modelling is adopted by the wave generation framework ihFoam. The development of this framework is described in (Higuera et al., 2013). Active wave boundary conditions are imposed at the wave generation inlet boundary \( x = 0 \) m. For the regular wave test case the waves are modelled with Airy wave theory with the following parameters; wave height \( H = 0.15 \) m, wave period \( T = 1.6 \) s. Damping in the system is specified directly through the mooring settings.

The computational mesh of the fluid domain is an unstructured hexahedral mesh. A narrow band of high resolution in the \( z \)-direction surrounding the still water level is made in order to better capture the motion of the generated waves (200 cells per wavelength and 8 cells per wave height). The structure of the global mesh can be seen in Figure 2.6. The total number of cells in the mesh is roughly 6.9 million. The numerical model has previously been validated in terms of grid convergence.

Close to the surface of the floater the resolution is increased in order to model the effect of the boundary layer. The small cells attached to the body are prone to high skewness during large displacements of the body, e.g. excessive pitch and surge motion. Adjustable time step with a Courant number limit of 0.2 was used. The computations were done on 32 cores of the DHI HPC cluster. The speed of the computations was monitored. A computational time of \( \sim 5 \) days for 20 s simulation time was reported.

![Figure 2.6 Computational mesh used in OpenFOAM of 6.9 million cells.](image)

In the following, measurements are compared with the results obtained with OpenFOAM. Some results were reached for the TLP in regular waves, but due to instability problems only by making a number of critical assumptions. Tests of the code showed that in the transcendent response period, the natural frequency of the TLP is excited, resulting in
fast oscillations of the heave motion with relatively large amplitudes. These kinds of ‘ringing’ heave motions have also been observed in simulations with StarCCM+. The damping in the system relieves the transcendent oscillations in StarCCM+. In OpenFOAM, the damping fails to affect the FSI system, with the result that flow velocities (hydrodynamics) and 6-DOF motion diverge with flutter instability to follow. Hence the weak two-way coupling between the body motion solver and the hydrodynamic solver in OpenFOAM fails to respond in time to the large growing amplitudes, which the damping should have facilitated as we see for StarCCM+ with strong two-way coupling. A weak two-way coupling, as in OpenFOAM, is in other words sensitive to large spikes in the motion amplitudes, excited by motions close to the natural frequency, resulting in each components of the FSI system diverges as the FSI system cannot recover.

In an attempt to overcome major instability issues in OpenFOAM the still water level was reduced by 20 cm. This leads to a 17% reduction in buoyancy. By keeping the total mass and moment of inertia of the system as in the original set-up, the line tension in each mooring is reduced to approximately one third of its original size. Furthermore, we adjusted the damping applied to the system in an iterative manner, in order to stabilize the simulation.

In Figure 2.7 the surface elevation is compared with wave gauge 2 in the measurements located ~3.5 diameter upstream the TLP. The results show that the wave height in OpenFOAM was damped during travelling from the inlet to the probing location. Besides the lacking magnitude of the wave height, the computed signal has the correct wave period, it does not show sign of being contaminated by wave reflections from the vertical boundaries and is otherwise regular. This implies that the coupling of the flexible mesh, free-surface Navier-Stokes solver and active wave boundary strategy works accurately, in the case with critical assumptions made. The deviation is most likely due to numerical dissipation of energy, as several of the 2nd order numerical schemes initially applied were replaced with 1st order upwind as a mean to stabilize the solution.

![Figure 2.7 Surface elevation probed 1.5 m (~3.5 diameters) upstream the TLP in both the model test and CFD simulation. Regular waves (H = 0.15 m, T = 1.8 s).](image)
Figure 2.8 depicts the motion response of the TLP. It can be observed that in case of the current TLP configuration the floater is most sensitive to surge motion. As expected the heave motion is of a less dominant nature. The period in both heave and surge motion corresponds to the wave period. The response signal in the heave motion computed with OpenFOAM is comparable to the measurements. However, the amplitude of the heave motion is less than in the measurements. The discrepancy stems from the reduced buoyancy in OpenFOAM. Considering change line tension in the OpenFOAM model, the surge motion compares to the measurements, however, with a slight difference in phase. The measurement shows two forms of oscillations in sway signal - a short and a long periodic motion. The short is in correspondence with the wave period, whereas the long looks like a second order effect of wave drift nature. This drift response is also present in the OpenFOAM signal.

