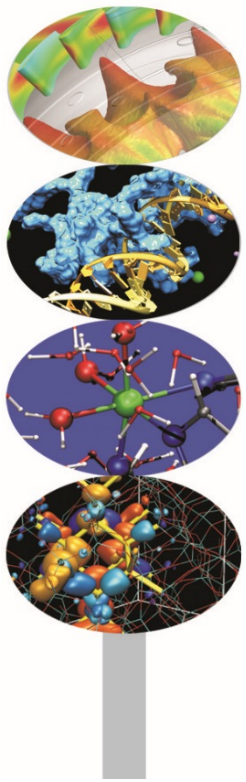
3D-numerical analysis of wave-floating structure interaction with OpenFOAM®



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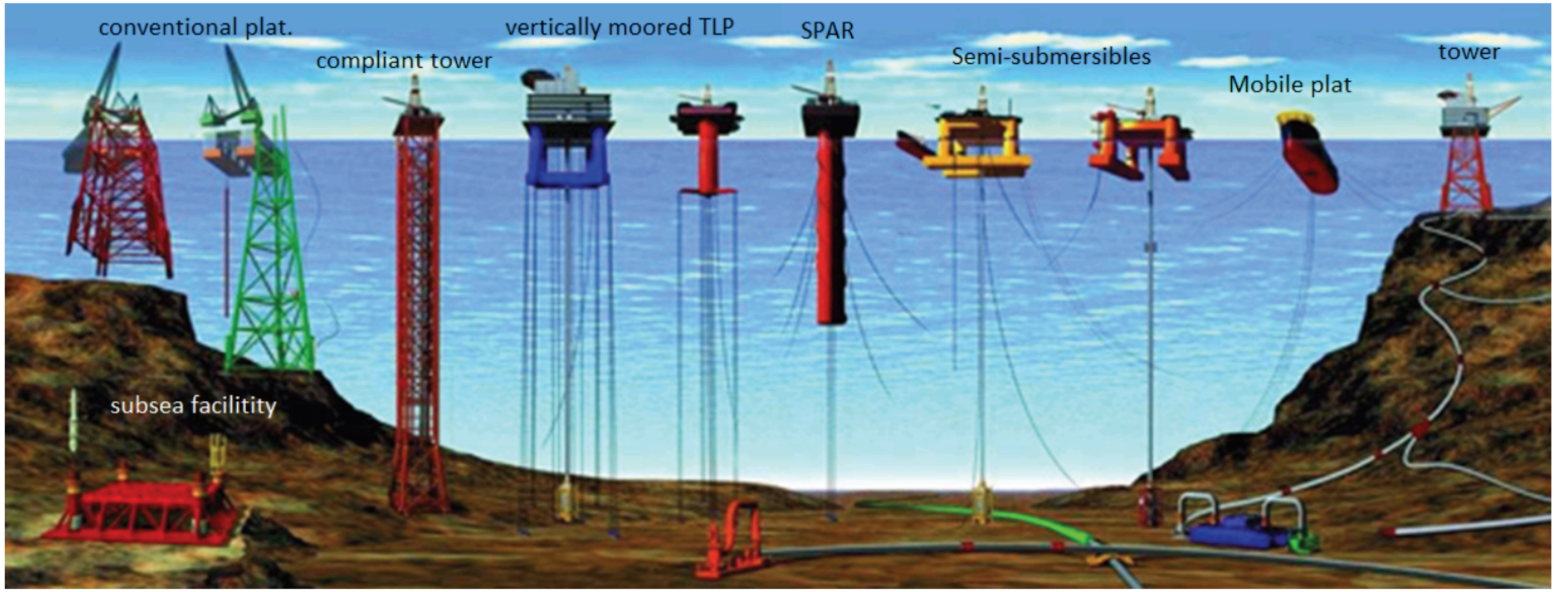
Introduction

- Offshore structures have special characteristics from the economic and technical points of view.
- They influence the world's market and our daily lives, due to the impact on several energy resources (oil, gas, wind…)
- It is a multidisciplinary field of engineering (structural, geotechnical and hydrodynamic design)
- It is a restrict market and engineering sector

