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Calculation of wave forces and internal loads on a semi-submersible at shallow draft using an IVOF method

by

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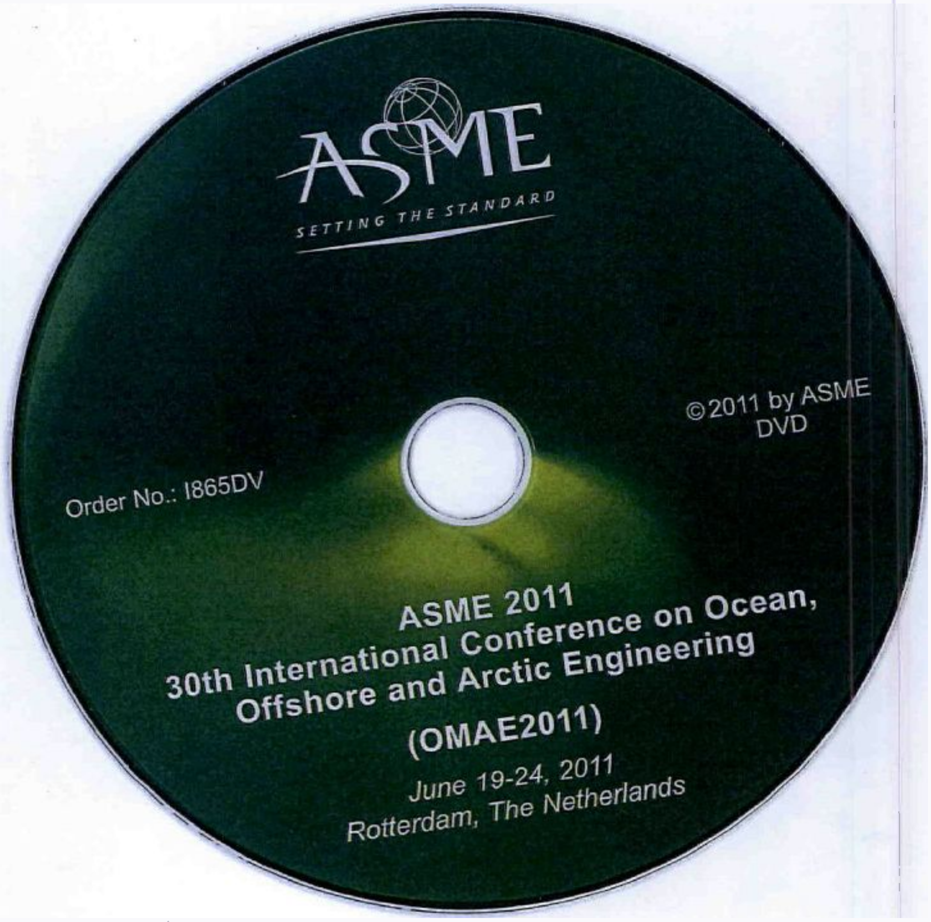
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CALCULATION OF WAVE FORCES AND INTERNAL LOADS ON A SEMI-SUBMERSIBLE AT SHALLOW DRAFT USING AN IVOF METHOD

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ABSTRACT

When semi-submersibles are floating at shallow draft, only a relatively thin layer of water may be present above the floaters. Model tests and full scale observations have shown that in such cases, even in low waves, non-linear effects significantly influence the wave pattern around the floaters. These non-linear effects make conventional methods based on linear diffraction theory less reliable for the calculation of wave forces and internal loads on a semi-submersible at shallow draft.

This paper describes and analyzes the non-linear hydrodynamics affecting the wave loads and internal loads at shallow draft. The feasibility of both ComFLOW and linear diffraction method for the calculation of these loads are assessed.

CFD simulations were performed using ComFLOW, a program based on the incompressible Navier-Stokes equations and the improved Volume Of Fluid (iVOF) method. First, the wave loads acting on a fixed semi-submersible in regular waves were calculated with ComFLOW and compared with linear diffraction theory and model tests. Secondly, internal loads were calculated for a moving semi-submersible in regular waves using both ComFLOW and linear diffraction theory. In the ComFLOW simulations, the motions of the semi-submersible were prescribed instead of solved by the method itself. Calculations and comparisons were performed for deep draft and shallow draft conditions.

The wave loads on the semi-submersible for shallow draft conditions derived with ComFLOW were reasonably close to the results from model testing, while the results from the linear diffraction method showed significant deviations from the model tests results. The internal loads calculated with ComFLOW were quite close to the results from the linear method, even for shallow draft conditions. Additional model testing is required for validation of the internal loads.

Keywords: iVOF, CFD, semi-submersible, shallow draft, structural assessment, wave loads, internal loads.

1. INTRODUCTION

Because of their favorable motion behavior, and many other extraordinary capabilities, semi-submersibles are widely used in the offshore industry. Examples of their application are drilling, oil production, heavy lifting and providing offshore accommodation.

When a semi-submersible is floating at shallow draft, the layer of water above the floaters may be relatively thin. Both full scale observations and model tests have shown that in this condition the wave pattern in the vicinity of the floaters is significantly different from that corresponding to a deeper draft. Due to the limited water depth above the floaters, non-linearities in the wave pattern are introduced, even for low waves [9]. The waves above the floaters become isolated from the surrounding sea, breaking waves are observed and when a part of the floaters emerges above the water, this involves rapid changes in water plane area.

Conventional methods for global strength analysis of semi-submersibles are generally based on linear diffraction theory [8], which assumes a linear relation between the wave height and the internal loads and no changes in water plane area. The non-linear effects related to the shallow layer of water above the floater may make these conventional linear methods less applicable for shallow draft conditions.

This paper studies the non-linear phenomenon described above using computational fluid dynamics (CFD). The objective is to evaluate the wave forces on and internal loads of a semi-submersible at shallow draft using the improved volume of fluid (iVOF) method incorporated in the program ComFLOW. The results are compared with measurements from model tests and results from linear calculations.