![Plot of motion response](image)

Figure 2.8 Heave, sway and surge motion of the floater in regular waves. The blue curves are measurements and the solid black lines depict results from OpenFOAM.

Figure 2.9 compares the simulated angular response of the TLP to the measurements. It can be observed that in case of the current TLP configuration the floater exhibits no rotational motion compared to the physical lab test. A weak pitch motion can be sensed with a double peak as in the measurement. The computed amplitudes are order of magnitudes smaller than the measured.

The discrepancy between the measurements and the CFD simulation can partly be ascribed to the reduced line tension in OpenFOAM and partly to the fact that the waves in OpenFOAM did not have the correct wave height compared to the measurement, see Figure 2.7.
Figure 2.9    Angular motion of the floater in regular waves. The blue curves are measurements and the solid black lines depict results from OpenFOAM.

Forces in the mooring lines are compared to measurements in Figure 2.10, taking into account that the line tension in each mooring is reduced to approximately one third of its original size. It is observed that the forces in the mooring display comparable dynamic behaviour to the measurements.

Albeit no general conclusion should be drawn from the present test case, it served to demonstrate that OpenFOAM despite its challenges in the flexible mesh approach and deficiency in the two-way coupling can capture complex interaction between the mooring system and the floating structure, if the combination of waves and floater system is not affected by system resonances.

A result of the flexible mesh approach is often highly distorted computational cells adjacent to the floating structure (Heilskov et al., 2014). The problem becomes more pronounced if motion of the floater is large. Distortion of boundary layer cells obviously has a negative impact on the viscous forces computed. A way to remedy the numerical instability and fluid motion accuracy close to the wall boundary is to divide the computational mesh into two regions: One mesh rectangular region encapsulating the floating WEC containing the refined part of the mesh and another much coarser surrounding mesh region. By using the \texttt{subSetMotion}\textsuperscript{16} library in OpenFOAM, it allows us to freeze the cells in the inner mesh region, such that they do not deform but follow the motion of the body. Thus now only the cells in the surrounding mesh region far from the floater can deform due to motion of the floater. Evidently, this provides a more accurate computation of the flow field in the vicinity of the WEC. Furthermore, due the larger sizes of the cells in the surrounding region, they become much less distorted in case of large motion of the floater. Hence the model is much less sensitive to instabilities of the flexible mesh approach.

\textsuperscript{16} \texttt{SubSetMotion} library is available in OpenFOAM 1.6-ext, and has to be transferred to OpenFOAM 2.2.
Figure 2.10 The tension force measured in each of the four mooring lines at the attachment point to the floater. The blue curves are measurements and the solid black lines depict results from OpenFOAM. The values of OpenFOAM have been multiplied by a factor of ~2.8, which reflects the difference in pre-tension applied in the CFD model compared to the value used in the measurements.
2.3 StarCCM+

StarCCM+ (9.06) is applied in the following. The size of the computational domain in the horizontal plane is more than double the size of the domain used in the OpenFOAM model. Contrary to OpenFOAM, StarCCM+ demands a band of additional computational cells adjacent to the vertical wave outlet boundaries for wave damping purposes. In StarCCM+ a wave relaxation technique is used to eliminate wave reflections from outlet boundaries when waves leave the domain. The waves are degraded as they pass through the wave damping zones. The width of the relaxation zone needed is by a rule of thumb about one wave length. In the case of regular waves, the wave length is \( \sim 5 \) m. Similar size of the relaxation zones is used in the case of irregular waves with significant wave height \( H_s = 0.15 \) m and peak wave period \( T_p = 1.6 \) s. Damping in the dynamic system is specified directly through a force applied acting in the centre of gravity of the TLP.