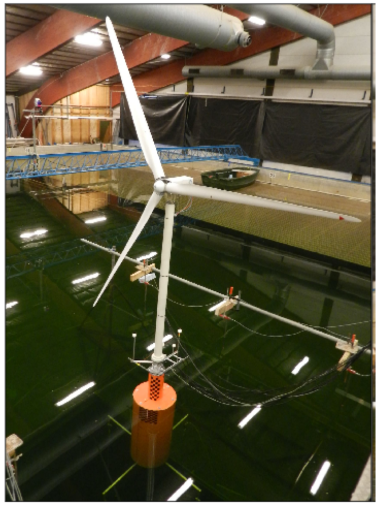


Oil & Gas typical offshore structures, fixed and floating. Source – Ocean Explorer NOAA gov. USA

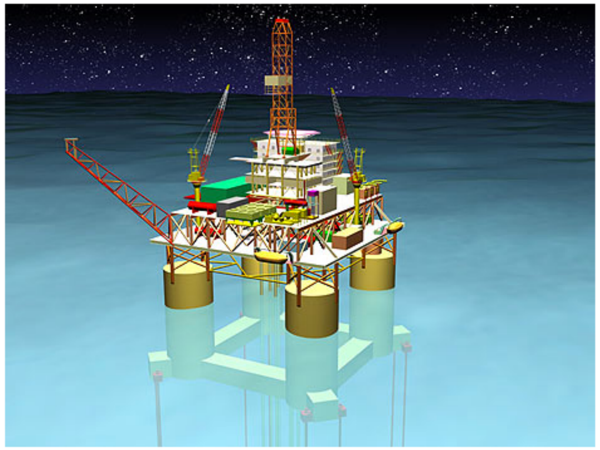
Introduction

Floating structures are widely adopted in offshore engineering, because the necessity to exploit resources from offshore is increasing. For example, floating wind turbine technology would open up a large majority of the continental shelf as a wind power resource. Floating oil-platform technology can provide a basis for design; however further study is required as the floating systems need to be stable, structurally sound, and economical convenient.

Hywind floating wind turbine prototype (web source)



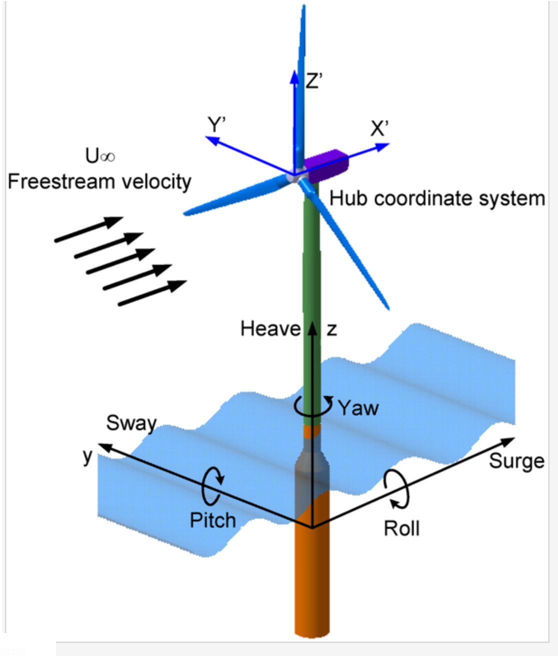
Laboratory tests on wind turbine with SPAR buoy and mooring system (EU-HYDRALAB-IV project, Tomasicchio et al.)