The outline of the paper is as follows: First, the approach is discussed, followed by a description of the ComFLOW program. Then, a description of the semi-submersible used as test case is provided and the experimental setup for the model tests is described. The next sections elaborate on the setup for respectively the linear calculations and the ComFLOW calculations. Results are provided in two sections: the first covering the wave loads acting on a fixed semi-submersible and the second dealing with the internal loads of a moving semi-submersible. The final section assesses the findings of the study.

2. APPROACH

A test case semi submersible was first selected. This was a fictive design, for which model tests at shallow draft were available at GustoMSC. For this test case, the wave loads and internal loads were calculated using the conventional linear method as well as the non-linear ComFLOW method. Simulations were performed for the semi-submersible at two drafts: a shallow draft, where non-linearities were observed during the model tests, and a deep draft, where the flow behaves in a more linear fashion.

The linear calculations were performed using the diffraction program WAMIT and the GustoMSC internal load calculation program DYNLOAD [8]. An extensive description of the linear method is provided in Section 6. Two series of simulations were performed with the program ComFLOW. The first included simulations with the fixed semi-submersible in regular waves. The second included simulations of the moving semi-submersible, due to the interaction with regular waves. The motions of the semi-submersible were not solved by ComFLOW, but prescribed. The ComFLOW program is discussed in detail in the next section.

The ComFLOW calculations were verified by performing a convergence study for various parameters, such as grid dimensions and boundary conditions. As far as model tests were available, these were used to validate the ComFLOW calculations. Unfortunately, internal loads were not measured during the model test program; such that only wave loads acting on the fixed semi-submersible could be validated. The internal loads could not be validated. However, for the deep draft example, the linear method was assumed to provide reasonably correct results and was used to verify the ComFLOW calculations.

3. COMFLOW PROGRAM DESCRIPTION

ComFLOW is a program for the numerical simulation of complex fluid flow. The program was developed initially by the University of Groningen (RuG) to study the sloshing of liquid fuel in spacecraft [5]. The micro-gravity environment involved required a very accurate and robust description of the free surface. In close co-operation with MARIN, the methodology was extended to maritime applications including:

- Green water loading [7].
- Anti-roll tanks [3].
- LNG Sloshing [1,2]
- Wave run up [4].

The method is based on a staggered finite volume discretisation of the Navier-Stokes equations, which describe conservation of mass and momentum of a fluid. To solve the Navier-Stokes equations, boundary conditions are needed. At solid boundaries, no fluid can go through the boundary and the fluid adheres to the wall because of viscosity (no-slip condition). At the free-surface continuity of normal and tangential stresses are imposed. Forces on objects are computed using the pressure only, since viscous forces are negligible in wave applications.

At inflow boundaries incoming waves should be able to enter the domain and waves generated inside the domain (for example by diffraction from objects) should be able to leave the domain without reflecting back into the domain. For that purpose a Generating and Absorbing Boundary Condition (GABC) was developed [10]. This boundary condition absorbs outgoing waves (also for a range of frequencies unlike the Sommerfeld condition) while simultaneously generating incoming waves. For regular wave simulations, a Sommerfeld condition can be used.

The flow domain is covered with a Cartesian grid with staggered variables. The pressures are defined in cell centers, the velocity components at cell boundaries. Complex structures are covered with a Cartesian grid, thus cells of different character appear. This difference in character is incorporated in the numerical method by introducing edge and volume apertures. These edge and volume apertures are used to indicate which part of a cell is open for fluid and which part is blocked by the solid geometry.

The Navier-Stokes equations are discretised in time and space. For the time discretisation, the Forward Euler method (first-order accuracy), or the Adams-Bashforth method (second-order accuracy) can be used. The spatial discretisation is based on the finite volume method. A choice can be made between (second-order) central discretisation and first or second order upwind discretisation. For the solution of the discretised Navier-Stokes equations, at each time step a Poisson equation for the pressure, which can be found after rearranging the discretised equations, is solved.

When the pressure solution is found, the new velocity field is computed and subsequently the free surface is displaced using the VOF-method [6] combined with a local height function. The time step is automatically adjusted using the CFL stability condition.

4. SEMI-SUBMERSIBLE DESCRIPTION

The semi-submersible used as test case in this study was a fictive design suitable for benign areas. As in such areas, only a small air gap is required, the unit has relatively large volume floaters and short columns. The unit consists of a ring shaped floater, four columns and a square deck box.

The main dimensions at full scale were:

- floater length 59.5 m
- floater width 13.5 m
- floater height 7.5 m
- column width 14.0 m
- column height 39.5 m

The two loading conditions considered were as follows:

Table 1: Loading conditions (full scale)

draft	25.0	11.5	[m]
displacement	43670	32982	[t]
KG	26.2	23.5	[m]
GM	6.0	13.2	[m]

The definition of the wave forces on the captive semi-submersible is shown in Figure 1. These are respectively: Fx, Fz and My, defined at the centre of gravity of the semi-submersible.

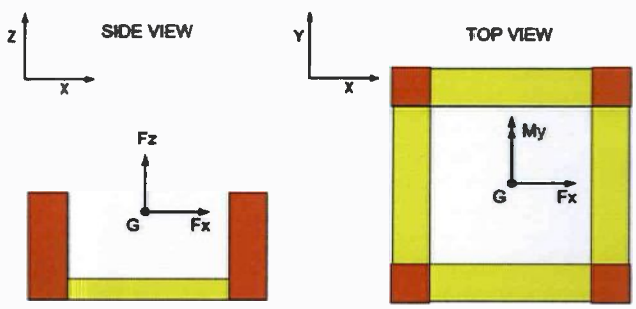

Figure 1: Definition of wave forces

Internal loads were calculated on the aft section of the semi-submersible (Fx and My), see Figure 2. The forces on the aft section represent the internal loads on the yz –plane of symmetry. The moment is defined at the neutral axis of this section.

