Nonlinear computations of heave motions for a generic Wave Energy Converter

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Abstract. A bench-marking activity of numerical methods for analysis of Wave Energy Converters (WEC) was proposed under the Ocean Energy Systems (OES) International Energy Agency (IEA) Task 10 in 2015. The purpose of the benchmark is to do a code-2-code comparison of the predicted motions and power take out for a WEC. A heaving sphere was used as a first simple test case. The participants simulated heave decay and regular and irregular wave cases. The numerical methods ranged from linear methods to viscous methods solving the Navier-Stokes equations (CFD). An overview of the results from the first phase of the benchmark was reported in [1]. The present paper focus on the simulations of the sphere using one fully nonlinear time-domain BEM one transient RANS method and one transient Direct FE method with no turbulence model. The theory of the three methods as well as the modeling of the sphere are described. Heave decay and heave motions for steep regular waves were selected as test cases in order to study and compare the capability to handle nonlinear effects. Computational efficiency and applicability of the three methods are also discussed.

Keywords. Wave Energy Converter, WEC, benchmark, sphere, heave, CFD, BEM, RANS, DNS

1. Introduction

Numerical simulation methods are extensively used in the development of Wave Energy Converters (WEC). A large number of codes are available for the prediction of wave loads and response of a WEC, both under operational conditions and under extreme wave conditions. Different approximations and numerical approaches are used in the codes. A bench-marking activity was proposed under the Ocean Energy Systems (OES) International Energy Agency (IEA) Task 10 in 2015. The purpose is to gain confidence in

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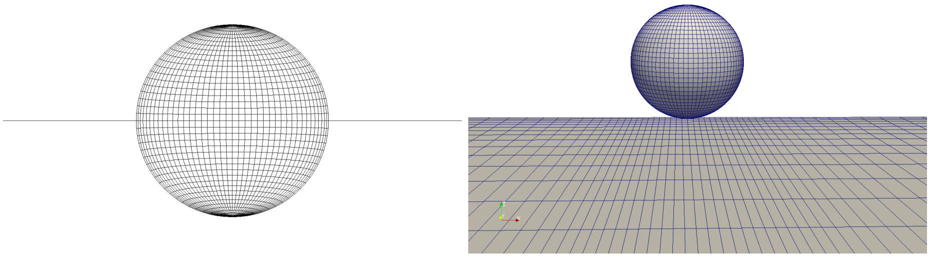
using the codes and to asses the accuracy of the codes. In total 25 organizations from 11 countries are engaged in the benchmark activities using 30 hydrodynamic codes ranging from simple linear codes to fully nonlinear time accurate viscous codes. An overview of the first results for all participants are presented in [1]. The present paper concerns the bench-marking activities carried out by the three Swedish participants Chalmers University of Technology (Chalmers), Royal Institute of Technology (KTH) and SSPA Sweden AB (SSPA) using the codes SHIPFLOW-Motions, Unicorn-FEniCS-HPC and LEMMA-ANANAS respectively. All three codes are time accurate and nonlinear. The two latter methods also include the effect of viscosity. The first using a URANS method with a turbulence model and the second is a Finite Element Direct Numerical Simulation method. The codes therefore represent the high end of hydrodynamic codes.

2. Benchmark cases

A floating sphere was used for the first benchmark study. The geometry is simple, but taking the intersection between the sphere and the wavy free surface into account both geometrical non-linearities as well as hydrodynamic non-linearities will be included. The sphere is allowed to move in heave only for all benchmark studies. The radius of the sphere is 5.0 m and at rest the origin is located at the un-disturbed free surface level, see Figure 1a. The center of gravity is located 2.0 m below the free-surface. The water density is 1000.0 kg/m^3 and the mass of the sphere is $261.8{\cdot}10^3$ kg. Computations were carried out for heave decay in calm water and for regular incoming waves.


(a) Sphere at rest in calm water

(b) Initial heave position 5.0 m

Figure 1. Benchmark heave decay in calm water

2.1. Heave decay in calm water

Heave decay was computed in calm water for two initial heave positions 1.0 m and 5.0 m. Figure 1b shows the initial position for 5.0 m. No additional damping was used during the free decay computations

2.2. Regular incoming waves

The heave motion of a sphere was computed in regular waves for a wave steepness S=0.01 were $S = H/(gT^2)$. H is the wave height, T is the wave period and g is the gravitational acceleration. 4 wave periods where computed, see Table 1. No additional damping was applied.