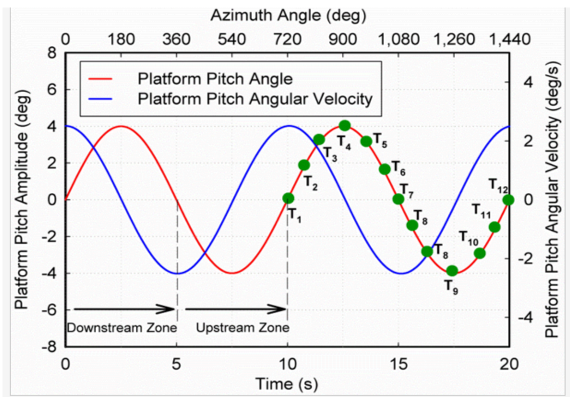


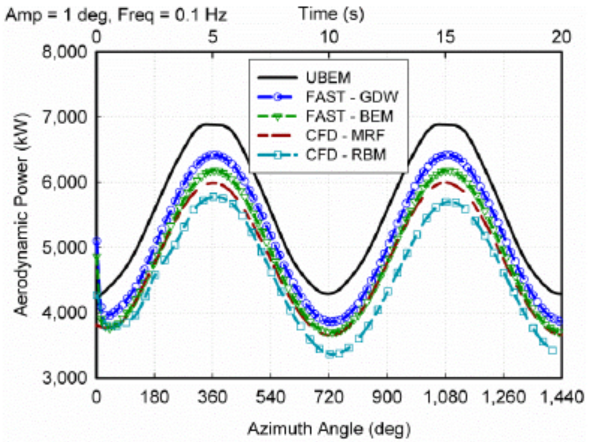
TLP platform on Gulf of Mexico (render from web source)

Introduction

Designing new floating structures engineering requires detailed knowledge of forces, flow directions and velocities, rotations and displacements. Traditionally, this was done in towing tank, but in the last years computational fluid dynamic (CFD) methods developed to a stage, where they become interesting, not only from a financial but also from a performance point of view, as an extra input or a full alternative to the experiments. Several codes have been implemented, one of the open-source is OpenFOAM®.



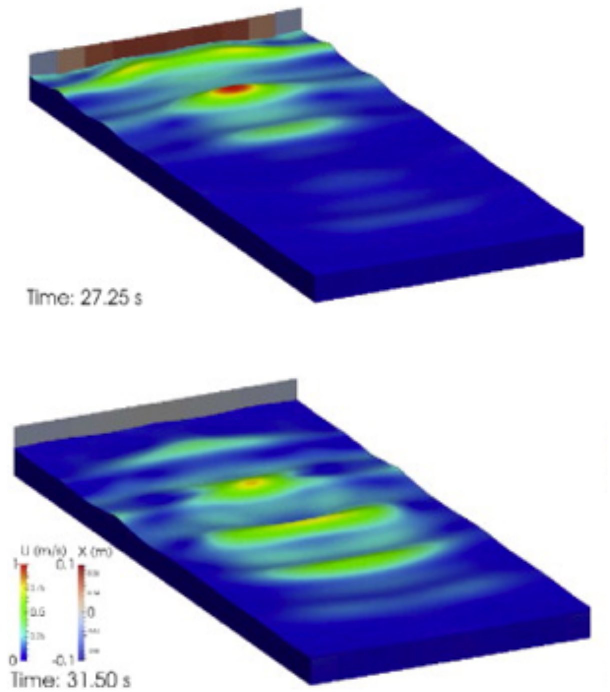




(from Tran et al., *Energies 2014, 7, 5011-5026*)

Wave generation in OpenFOAM®: implementation in IHFoam

IHFOAM (http://ihfoam.ihcantabria.com) is a newly developed 3D numerical two-phase flow solver specially designed to simulate coastal, offshore and hydraulic engineering processes.
Specific boundary conditions allow to generate any type of wave in a 3D domain, from the most simple regular waves (Stokes I, II and V, streamfunction…) to complex, real and fully 3D irregular (random) directional sea states, overimposed also to currents.
Also a moving boundary has been implemented to reproduce laboratory wave paddles.
Active wave absorption has been programmed to work simultaneously with the wave generation to absorb any incident waves on the boundaries.

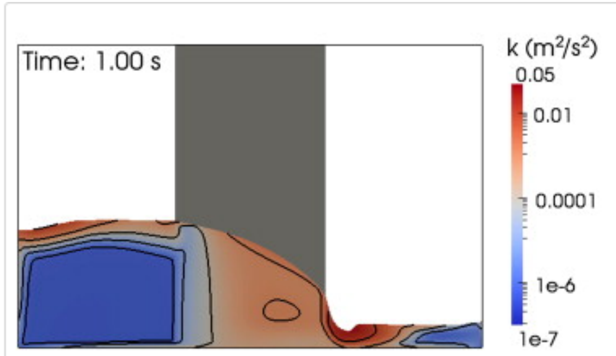


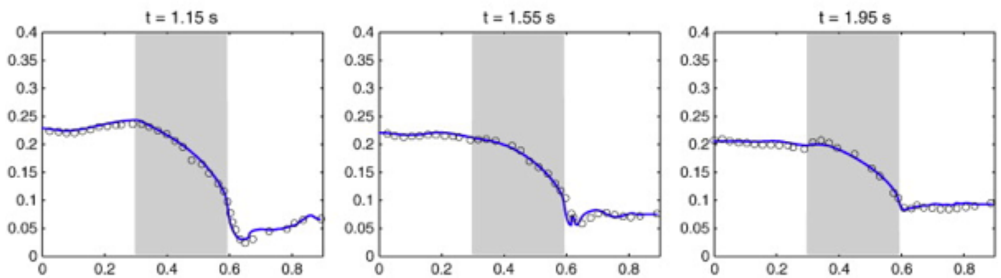
(from Higuera et al., Coast. Eng., 2015, 101, 35-47)