As we apply the overset grid method, two independent regions have to be made and meshed separately. The computational mesh of the fluid domain is in both regions an unstructured hexahedral mesh. Several mesh zones have been defined in order to minimize the usage of computational cells.

![Computational mesh used in StarCCM+ of 2.7 million cells.](image)

The overset mesh region surrounding the TLP was meshed with the aim of having a high quality mesh growing from the wall boundaries. A narrow band region of high resolution surrounding the still water level was made in order to better capture the motion of the generated waves (80 cells per wavelength and 11 cells per wave height). An identical region was defined in the background mesh region, however, extending all the way to 5 m from the vertical boundaries of the domain. In the background mesh an additional region closely surrounding the surface region with a courser mesh resolution was built, however, extending all the way to the vertical boundaries of the domain. This is plausible as much fewer cells are needed in the relaxation zone. The structure of the global mesh can be seen Figure 2.11. The total number of cells in the mesh is roughly 2.7 million. A constant time step was used corresponding to a Courant number below \( \sim 0.03 \) in the top part of the undisturbed regular wave.

The computations were done on 80 cores of the DHI HPC cluster Hydra2. The StarCCM+ model runs with optimum speed when distributing about 40-50k cells on each core. The speed of the computations was monitored. A computational time of \( \sim 2 \) days for 20 s simulation time was reported.
2.3.1 Regular Waves

The Airy wave modelling in StarCCM+ was done in a similar way as by Jacobsen et al. (2011). For the regular wave test case we applied a regular wave using Airy theory with the following parameters: wave height $H = 0.15\, \text{m}$, wave period $T = 1.6\, \text{s}$.

Figure 2.12 shows a snapshot of the TLP in a crest of the wave at 18 s and in a wave trough at 18.9 s. The corresponding snapshots have been taken during the measurements and are shown in Figure 2.13. The numerical water surface is depicted by plotting the isosurface of the VOF volume fraction equal 0.5. Furthermore, the mooring lines can be sensed through the surface.

Comparing the snapshots of the TLP in the wave crest situation, we see that the top face of the large cylinder is/will be covered with water, and run-up on the small cylinder is likely to occur as the wave passes the TLP. In the trough situation a part of the TLP has moved out of the water, and it is observed that the model captures water running down from the top face of the large cylinder as seen in the measurements.

As previously mentioned, the design draught of the TLP matched exactly the height of the large cylinder on which the small cylinder part of the body is mounted. Thus, the design still water level coincides with the interface between the top face of the large cylinder. With such a set-up, the TLP is prone to large changes in buoyancy as waves pass the floater. In a wave trough the TLP will experience a large reduction in buoyancy compared to the small increase in buoyancy when a wave crest passes the TLP. The relatively large oscillations in buoyancy depend on the wave height and will add significantly to the vertical acceleration of the floater.

In Figure 2.14 the surface elevation is compared with wave gauge 2 in the measurements located ~3.5 diameters upstream the TLP. The results show a good match with same wave period regular shape.

In Figure 2.15 ring formed waves radiating away from the TLP are observed as the waves pass the cylindrical structure. The formation of the pronounced ring waves arises from a combined effect of the geometrical shape of the TLP and enhanced acceleration of the heave motion, due to the aforementioned large changes in buoyancy. By geometrical shape, we have the effect of the interface between the large diameter and smaller diameter coinciding with the still water surface in mind with the result that waves are created due to heave motion excited by the incoming waves. The radiation of ring shaped waves from the TLP is also observed in the numerical simulation, Figure 2.12.

Figure 2.16 depicts the motion response of the TLP. It can be observed that in the case of the current TLP configuration the floater is most sensitive to surge motion. As expected, the heave motion is of a less dominant nature in terms of amplitude. The period in both heave and surge motion corresponds to the wave period, which is also observed in the measurements. The response amplitude in both heave motion and surge motion computed with StarCCM+ is comparable to the measurements. In both the measurement and simulation, the TLP moves with the wave period with an amplitude of about 4 cm in surge.