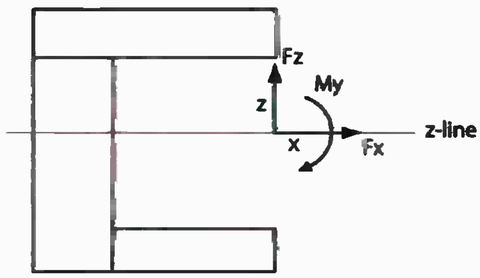

Figure 2: Forces on aft section - yz-plane

5. EXPERIMENTAL SETUP

Model experiments were conducted for the test case semi-submersible in the towing tank of the Delft University of Technology (TU Delft) in 2004. Towing tank dimensions are as shown in Table 2. The objective of these model tests was to investigate the hydrodynamic behavior of a semi-submersible floating at shallow draft. Captive tests and free motion tests were performed. The scale of the model was 1:100. In the current study the results from the captive model tests in regular waves were used for validation of calculations. A photograph of the captive experiment at shallow draft is shown in Figure 3.

Table 2: Dimensions towing tank (model scale)

Length	85.00	[m]
Width	2.75	[m]
Water depth	1.20	[m]

Figure 3: Photograph captive experiment

In the captive experiment the model was fixed in a measurement rig. Forces on the semi-submersible were measured during the experiment using force transmitters in both x and z directions. Additionally, the free surface elevation was measured at two different locations using wave probes, located respectively in front and beside the model. The set-up of the captive model test is presented in Figure 4. The wave direction coincides with the positive x-axis.

Forces as well as wave amplitude and time were scaled up to full scale using Froude scaling. Regular waves were tested with wave amplitudes between 1 and 3 meters and wave frequencies between 0.1 and 0.8 rad/s, as shown in Table 3. The maximum wave steepness considered in this study was 4 percent.

Table 3: Regular wave parameters captive experiment (full scale)

ω [rad/s]		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
ζ_a	1 m	x	x	x	x	x	x		
	2 m	x	x	x	x	x	x	x	x
	3 m	x	x	x	x	x	x		

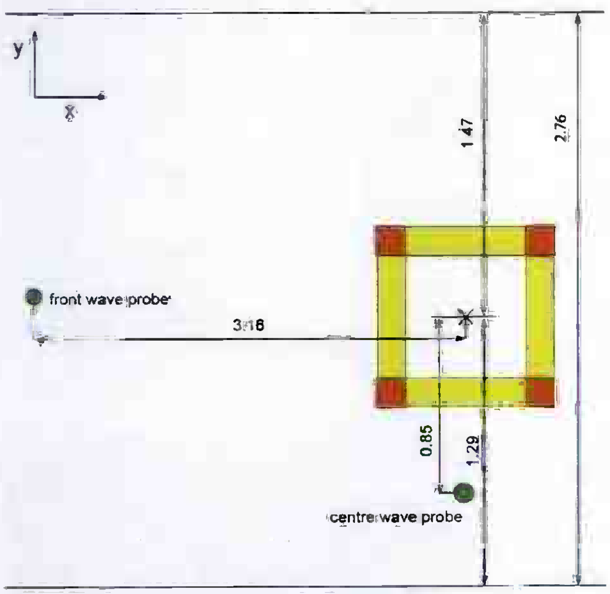

Figure 4: Set-up captive experiment (model scale)

6. LINEAR CALCULATION SET-UP

Linear calculations were performed for both wave loads and internal loads on the semi-submersible using linear diffraction theory. First, diffraction calculations were performed with the program WAMIT. Secondly, the internal loads on the semi-submersible were calculated using the GustoMSC software DYNLOAD. In all cases, the wave direction coincided with the positive x-axis and the motions were restricted to surge, heave and pitch.

A panel model was used for solving the radiation-diffraction problem. Modeling only a quarter of the underwater part of the semi-submersible was sufficient, because the geometry is double-symmetric. The model is built up of square panels of 2.0 meter per side, being amply sufficient for the considered wave frequencies. A picture of the panel model for shallow draft is shown Figure 5.

From the diffraction program, wave forces and hydromechanical coefficients (added mass, damping and hydrostatic restoring spring matrices) were derived. The motions of the semi-submersible were obtained by solving the equation of motion in the frequency domain. Viscous effects were approximated by using the linearized drag from Morison elements. The properties of the Morison elements were tuned based on model tests.

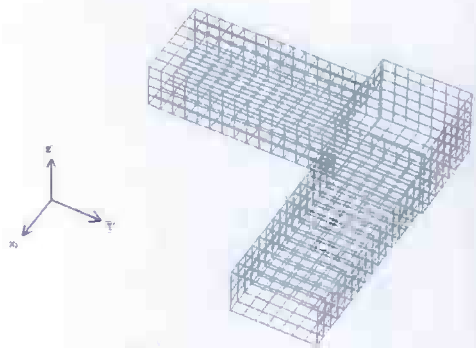

Figure 5: Panel model for Td = 11.5 meter

Internal loads were calculated with the program DYNLOAD. This program is a shell around the diffraction program and the finite element program, which combines hydromechanical, gravity and inertial loads on floating structures in waves. The loads are calculated on the nodes of a quasi-static structural model.

All dynamic loads are obviously dependent on the motions of the unit. Because the method is linear, the different components can be treated individually and summed up at the end using the proper multiplication and phase shifts. The hydrodynamic forces on the wetted part of the hull are obtained from the diffraction program. These hydrodynamic forces are a summation of wave-excited forces and hydromechanical reaction forces (added mass, damping and hydrostatic stiffness).

Gravity-induced dynamic loads occur due to pitch motions and are defined in Eq. (1). These loads have to be taken into account, because the loads are calculated in a body fixed axis system.

$$F_{gx} = mg \sin\theta \tag{1}$$

Inertial forces are proportional to the accelerations of the unit. For the calculation of the distribution of inertial forces a mass model was used, in which the mass properties were defined on local scale. The equivalent local forces and moments were converted on the nodes of the structural model.

For the calculation of dynamic internal loads all dynamic loads acting on a specific section of the semi-submersible were integrated following Eq. (2).

$$\overline{F}_{section} = \sum_{i=1}^{n} \overline{F}_{wi} + [\omega^2 (A_i + M_i) + i\omega B_i - C_i]\overline{x} + \overline{F}_{gx} \qquad (2)$$

In which M_i is the mass property of element i, F_{wi}, A_i, B_i and C_i are the wave forces, added mass, damping and spring coefficients with respect to the structural element i and $\overline{x}$ is the motion vector. Eq. (2) can be written more simple as:

$$\overline{F}_{section} = \overline{F}_{in} + \overline{F}_g + (\overline{F}_w + \overline{F}_a + \overline{F}_b + \overline{F}_c) \qquad (3)$$

7. COMFLOW COMPUTATIONAL SETUP

Two series of full scale simulations were performed with ComFLOW. Both series were carried out for the test case semi-submersible at deep and shallow drafts. The simulations series are:

A. Simulations of the captive semi-submersible in regular waves. Results were the wave loads on the fixed semi-submersible.
B. Simulations of the moving semi-submersible due to the interaction with regular waves. Results were the internal loads on the semi-submersible.