Wave generation in OpenFOAM®: implementation in IHFoam

IHFOAM has also been developed to address the lack of rigorous treatment of two-phase porous media flow in OpenFOAM®.

The implementation of VA (Volume Average over porous media)-RANS equations and Forchheimer formulation allows of reproducing such as validated simple flow through a porous medium, but also more complex wave interaction with porous structures in 2D and 3D.





(from Higuera et al., Coast. Eng., 2014, 83, 2423-258)

Wave generation in OpenFOAM®: theory and implementation in IHFoam

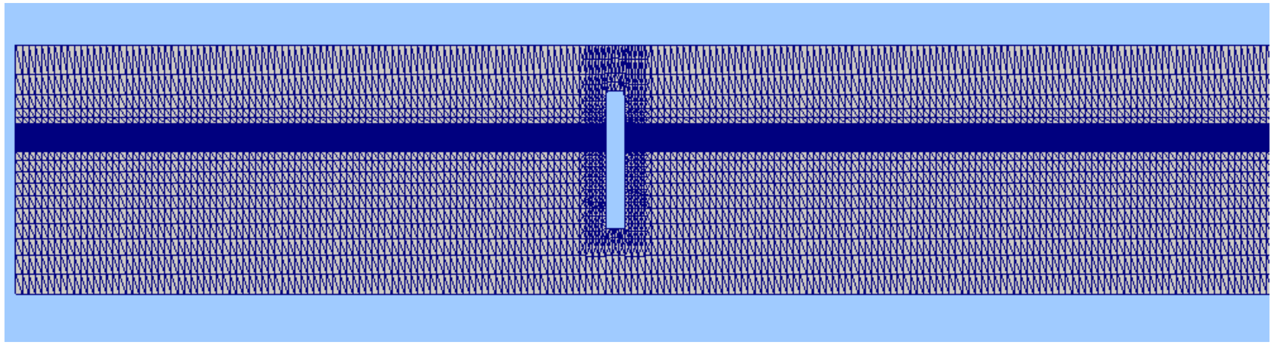
To adapt the changing computational domain when simulating moving bodies, different algorithms are available. OpenFOAM supports mesh morphing six degree of freedom (6-DoF) body motion. A 6-DoF solid body can be specified through a boundary condition on a patch prescribing the boundary of the solid body. With the dynamic mesh method, the mesh quality around the body is preserved without performing expensive remeshing even when simulating arbitrary angles of rotation.

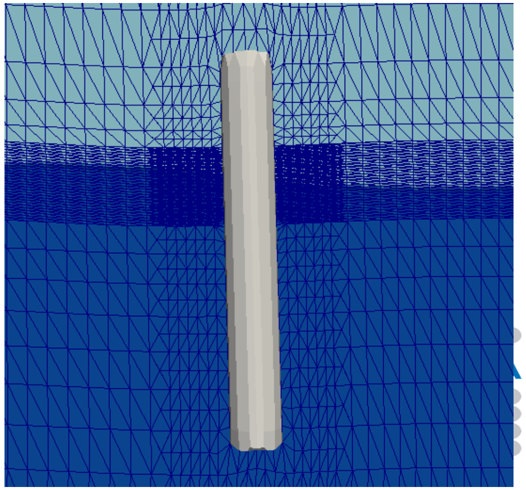
IHDyMFOAM is an enhanced version of IHFoam, which handles remeshing after each time step ("DyM" stands for dynamic mesh of OpenFOAM® features). Hence it can simulate floating body movements or support dynamic mesh refinement along the free surface, while solving the governing equations and generating waves.

Code set-up

In the adopted version, 2.3.0, the rigid body motion framework uses a specialized motion solver, which works with a spherical linear interpolation of displacement and rotation based on the distance to the object to move.