The high-frequency oscillations in the measured signals do most likely stem from wave excitation of a complex modal eigenfrequency\textsuperscript{17}. However, the small oscillations overlaying the heave motion response in the simulation are clearly the natural period of the TLP, which is readily determined to ~0.37 s (mass spring system including added mass).

\textsuperscript{17} Even though this study is only focusing on the TLP substructure, the measurements could potentially be influenced by complex eigenmodes of the non-active wind turbine superstructure mounted on top.
Figure 2.12  Snapshots of the simulation of the TLP in regular waves (H = 0.15 m, T = 1.8 s) in a crest (top) and trough (bottom) situation. The water surface is depicted by plotting the isosurface of the VOF volume fraction equal 0.5. The contour colours illustrate the height of the surface elevation.
Figure 2.13  Snapshots of the TLP in regular waves from the physical lab test in a ‘crest’ (top) and ‘trough’ (bottom) situation. (Tomasicchio et al., 2014).

In the simulated surge response, Figure 2.16, two forms of oscillations can be observed - a short and a long periodic motion. The short is in correspondence with the wave period of 1.8 s, whereas the long looks like a second order effect of wave drift nature. This wave drift response is not present in the model test signal. When we take a second look at the results obtained with the OpenFOAM model, Figure 2.8, a wave drift nature can also be observed in the surge signal. The wave drift nature in the surge signal is much less pronounced in the OpenFOAM model, due to effects of the reduced buoyancy in the model. The absence of surge wave drift in the model tests may be due to a combination of imperfections in the mooring configuration (non-vertical tension legs, deviation in draft, body position inclination errors in the water, deviations in pre-tension setting in the four moorings), and spurious wave reflections from basin walls in the lab.
Figure 2.14  Surface elevation probed 1.5 m (~3.5 diameters) upstream the TLP in both in the model test and CFD simulation. Regular waves (H = 0.15 m, T = 1.8 s).

Figure 2.15  Bird view snapshot of the TLP in regular waves from the physical lab (Tomasicchio et al., 2014). Notice the ring waves radiating away from the structure.

For the sway motion, the measurement shows two forms of oscillations, Figure 2.16, a short and a long periodic motion. The short period is in correspondence with the wave period, whereas the long period looks like a second order effect. No short period motion
is observed in the simulation. On the other hand, StarCCM+ does capture a sway response of second order character, just as was seen in the OpenFOAM model, Figure 2.8. The signal is more pronounced in the StarCCM+ model than in the model tests.

![Figure 2.16](image)

**Figure 2.16** Heave, sway and surge motion of the floater in regular waves. The blue curves are measurements and the solid black lines depict results from StarCCM+.

Figure 2.17 compares the simulated angular response of the TLP to the measurements. As expected, the pitch motion is one of the dominating motions of the TLP. The pitch response in the simulation compares roughly with the corresponding measured response in both amplitude and motion period. However, the simulation does not capture the double peak of the pitch motion clearly seen in the measurement signal. Instead we observed small oscillations overlaying the simulated pitch response which has a period corresponding to the previously mentioned heave natural period of the TLP ~0.37 s. It is expected that in the measurement, the damping in the system has more effectively eliminated excitation of this natural frequency, which in the numerical model materializes and contaminates the pitch response.

The yaw response was, however, not expected to be as pronounced as the pitch motion, and in particular in the numerical model with no imperfections to trigger the otherwise axis symmetrical structure into a regular yaw motion. The numerical model exhibits a yaw rotational motion comparable to the physical lab test. The amplitudes are not constant as in the measurements.

The roll motion of the TLP is non-existing in the numerical model. In the measured roll response small double peaked oscillation with a period corresponding to the wave period can be observed. However, the roll motion is negligible compared to the other motions of the TLP. Contrary to in the physical lab, there are no wave reflections from the wave tank walls contaminating the wave field impacting on the TLP. As a result of this ideal situation in the CFD wave basin, the roll motion of the symmetric TLP is insignificantly small. In the case of large KC-number (Keulegan-Carpenter number), vortex shedding can induce roll motion of the TLP, but this not the case here.
Figure 2.17 Angular motion of the floater in regular waves. The blue curves are measurements and the solid black lines depict results from StarCCM+.