Table 1. Regular wave cases

Case	T [s]	f [Hz]	λ [m]	H [m], S=0.01
1	4.4	0.227	30.20	1.899
2	5.0	0.200	39.00	2.453
3	6.0	0.167	56.16	3.532
4	7.0	0.143	76.44	4.807

3. Description of codes

3.1. SHIPFLOW-Motions

SHIPFLOW-Motions is a fully nonlinear time-domain potential flow BEM. The fluid is assumed to be inviscid, incompressible and irrotational. The fluid motion can then be described by a velocity potential ϕ. In the fluid domain the velocity potential satisfies the Laplace equation $\nabla^2\phi = 0$, which is the governing equation for the flow. The computational domain consists of a truncated free surface with a floating body. The domain is assumed to be part of a larger outer domain where the solution is known a priori. The outer domain is calm water or described analytically by an undisturbed incident wave field. On the free surface the velocity potential satisfies the nonlinear kinematic and dynamic boundary conditions. An impermeability condition is applied on the body surface. The unsteady pressure can be computed at any point of the computational domain from the unsteady Bernoulli equation.

In SHIPFLOW-Motions a Boundary Element Method (BEM) combined with an automatic mesh generator, a time integration scheme, a free surface interpolation scheme and a rigid body 6DOF model of the floating object, see [2] and [3]. The BEM is based on quadrilateral first order panels with a constant source strength distribution [4]. The free surface model is based on a mixed Euler-Lagrange (MEL) method. The time integration scheme is a forth order Adams-Bashforth-Moulton scheme.

The evolution of the free surface position and potential is based on a Mixed Euler-Lagrange (MEL) method. In the Eulerian step the boundary value problem is solved using the BEM to obtain the potential and the velocities. In the Lagrangian step the free surface position and the potential is evolved by integrating the free surface boundary conditions in time.

The total unsteady pressure is computed directly from the Bernoulli equation and thus implicitly takes into account the effects from and the nonlinear interactions between the forward speed, the steady ship generated waves, diffraction, radiation and the fully non-linear incident wave field.

3.2. Unicorn-FEniCS-HPC

The methodology is denoted Direct FEM Simulation (DFS) which employs an implicit LES approach (automatic parameter-free turbulence simulation), together with a compression technique, for an incompressible variable-density Navier-Stokes model and opens up for goal-oriented adaptive error control, which we have previously extensively and successfully employed for constant-density high Reynolds number flow. The methodology is realized in the Unicorn solver part of FEniCS-HPC [5,7]. We formulate the variable density incompressible Navier-Stokes system of equationsin a space-time domain $\Omega \times I$, in dimensionless form:

$$\mathbf{R}(\hat{\mathbf{u}}) = \mathbf{0} \begin{cases} \rho(\partial_t \mathbf{u} + (\mathbf{u}\cdot\nabla)\mathbf{u}) - \frac{1}{Re}\nabla\cdot(\nabla\mathbf{u} + \nabla\mathbf{u}^t) + \nabla p - \frac{1}{Fr^2}\rho\mathbf{e}_z = 0, \\ \partial_t \rho + (\mathbf{u}\cdot\nabla)\rho = 0, \\ \nabla\cdot\mathbf{u} = 0 \end{cases} \tag{1}$$

where the variables $\rho, \mathbf{u}$, p and μ, all functions of $(x,t) \in \Omega \times I$, are dimensionless variables scaled through a selection of appropriate characteristic scales L_0, U_0, ρ_0, μ_0 for the length, velocity, density and viscosity, respectively. To complete the system we also need to add initial and boundary conditions to (1). We denote by $\hat{\mathbf{u}} = (\mathbf{u}, \rho, p)^T$ the vector of unknowns.

In some of our benchmark problems we can consider very high Reynolds numbers, we drop all viscous terms in the Navier-Stokes equations, corresponding to the inviscid Euler equations with slip boundary condition for the velocity.