The solver employed in this study is the interDyMFoam or IHDyMFoam when waves are generated. Hence it can simulate floating body movements or dynamic mesh refinement along the free surface. 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.

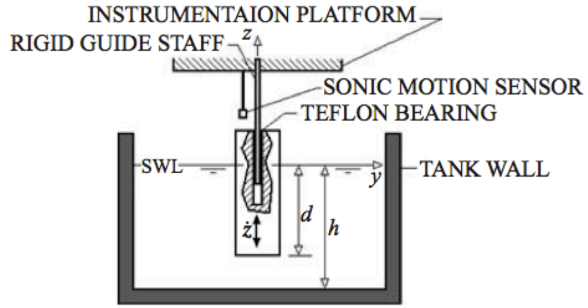




Free decay test in heave

To evaluate the capabilities of OpenFOAM® in simulating floating structures and validate the code, a free decay test in heave was performed.

Firstly the unmoored cylinder, with diameter of 0.2 m and mass of 31.42 kg, was implemented, in order to exactly reproduce the experimental data in McCormick (2009).



Cross-section of the laboratory tank (McCormick (2009))

The imposed initial displacement, Z_0, was equal to 0.3 m, while *d* and *h* equal to 1.0 m and 1.5 m respectively.

The linear motion *z* for a purely heaving floating cylinder in calm water can be analytically predicted by the solution of the equation:

$$(m + a_{wz})\frac{d^2z}{dz^2} + (b_{rz} + b_{vz})\frac{dz}{dt} + (\rho g A_{wp} + N k_s)z = 0$$

where a_{wz} is the added mass, b_{rz} is the radiation damping coefficient, b_{vz} is the viscous damping coefficient, A_{wp} is the waterplane area when the body is at rest, k_s is the effective mooring spring constant of each line and N is the number of lines.

Free decay test in heave

The most relevant hydrodynamic parameters are

- the natural heaving frequency ω_n as

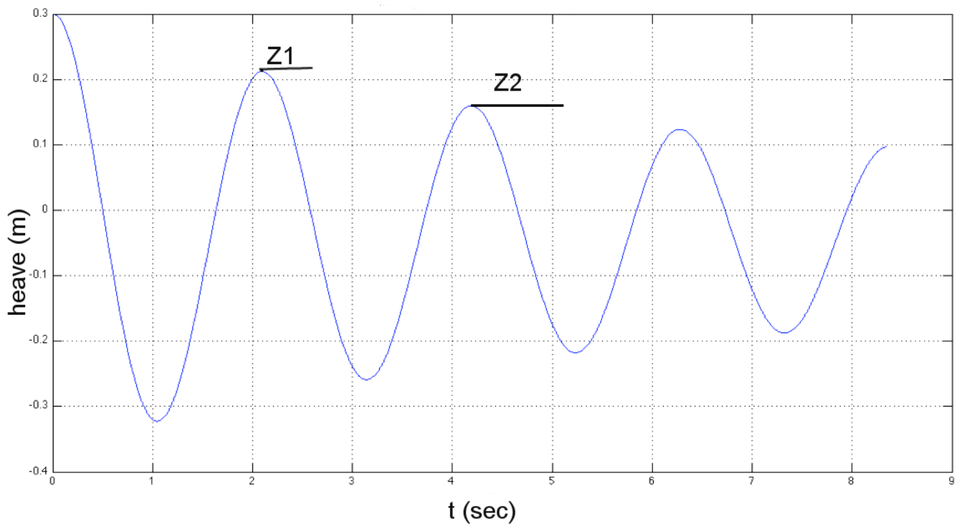
$$\omega_n = \frac{2\pi}{T_{nz}} = \sqrt{\frac{\rho g A_{wp} + N k_s}{m + a_{wz}}}$$

with T_{nz} is the natural heaving period

- the damping ratio Δz as

$$\Delta z = \frac{b_z}{b_{cr}} = \frac{b_{rz} + b_{vz}}{b_{cz}} = \frac{b_{rz} + b_{vz}}{2\sqrt{(\rho g A_{wp} + N k_s)(m + a_{wz})}} = \frac{\ln\left(\frac{Z_j}{Z_{j+1}}\right)}{\sqrt{\pi^2 + \left[\ln\left(\frac{Z_j}{Z_{j+1}}\right)\right]^2}}$$

Heave values in time for the vertical cylinder



Second and third oscillation amplitudes were evaluated as Z_1 and Z_2 respectively, to estimate the resonant damping ratio.