All simulations were started from an undisturbed fully developed wave field using a 5th order Stokes wave definition.

The simulation time was set to four wave periods. With this duration, sufficient information is obtained in terms of wave forces and internal loads. A longer simulation time has the disadvantage that reflections become more dominant. The time step during the simulations was controlled by ComFLOW, using the CFL stability criterion. The CFL-limits were set to $0.25 < CFL < 0.80$. The maximum limit for the time step was set at T/250. In order to satisfy all the criteria for the time step, while keeping computation time reasonable, it was decided to perform the simulations at full scale. Since viscous forces can be considered negligible for this type of wave applications, the scale difference between the simulation and the experiment was considered to be acceptable.

The Sommerfeld condition implemented in ComFLOW is a robust choice for absorbing regular waves at the outflow boundary of the computational domain. So a Sommerfeld outflow boundary condition was applied for all simulations in series A. Since for moving body simulations neither Sommerfeld nor GABC are currently compatible, a numerical beach was applied in the simulations of series B. No absorption boundary was applied at the end of the numerical beach, resulting in a negligible increase of the water volume during the simulation.

The computational domain was based on the dimensions of the towing tank. Since computational power is still a limiting factor, reductions were applied on depth and length of the domain. For the simulations with associated wave frequency larger than 0.4 rad/s, the domain depth was reduced to 90 meters instead of the full depth of 120 meters. Experience has shown that for wave simulations it is sufficient to use a domain depth larger or equal to $d/\lambda = 0.25$. The domain lengths were based on the wave lengths of the incoming waves. For short waves, the domain is relatively long compared to the wave length, in order to reduce wave reflections at the inflow and outflow boundary. For long waves, the domain can be shorter, because wave reflections are less dominant. Dimensions of the computational domain used for the captive simulations are shown in Table 4. For the simulations of series B the domain length was extended with the length of the numerical beach, which was approximately 0.8 times the wave length. A snapshot of a captive simulation for shallow draft is shown in Figure 6.

Table 4: Computational domain captive simulations

ω [rad/s]	Domain length [-]	Depth [m]	Nr cells [x10^6] Grid B	Nr Cells [x10^6] Grid C
0.3	$-0.5\lambda < x < 0.5\lambda$	120	9.5	6.0
0.4	$-0.8\lambda < x < 0.7\lambda$	120	8.1	5.0
0.5	$-1.0\lambda < x < 0.8\lambda$	90	5.3	3.4
0.6	$-1.1\lambda < x < 0.9\lambda$	90	4.2	2.7
0.7	$-1.2\lambda < x < 1.1\lambda$	90	3.7	2.3
0.8	$-1.5\lambda < x < 1.3\lambda$	90	3.5	2.1

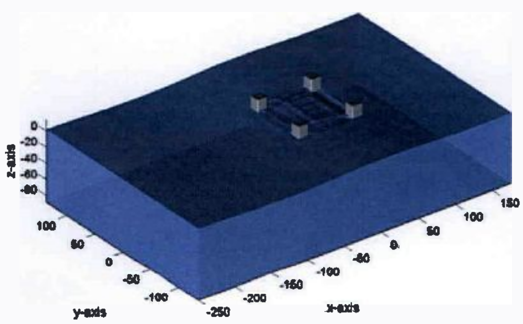

Figure 6: Snapshot of captive simulation (shallow draft)

For the simulations of series A the complete semi-submersible model as well as the total width of the tank were modeled, while for series B only half of the model and tank width were modeled. By using this symmetry relation the number of computational cells could be reduced by a factor of two. In this way the increase in domain length that comes with the application of a numerical beach was compensated. On the solid walls of the domain the default no-slip boundary condition was applied. For the moving body simulations a no-slip condition was also applied at the symmetry-axis instead of the more appropriate symmetry boundary condition available in ComFLOW. Unfortunately at the time of this study, this symmetry boundary condition was not compatible with moving bodies.

The grids used had uniform cells in the vicinity of the semi-submersible and were linearly stretched to the domain boundaries in the x, y and z directions. The applied stretching factors are maximum three percent. With the same types of grids good results have been derived for wave run-up simulations on a fixed semi-submersible [4]. Since a piecewise linear interpolation is used for the discretisation of the object geometry, a sufficiently fine grid is required for an accurate description of the semi-submersible.

The required grid size was derived from a grid convergence study for a captive simulation, which was done for both deep and shallow draft conditions and one set of wave parameters (ω = 0.5 rad/s and ζ_a= 2.0 m). The uniform grid sizes considered were; 0.8, 1.0, 1.2 and 1.5 meters. The total number of cells of these grids is shown in Table 5. Results of the grid convergence study are shown in Figure 7-10. Convergence of the dynamic vertical force on the semi-submersible is shown, as well as the relative amplitude of this force. This relative amplitude is defined as the amplitude divided by the mean amplitude of the four grids.

For the captive simulations (series A) the grid size was 1.2 meters (grid C) for deep draft and 1.0 meters (grid B) for shallow draft. For the moving body simulations (series B) the grid size was 1.0 meter (grid B). The total number of computational cells for the captive simulations is given in Table 4 for each wave frequency. For the simulations of series B the maximum number of computational cells is 3.5 million.

The chosen integration scheme is forward Euler in time and first order upwind in space. The convergence of the Poisson solver is set to $5x10^{-5}$, while the maximum number of iterations is set to 2000. Four integration points are used per cell. This number of integration points determines how smooth the object can be discretised.