3.3. Finite element method

The DFS finite element method for the model 1 is a space-time stabilized finite element formulation with continuous piecewise linear approximation in time, and corresponding piecewise constant test functions in time, over a time interval I_n as. the standard form is a Galerkin Least-Squares stabilization with shock-capturing. The method reads as: find $\hat{\mathbf{u}} \equiv \hat{\mathbf{u}}(t_n) \in (W_0)^3 \times W \times W$ such that

$$\mathbf{r}(\hat{\mathbf{u}}, \hat{\mathbf{v}}) + (\tau\,\mathbf{R}(\hat{\mathbf{u}}),\ \mathbf{R}(\hat{\mathbf{v}})) + \mathrm{SC} + \mathrm{CMP} = 0\,, \quad \forall \hat{\mathbf{v}} \in (W_0)^3 \times W \times W\,, \tag{2}$$

where $\hat{\mathbf{v}} = (\mathbf{v}, \eta, q)^T$ is the vector of test functions, W a standard finite element space of piecewise linear Lagrange basis function, and $(W_0)^3$ the corresponding finite element space of vector functions satisfying a slip boundary condition. SC is a standard residuak-based shock-capturing term, and CMP a compression term described in detail in [7].

Here we also investigate a new stabilization variant under development, where we investigate a Variational Multiscale (VMS) approach and aim to sharpen the shock-capturing. The new stabilization takes the form: $(\tau\,\mathbf{R}(\hat{\mathbf{u}}),\ \mathscr{L}^*(\hat{\mathbf{v}}))$ with the corresponding space differential dual operator.

3.4. LEMMA-ANANAS

LEMMA-ANANAS is a flexible CFD solver that uses a mixed finite volume and finite element method to solve Navier-Stokes equations with higher-order time and space schemes for viscous compressible and incompressible flows. The code utilizes fully unstructured tetrahedral mesh that can handle a large degree of deformation and to allow the simulation of moving objects in the flow with 6 degrees of freedom. The mesh deformation combined with level-set technique, provides a suitable tool to resolve the free-surface flow with minimum computational cost. The turbulence model used in the simulation is standard Spalart-Allmaras model.

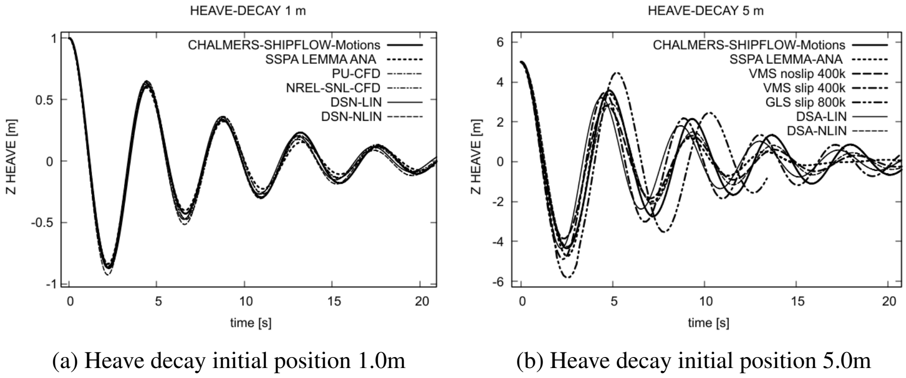
To define the incident wave in the domain, SWENSE (Spectral Wave Explicit Navier-Stokes Equations) approach [6] is used in ANANAS solver. In the this method, incident wave terms are computed with a potential flow model and superimposed on to the viscous domain. Therefore, the final simulated wave system is the sum of an incident variable and a diffracted one computed by RANSE solver. SWENSE coupled to the level-set approach allows breaking wave and complex free surface to be simulated during large motions of the object in the flow domain. The meshes used in simulations were slightly adjusted to capture the free surface position better, but in average they consist of 2.7M vertices (16M tetrahedral cells). Since the flow is considered symmetric, only half of the domain was simulated to decrease the simulation cost.