Figure 2.18 The tension force measured in each of the four mooring lines at the attachment point to the floater. The blue curves are measurements and the solid black lines depict results from StarCCM+. 
Figure 2.18 depicts the tension forces in the four mooring lines at the attachment point. No. 1 and 3 no. are the mooring line upstream and downstream the TLP, respectively. With the cross mooring configuration, they both exhibit the largest peak values, as expected. The forces in mooring line no. 2 and no. 4 are almost identical with the same magnitude of peak values. The peak values are approximately 20% lower than the forces measured in no. 1 and no. 3. The forces over time in all four mooring lines show excellent agreement to the signals of the physical lab test. A main frequency corresponding to the wave frequency is observed in all of the force signals.

Measurement of the force in tension leg no. 1 shows a double peak similar to the one observed in the pitch response, which gives evidence that the pitch motion and tension in line no. 1 are clearly coupled. The largest discrepancies are observed in tension leg no. 1 and no. 3.

2.3.2 Irregular Waves

At the inlet a wave boundary condition is specified. The irregular VOF wave boundary condition in StarCCM+ is based on DNV-RP-C205 (2007). The wave conditions at the imagined site are represented by a JONSWAP spectrum with a peak enhancement parameter of 3.3, significant wave height $H_s = 0.15$ m and peak wave period $T_p = 1.6$ s. Only unidirectional waves are considered. The spectrum is modelled by imposing a pre-calculated velocity field synthesized as a linear superposition of Airy waves with different amplitudes, periods, phases and directions, to produce a realisation of the JONSWAP spectrum. The method is outlined in Section 3.3.2 in DNV-RP-C205. Even though the wave field is synthesized from linear theory its propagation through the computational domain is governed by the full non-linear Navier-Stokes equations.

A minimum number of sinusoidal wave components needed to represent the theoretical spectrum are computed, hence reducing the resolution. The irregular wave signal was created using 450 partial waves. Due to the large computational demand of the present complex model, the simulation time had to be limited to relatively short time series. The intended time series were selected to 600 s (10 min). Contrary to OpenFOAM, it is not possible in StarCCM+ to choose the time series which best reproduced the wave spectra, and included one or more extreme events within the 600 s. In other words, make sure that the wave spectra for the short time series do not differ significantly from the corresponding spectra for full 3-hour time series.

Figure 2.19 compares the CFD results of the free wave fields to the corresponding time signal of the surface elevation from the measurement at WG2\textsuperscript{18}. A 20 s sample of the surface elevation is illustrated in Figure 2.20. The significant wave height in ~3.5 diameters upstream the TLP was measured to $H_s = 0.15$ m, whereas the CFD computation resulted in a significant wave height of $H_s = 0.13$ m. The peak period of $T_p = 1.6$ s in the CFD simulation corresponds to the peak period of the JONSWAP spectrum imposed at the inlet wave boundary. This is not the case when evaluating the surface elevation measured in the lab, which results in a peak period, $T_p = 1.5$ s. The discrepancy between the measurements and the CFD simulation can be ascribed to the fact that the CFD spectrum is based on only 1/4 of time statistics compared to the measurement. Another likely additional explanation may be sought in relation to the spatial resolution of the computational grid. A too coarse grid will not capture the many small waves accurately, and cause energy to be diffused out of the system which again will result in decreasing wave heights. Further refinement and optimization near the free surface may reduce the discrepancy.

\textsuperscript{18} Wave Gauge no. 2, which position is 1.5 m upstream the TLP.
Figure 2.19 The surface elevation was probed 1.5 m (~3.5 diameters) upstream the TLP in both the model test and CFD simulation. The corresponding wave spectra are compared. The JONSWAP wave spectrum with $H_s = 0.15$ m, $T_p = 1.6$ s and gamma = 3.3 was used as input in both the CFD simulations and measurements.