Table 5: Grids used for convergence study

Number of computational cells [x10^6]			
Grid	Δgrid [m]	Td = 25 m	Td = 11.5 m
A	0.8	10.5	9.5
B	1.0	5.5	5.0
C	1.2	3.2	3.0
D	1.5	1.6	1.4

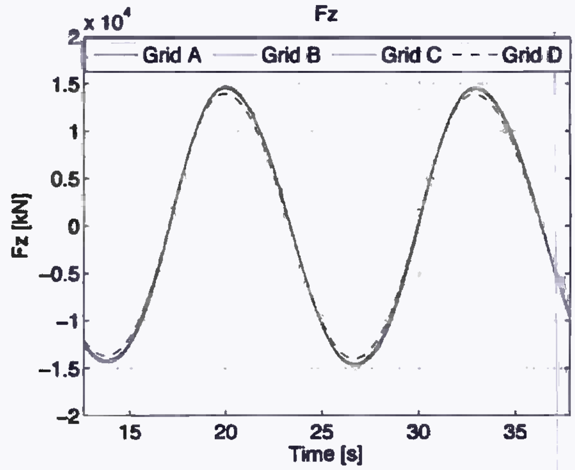

Figure 7: Convergence wave force Fz (Td = 25 m)

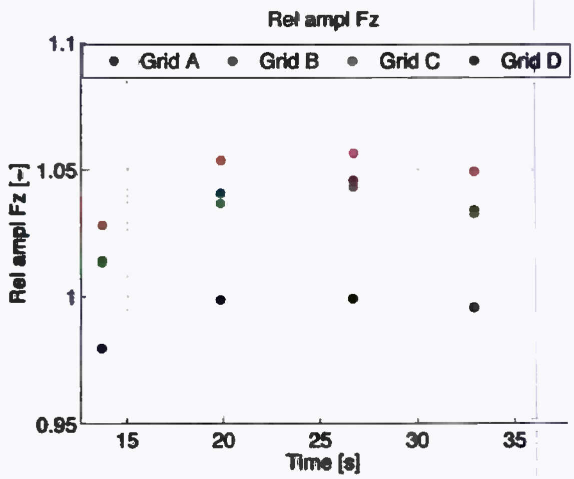

Figure 8: Relative amplitudes Fz (Td = 25 m)

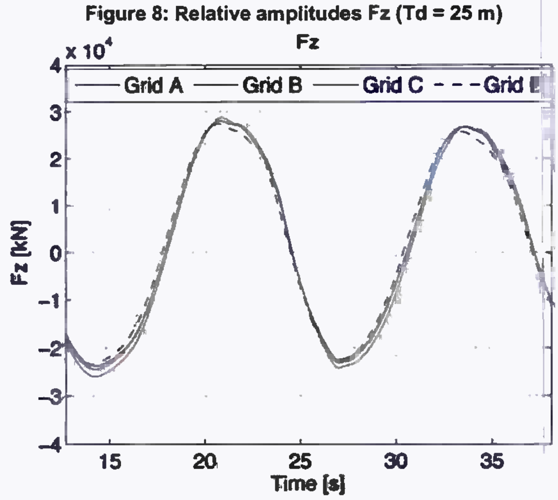

Figure 9: Convergence wave force Fz (Td = 11.5 m)

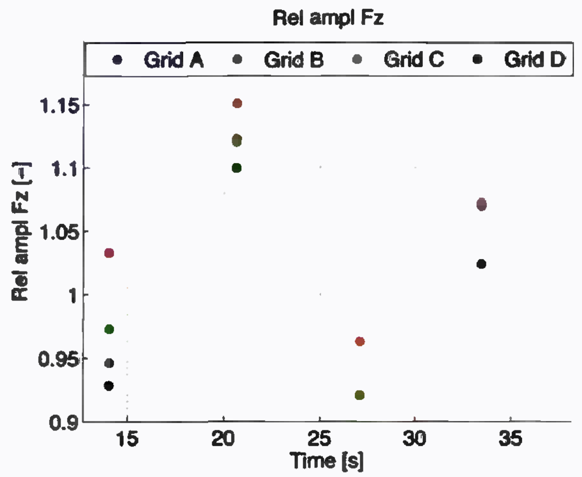

Figure 10: Relative amplitudes Fz (Td = 11.5 m)

Internal loads were derived for the semi-submersible, which is moving due to the interaction with the waves. While it is possible to perform interactive-motion simulations in ComFLOW, the motions of the semi-submersible in response to the waves were not solved in ComFLOW. At this moment the interactive-motion solver is very time consuming and requires additional testing and validation. In the ComFLOW simulations the motions of the semi-submersible were prescribed, using the linear motions from the diffraction calculation.

Comparisons with model test results showed that the motions from the model test were very close to those from the diffraction calculation. This was also the case for the shallow draft conditions. For this reason, the complexity of the problem could be reduced by prescribing linear harmonic motions, derived from the diffraction calculation. It should be noted that prescribing the motions may lead to a physically unrealistic flow, since the total hydromechanical and gravity loads on the semi-submersible may not be in equilibrium with the inertial loads.

The hydromechanical forces on the sections of the semi-submersible were calculated outside ComFLOW by integration of the pressures from ComFLOW over the considered section of the hull, defined by Eq. (4).

$$\overline{F}_{hydromechanic} = \int_{\Delta S} p \cdot \overline{n}\, ds \qquad (4)$$

The internal loads were calculated as in Eq. (5), in which the hydromechanical loads were derived from ComFLOW simulations. The inertial and gravity loads were derived using linear theory, because linear motions were applied. For further explanation of the inertial and gravity loads reference is made to Section 6.

$$\overline{F}_{section} = \overline{F}_{in} + \overline{F}_{g} + \overline{F}_{hydromechanic} \qquad (5)$$

8. WAVE LOADS ON FIXED SEMI-SUBMERSIBLE

Examples of calculated wave loads on the fixed semi-submersible are presented in Figure 11-16 and 18, 19. Since for a semi-submersible at deep draft the wave loads can be described adequately with linear theory, this section will focus on the non-linear wave loads for the semi-submersible at shallow draft.