4. Results

4.1. Heave decay in calm water

A grid and time step dependence study was carried out for SHIPFLOW-Motions. The number of panels on the sphere and the surrounding free surfe was varied as well as the size of the free surface. For case 1 in Table 1 It was concluded to use 40*40 panels for the sphere and 70*20 panels on the free surface. The size of the free surface was 5 sphere diameters upstream, downstream and in the transverse direction. After a time step variation study, the time step 0.01 s was selected.

The computational cost for SHIPFLOW-Motions was about 1 hour on a 6 core desktop PC for a heave decay case. LEMMA-ANANAS used about 20 hours on a 32 core cluster and for Unicorn-FEniCS-HPC two meshes were used, “r00” with 400k vertices, and “r02” with 800k vertices, where two local bisections were performed in a region of size $2r$ around the sphere. The computational cost was appx. 4h for r00 and 10h for r03 using 1000 cores.



(a) Heave decay initial position 1.0m

(b) Heave decay initial position 5.0m

Figure 2. Comparisons of heave decay

Heave decay results are shown in Figure 2a for 1.0 m and in Figure 2b for 5.0 m. The initial position 5.0 m is shown in Figure 1b. In Figure 2a the heave decay for SHIPFLOW-Motions and LEMMA-ANANAS are compared to four codes from the IEA OES Task 10 benchmark study [1]: PU-Plymouth University using OpenFoam, NREL-SNL using an in-house CFD code, one linear DSA-LIN and one weakly nonlinear code DSA-NLIN from Dynamic System Analysis. The two latter codes are typical representatives for linear and weakly nonlinear codes in the benchmark study. SHIPFLOW-Motions compares well to the results by the weakly nonlinear code DSA-NLIN. This is expected since the initial position 1.0 m gives a small disturbance of the free-surface. The LEMMA-ANANAS code compares well with the results from the other CFD codes. The amplitude from the CFD codes including LEMMA-ANANAS is smaller than for SHIPFLOW-Motions and DSA-NLIN. This is expected since viscous damping is neglected in the two latter codes.

Figure 2b shows the heave decay for the initial position 5.0 m. There is now a difference in amplitude between the fully nonlinear SHIPFLOW-Motions code and the weakly nonlinear code DSA-NLIN. This is expected since the initial position 5.0 m gives a large nonlinear disturbance of the free-surface. LEMMA-ANANAS predicts the heave period well during the first 10 seconds. The heave amplitude is lower than for SHIPFLOW-Motions, but this is expected since viscous damping is included in LEMMA-ANANAS. After the 10 seconds the heave amplitude decays very rapidly for LEMMA-ANANAS. The linear code DSA-LIN shows a decay and heave period that is different from the nonlinear codes. For Unicorn-FEniCS-HPC investigations were carried out for two stabilization methods, GLS and VMS, slip or noslip on the sphere and two mesh densities 400k and 800k. Three combinations are shown in Figure 2b. VMS-noslip-400k show a heave amplitude that is smaller than SHIPFLOW-Motions while the amplitude for GLS-slip-800k is larger. The heave period for VMS-noslip-400k is similar to SHIPFLOW-Motions, VMS-slip-400k is shorter and GLS-slip-800 is longer.

The Figures 3a, 3b and 3c show the sphere and the free surface 0.7 seconds after the sphere is released. As can be seen the codes Unicorn-FEniCS-HPC and LEMMMA-ANANAS capture a wave breaking when the sphere hits the free surface while the inviscid code SHIPFLOW Motions gives a smooth free surface elevation.

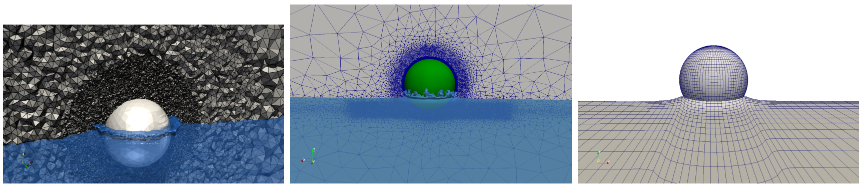
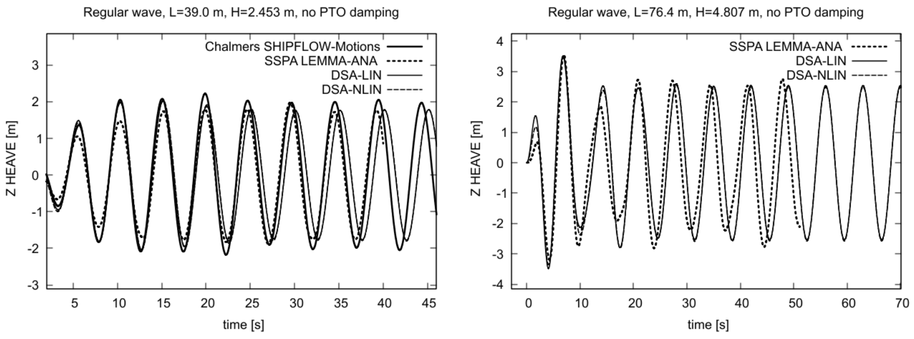