Figure 2.20 Surface elevation samples probed 1.5 m (~3.5 diameters) upstream the TLP in both in the model test and CFD simulation. Irregular waves; JONSWAP $H_s = 0.15$ m, $T_p = 1.6$ s and gamma = 3.3.
Figure 2.21 shows a snapshot of the TLP in the crest of the wave at 38.4 s. The wave field of irregular waves is clearly seen. The iso-surface of the volume-fraction variable in the VOF approach equal 0.5 is used to illustrate the free surface.

![Solution Time 38.4 (s)](image)

**Figure 2.21**  Snapshot of the simulation after 38.4 s of the TLP in irregular waves; JONSWAP $H_s = 0.15$ m, $T_p = 1.6$ s and gamma = 3.3. The water surface is depicted by plotting the iso-surface of the VOF volume fraction equal 0.5. The contour colours illustrate the height of the surface elevation.

The flow field around the TLP in both air and water phase is shown in Figure 2.22. The observed wave flow field looks plausible and clearly indicates the free surface interface.

Moreover, from Figure 2.22 it is observed that vortices are shed from the bottom edge of the substructure as the waves pass the TLP. This vortex structure interaction has a non-linear impact on the forces and motion of the floater.
Figure 2.22  Snapshot of the velocity in a plane parallel to the wave direction cutting through the centre of the TLP. Irregular waves: JONSWAP $H_s = 0.15 \text{ m}$, $T_p = 1.6 \text{ s}$ and gamma = 3.3. The flow field is depicted with line integral convolution of the vector field. The magnitude of the velocity is illustrated by contour colours.

Figure 2.23 depicts a sample of the motion response of the TLP. With an irregular wave signal, it is only possible to compare a measured evolution and numerical results in a gross manner. As in the case of regular waves, high-frequency oscillations in the measured signals of heave motion can be observed, and do most likely stem from wave excitation of a complex modal eigenfrequency. The overall level of the heave and sway motion response is underestimated, whereas the amplitude of the second order effect in the surge signal is slightly overestimated. The surge motion is as expected the most dominant displacement of the TLP.

Figure 2.24 compares the simulated angular response of the TLP to the measurements. It shows that the pitch motion is the dominating rotation of the TLP. The simulated level of the roll and yaw compares well with the measurements. Since measurements in both regular and irregular waves indicate that the TLP is sensitive to pitch motion, the large difference in amplitude observed in Figure 2.24 seems plausible when also considering the corresponding surface elevation measured upstream the TLP, see Figure 2.20.
Figure 2.23  Heave, sway and surge motion of the floater in irregular waves; JONSWAP $H_s = 0.15\,\text{m}$, $T_p = 1.6\,\text{s}$ and $\gamma = 3.3$. The blue curves are measurements and the solid black lines depict results from StarCCM+.

Figure 2.24  Angular motion of the floater in irregular waves; JONSWAP $H_s = 0.15\,\text{m}$, $T_p = 1.6\,\text{s}$ and $\gamma = 3.3$. The blue curves are measurements and the solid black lines depict results from StarCCM+. 
Figure 2.25 The tension force measured in each of the four mooring lines at the attachment point to the floater. The blue curves are measurements and the solid black lines depict results from StarCCM+.

Figure 2.25 depicts a sample of evolution in the tension forces in the four mooring lines at the attachment point. No. 1 and no. 3 are the mooring line upstream and downstream the TLP, respectively. With the cross mooring configuration, they both exhibit the largest peak values in the simulated case as well as in the physical lab test. The forces in mooring line no. 2 and no. 4 are almost identical with the same magnitude of peak values. The mean level in the four mooring lines shows excellent agreement to the size of the mean tension in the measurement.

Similar to the case of regular waves, the measurement of the force in tension leg no. 1 shows same evolution as observed in the pitch response, which gives further evidence that the pitch motion and tension in line no. 1 are coupled.