In Figure 11 a typical result is shown for the wave loads at deep draft. The vertical force on the semi-submersible is given for the following wave parameters: ω = 0.4 rad/s and ζ_a = 2 meters. The results from both ComFLOW and the linear diffraction method are reasonably accurate in comparison with the model test results. Furthermore, at this deep draft the wave forces hardly show non-linear characteristics.

Figure 12-14 shows results of the vertical wave force at shallow draft for ω = 0.4 rad/s and wave amplitudes of 1, 2 and 3 meter. In Figure 13 the wave force in vertical direction is shown for identical wave parameters as presented in Figure 11, but now for shallow draft. The wave force is non-linear and a phase shift exists between the results from the linear diffraction method and those from model testing. The phase shift grows with increasing wave amplitude, which is reflected in Figures 12-14. Since the phase shift grows with increasing wave amplitude it may be related to the non-linear flow pattern. The results obtained from ComFLOW are significantly closer to the model tests results than the results from the linear diffraction method.

When the non-linear characteristics of the wave forces are more pronounced, good results are still obtained with ComFLOW. The highly non-linear shape of the wave forces (F_z and M_y), shown in Figures 15 and 16, are also clearly recognized from the ComFLOW results.

The non-linear flow above the floaters of the semi-submersible in the simulation discussed above is shown in Figure 17. A snapshot of the simulation is made at t = 34 seconds. At this moment a wave crest passes the semi-submersible. The non-linear phenomenon, which is observed at this time instance, is associated with the event that all floaters are almost emerging from the water at the same time. At this moment the water height above the floaters is less than one meter.

Figure 18 and 19 again show reasonably accurate results for ComFLOW, where non-linear effects have large influence on the wave forces. For the wave forces (F_x and M_y), a significant difference in amplitudes is present between the results from the linear diffraction method and the experiment.

The non-linear flow in this simulation is visualized in Figure 20, which shows a snapshot of the simulation at t = 21 seconds. Compared to the non-linear phenomenon discussed above, different non-linear effects are observed for this wave length. The waves are almost breaking on the transverse floater which is exposed to the waves. Standing waves are observed on the longitudinal floaters. These standing waves are typical for semi-submersibles at shallow draft. The wave velocity of these waves is related to the depth of the layer of water above the floaters. Typically, this wave velocity is much higher than that of the incoming waves.

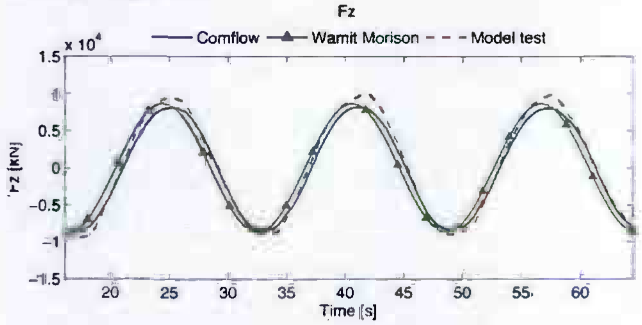

Figure 11: Wave load F_z (Td = 25 m, ω = 0.4 rad/s, ζ_a = 2 m)

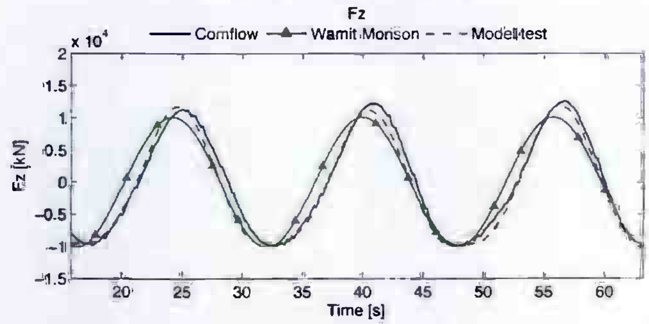

Figure 12: Wave load F_z (Td = 11.5 m, ω = 0.4 rad/s, ζ_a = 1 m)

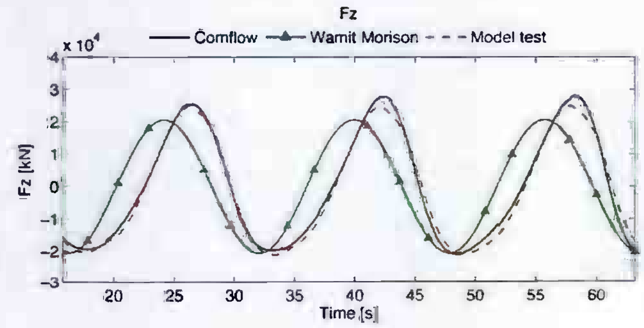

Figure 13: Wave load F_z (Td = 11.5 m, ω = 0.4 rad/s, ζ_a = 2 m)

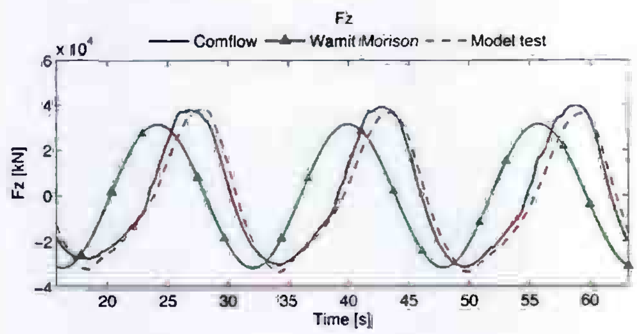

Figure 14: Wave load F_z (Td = 11.5 m, ω = 0.4 rad/s, ζ_a = 3 m)

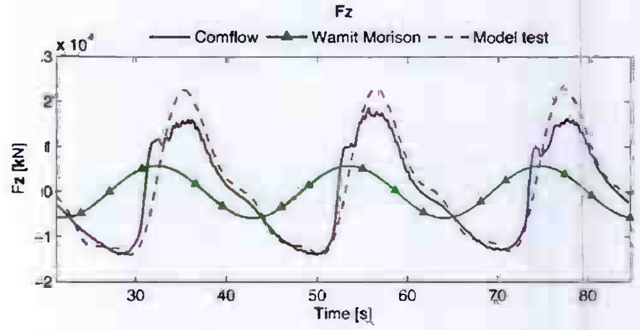

Figure 15: Wave load F_z (Td = 11.5 m, ω = 0.3 rad/s, ζ_a = 3 m)