(a) U-FEniCS GLS-slip-800k (b) LEMMA-ANANAS (c) SHIPFLOW-Motions

Figure 3. Heave position after 0.7 s

4.2. *Heave response in regular waves*

Simulations was carried out for the 4 cases in Table 1 using SHIPFLOW-Motions and LEMMA-ANANAS. The computed heave response for case 2 is in Figure 4a compared to simulations using the linear code DSA-LIN and the weakly nonlinear code DSA-NLIN. The difference in heave amplitude bewteen SHIPFLOW-Motions and the linear and weakly nonlinear codes is about 3 %. A shorter heave period is noted for SHIPFLOW-Motions and LEMMA-ANANAS. The difference becomes larger as time proceeds. This is traced to the nonlinear representation of the free surface. Nonlinear waves travels faster than linear waves. The heave amplitude is lower for LEMMA-ANANAS than for SHIPFLOW-Motions. This is expected since viscous damping is included in LEMMA-ANANAS.



(a) Case 2

(b) Case 4

Figure 4. Heave amplitude in regular waves

It was not possible to get a converged solution for case 3 and 4 in Table 1 using SHIPFLOW-Motions. After a number of wave encounters the wave is over-topping the sphere. The predicted wave is then locally very steep which will lead to wave breaking in a real flow situation. The assumption of inviscid flow in SHIPFLOW-Motions cannot handle the physics of the breaking wave which will lead to a non-converging solution. Figure 4b shows a comparison between LEMMA-ANANAS and the linear and weakly nonlinear codes for case 4. Again a shift of the heave period due to the nonlinear representation of the free surface can be noted for LEMMA-ANANAS. The linear and weakly nonlinear codes performs surprisingly well for case 4.

5. Discussion and Conclusions

Heave-decay benchmark cases have been computed using SHIPFLOW-Motions, Unicorn-FEniCS-HPC and LEMMA-ANANAS, and regular wave benchmark cases have been computed using SHIPFLOW-Motions and LEMMA-ANANAS. The heave-decay cases using SHIPFLOW-Motions compares very well to the results from other nonlinear codes. The heave-decay result using LEMMA-ANANAS compares well to other CFD codes for initial position 1.0 m

For the initial position 5.0 m LEMMA-ANANAS predict the heave period well during the first 10 seconds. The have amplitude is lower than for SHIPFLOW-Motions, but this is expected since viscous damping is included in LEMMA-ANANAS. After the 10 seconds the heave amplitude decays very rapidly for LEMMA-ANANAS. Stabilizatiom methods, boundary conditions on the sphere and mesh densities we tested using Unicorn-FEniCS-HPC. The heave decay is sensitive to the set up.

For the regular wave cases SHIPFLOW-Motions shows a good agreement with a linear and a weakly nonlinear code for case 1 and 2. For low wave steepness linear and weakly nonlinear codes perform well [1]. For severe wave conditions where wave breaking and overtopping occurs codes that can take viscous effects into account is needed. However, only a few wave encounters can be computed due to very long computing time. But it must be noted that linear and weakly nonlinear codes performs surprisingly well also for severe wave conditions. Computations of an operating WEC typically involves irregular waves during 1 - 3 hours. At present this is not possible using the high end codes due to the computing time, linear or weakly nonlinear codes must be employed for the WEC in operating conditions. The high end codes can on the other hand be used to compute detailed features of the flow such as wave breaking, local pressure and wave loads during a few wave encounters.

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