The exceedance curve for tension in the simulated mooring line no. 1 is compared to the corresponding results from the measurement in Figure 2.26. The plot based on simulated data of the peak and trough values shows same trends as results based on measurements. It is observed that a better match is found comparing peak values than comparing minima force responses in the mooring line. The largest deviation is found in either the largest peak events or in the minima in general. A maximum of ~25% in difference is observed. This result is plausible in view of the statistical difference in surface elevation shown in Figure 2.20, from which it is seen that in this part of the history of wave events, the waves in the measurements are more pronounced in wave height than in the simulation.

A better match between measurements and numerical results could most likely be obtained by applying the same input wave signal used in the physical model test to drive the paddles. The study by Wu et al. 2014 supports this, hence it is an obvious suggestion for future work.
Figure 2.26 Exceedance curve (data monitored at mooring line no. 1). Top: Peak force values. Bottom: Values of maximum depth of troughs, which in other words is the tension minima, the mooring line experiences. The same length of time data set was used in both analyses shown.
3 Conclusions and Recommendations

Two different CFD codes have been objects of this study, namely the open source code OpenFOAM with a flexible mesh approach and the CFD code StarCCM+ with the overset grid method. Both codes have been validated against measurements of a TLP substructure in regular waves and irregular waves. It has been demonstrated that we are able to capture the impact of non-linear effects on a floater with reasonable results. This includes complex interaction between the mooring system and the body. Hence, both the motions and the forces in the mooring lines were monitored. As part of the validation the sensitivity of the solver to body displacements has been assessed. Even for moderate body displacements and rotations the flexible mesh method in OpenFOAM fails due to numerical instabilities as a result of distortion of the mesh degrading the quality of the mesh significantly and the two-way coupling between the fluid solver and the 6-DOF solver. Tests have shown that OpenFOAM is particularly numerically sensitive to body discontinuities coinciding with the water surface interface. The StarCCM+ results illustrated that with the overset grid method, we are able to accurately capture effects of complicated non-linear wave interaction of complex viscous nature on the motion of a moored structure.

A major advantage in StarCCM+ was that it does not suffer from the same stability sensitivity towards problems with floating body motion strongly coupled to the solution of the hydrodynamics (a stiff FSI problem) as OpenFOAM. Improving stability in OpenFOAM can be done by implementing a strong FSI coupling by constructing a partitioned scheme using an iteration technique combined with a predictor-corrector scheme for solving the rigid body motion. The results obtained with StarCCM+ compared well with the measured motion of and tension forces on the TLP in regular waves in particular. Based on experience with StarCCM+, it is recommended to always combine tests of hydrodynamic behaviour of a floating WEC with overset grid method not only due to numerical robustness but also accuracy. This applies when simulating a WEC in survival condition (rough seas with motion dominating viscous effects for a WEC) and even if the operation conditions of the WEC imply only moderate motion.

Besides behaviour simulations of survival conditions, the CFD algorithm presented may bring significant value, in relation to tests and hydrodynamic optimization on floating WECs, when complex viscous flow phenomena as wave overtopping/breaking and wave run-up may influence its operational efficiency.

Finally, it should be mentioned that the OpenFOAM surface capturing algorithm often causes high artificial velocities parallel to the water surface in both the air and water phase, which potentially can influence an accurate modelling of the motion of a WEC depending on the structure of the WEC and wave climate. Furthermore, the current VOF implementations require a very regular mesh near the free surface in order to avoid stability issues.

Besides addressing the numerical instability issue in OpenFOAM, future developments should include Power Take Off (PTO) in terms of the implementation of PTO matrix constrains. Extension of the mooring library to include catenary mooring lines (present in StarCCM+) should be done in connection with implementing the two-way FSI strong coupling. Research into improving the surface capturing algorithm is ongoing in a post-doc research project at DHI/DTU. Further tests on coupling of the free-surface Navier-Stokes solver and active wave boundary strategy should naturally follow any change in the surface capturing algorithm; including wave reflection analysis related to floating WEC simulations.
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