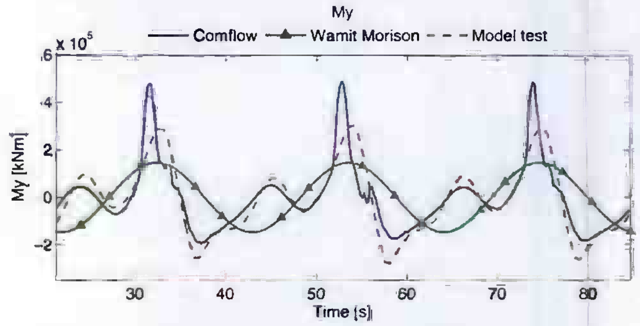

Figure 16: Wave load M_y (Td = 11.5 m, ω = 0.3 rad/s, ζ_a = 3 m)

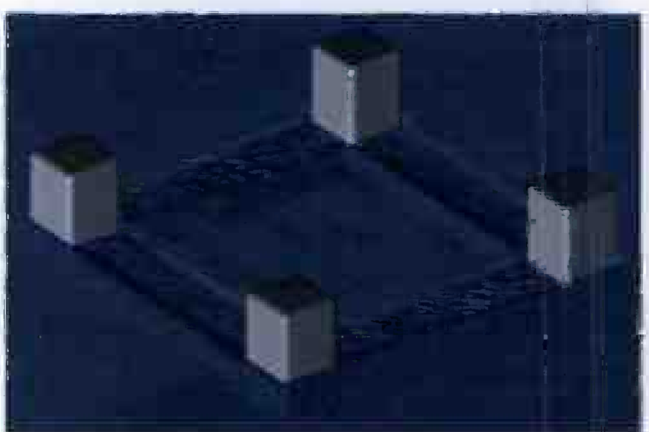

Figure 17: Snapshot of captive simulation at shallow draft (Td = 11.5 m, ω = 0.3 rad/s, ζ_a = 3 m, t = 34 s)

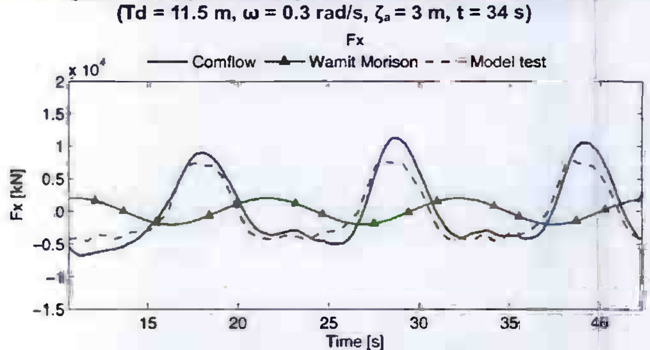

Figure 18: Wave load F_x (Td = 11.5 m, ω = 0.6 rad/s, ζ_a = 2 m)

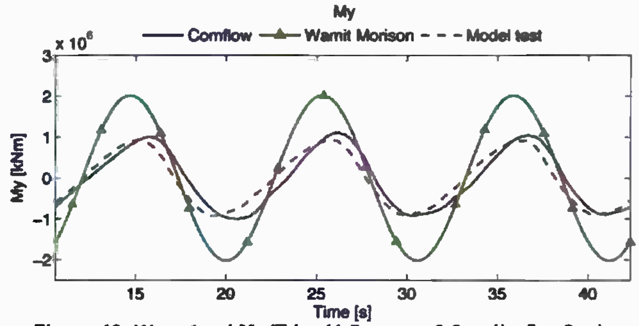

Figure 19: Wave load M_y (Td = 11.5 m, ω = 0.6 rad/s, ζ_a = 2 m)

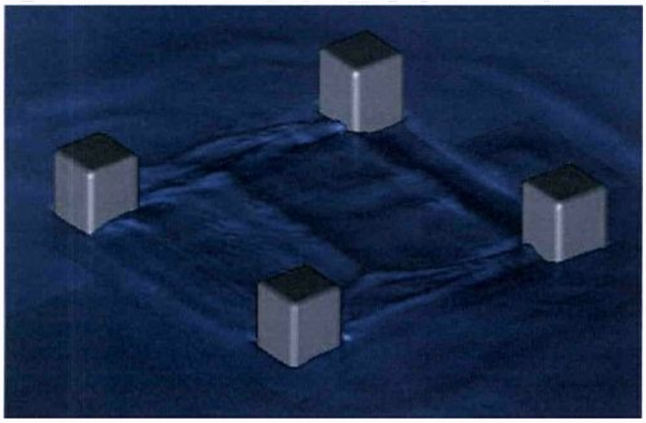

Figure 20: Snapshot of captive simulation at shallow draft (Td = 11.5 m, ω = 0.6 rad/s, ζ_a = 3 m, t = 21 s)

9. INTERNAL LOADS ON MOVING SEMI-SUBMERSIBLE

This section discusses results in terms of internal loads on the moving semi-submersible. The loads on the aft section of the semi-submersible (Fx and My) are presented in Figures 21, 22 and Figures 23, 24, for the deep and the shallow draft, respectively. The following wave parameters are used for both cases: ω = 0.6 rad/s and ζ_a = 2 meter.

The internal loads for deep draft conditions, of which typical results are shown in Figure 21 and 22, show a satisfactory agreement between the results from ComFLOW and the linear method (DYNLOAD). In deep draft conditions, the linear method is known to give reasonably good results. This indicates that reliable results can also be provided with ComFLOW.

The results for shallow draft, presented in Figure 23 and 24, show a larger difference between the results from both methods. Typically, ComFLOW gives smaller amplitudes for the internal loads than the linear method. However, the differences between the results from ComFLOW and the linear method are not as significant as for the wave loads on the fixed semi-submersible.

For the simulations discussed in this section the semi-submersible is moving along with the waves. Therefore, the non-linear effects, which are related to the thin layer of water above the floaters, are significantly reduced compared to the captive simulations. This is reflected in the results of the internal loads for the semi-submersible at shallow draft.

While the results of the internal loads obtained with ComFLOW seem reasonable, it should be noted that there are a number of limitations in this method. First, the preferred boundary conditions could not be applied at the symmetry boundary and at the outflow boundary, as discussed in Section 7. Also, the motions in the simulations were prescribed instead of calculated by the method itself. As discussed in Section 7, this could result in a physically unrealistic flow, due to an imbalance in the forces acting on the total semi-submersible.

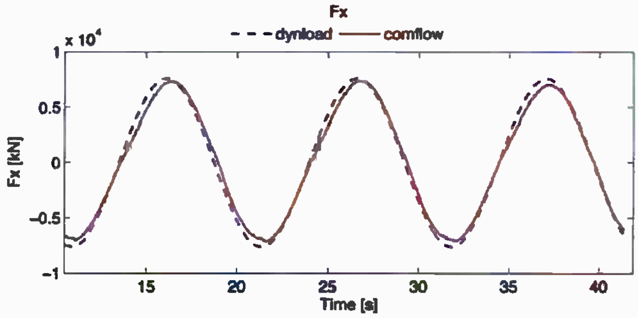

Figure 21: F_x aft section (Td = 25 m, ω = 0.6 rad/s, ζ_a = 2 m)

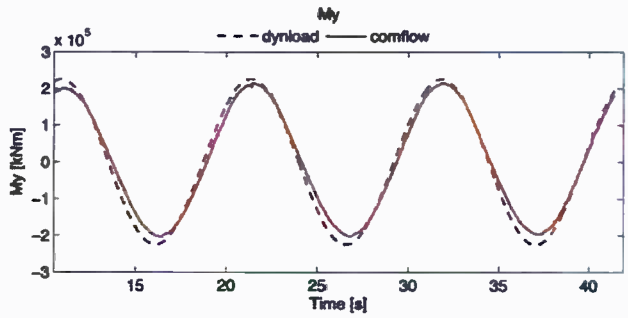

Figure 22: M_y aft section (Td = 25 m, ω = 0.6 rad/s, ζ_a = 2 m)

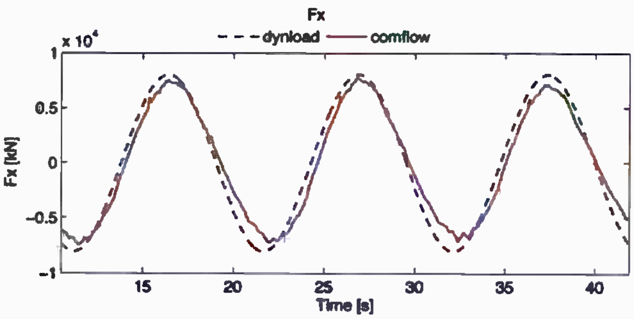

Figure 23: F_x aft section (Td = 11.5 m, ω = 0.6 rad/s, ζ_a = 2 m)

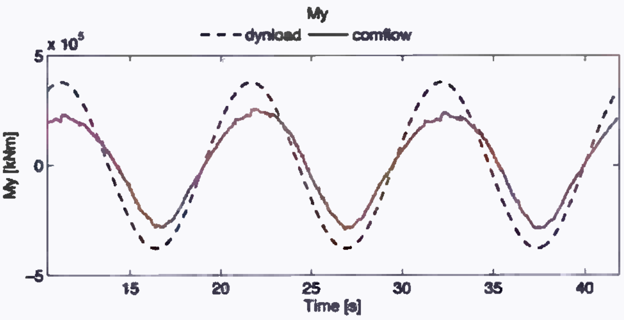

Figure 24: M_y aft section (Td = 11.5 m, ω = 0.6 rad/s, ζ_a = 2 m)

10. CONCLUSIONS

This section provides conclusions on the assessment of wave loads and internal loads, in which the non-linear flow around the floaters of a semi-submersible at shallow draft is assessed using both ComFLOW as the conventional linear diffraction method. The feasibility of both ComFLOW and the linear method for the calculation of these loads are assessed.

The first part of this study dealt with the wave loads on a fixed semi-submersible. The assessment led to the following conclusions:

- ComFLOW gives good results for the calculation of wave loads on a fixed semi-submersible compared to model test results for both deep and shallow draft conditions.
- In shallow draft conditions, the results from ComFLOW are much closer to the model test results than those obtained with the diffraction program WAMIT.
- The calculation of non-linear wave loads for a semi-submersible at shallow draft with the program ComFLOW is eminently feasible. However, this recommendation is limited to applications in which regular waves are used, since irregular waves were not assessed in this study.

The second part of this study focused on the assessment of internal loads for the semi-submersible using ComFLOW with prescribed motions. The results could not be validated, but comparisons with results from a conventional linear method were used for verification. The following conclusions were drawn from this assessment:

- For the calculation of internal loads for the semi-submersible at deep draft, a reasonable agreement was found between the results from ComFLOW and the linear method.
- The non-linear characteristics in the internal loads for the semi-submersible at shallow draft provided by ComFLOW were less pronounced than the non-linear characteristics in the wave loads on the fixed semi-submersible.
- Validation of the ComFLOW method for the calculation of internal loads is recommended. This requires additional model testing with the test case semi-submersible, including measurements of internal loads.
- The feasibility of ComFLOW for the application in a global strength assessment is at the moment limited by the implementation of boundary conditions, post-processing and interactive motions in the current version of the program. It is currently one of the objectives of the developers of the program to make these kinds of applications feasible in the near future.

NOMENCLATURE

Symbols:

- d — domain depth
- F_{gx} — gravity induced dynamic load in x-direction
- g — gravitational acceleration = 9.81 [m/s^2]
- KG — vertical center of gravity measured from base-line
- GM — distance between the vertical center of gravity and the metacenter
- m — mass
- $\vec{n}$ — normal vector
- p — pressure
- S — hull surface
- ΔS — hull surface of section
- T — wave period
- Td — draft

Greek Symbols:

- ζ_a — wave amplitude
- θ — pitch motion
- λ — wave length
- ω — wave frequency

Units:

- [m] — meters
- [rad] — radians
- [t] — metric tons = 1000 kg
- [s] — seconds

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