Free decay test in heave

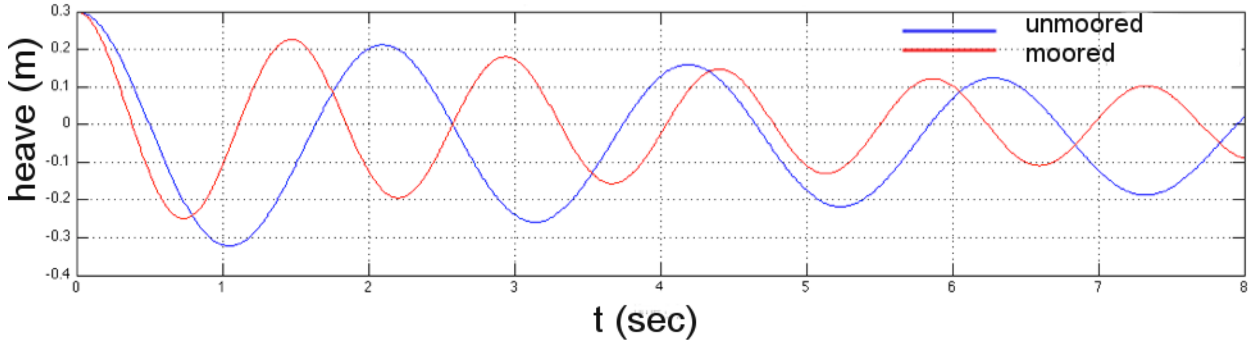
The table shows the comparison of the main hydrodynamic parameters of the test from the numerical simulation performed with OpenFOAM® and the experimental data.

	Experimental Data (McCormick, 2009)	OpenFOAM data unmoored cylinder
Z_1 (m)	0.22	0.211
Z_2 (m)	0.17	0.16
T_d (sec)	2.12	2.08
ϖ_{dz} (rad/sec)	2.96	3.02
$\ln(Z_j/Z_{j+1})$	0.258	0.277
Δz	0.082	0.088
ϖ_{nz} (rad/sec)	2.97	3.03
a_{wz} (kg)	3.43	2.09
b_{cz} (Nsec/m)	207.28	203.26
b_z (Nsec/m)	16.95	17.83
b_{rz} (Nsec/m)	1.08	1.14

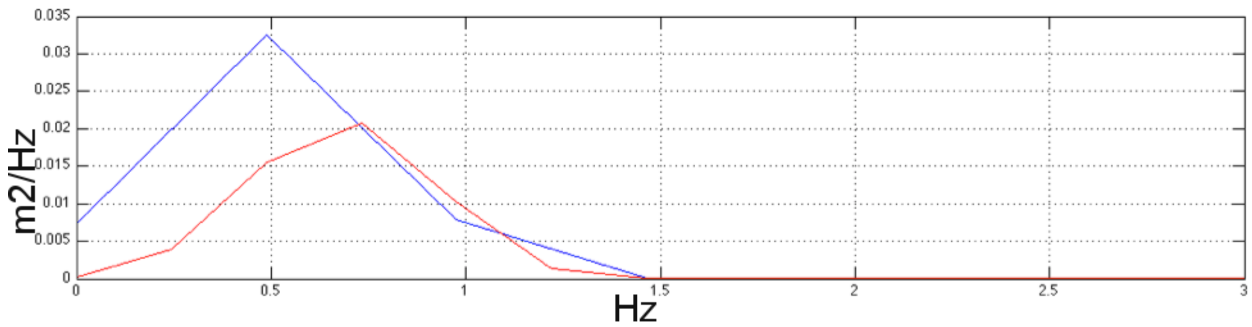
Decay test for a moored cylinder

Then, the moored cylinder was simulated. The line stiffness, k_s, was set equal to 308 N/m. That value was calculated considering a line force equal to the difference between the weight and the buoyancy of the object.

Heave values in time for the vertical cylinders (unmooerd and moored)



Psd of the signals for the vertical cylinders (unmooerd and moored)



Decay test for a moored cylinder

The natural damped period, T_d, decreased and the critical damping coefficient, b_{cz}, increased, as the natural damped period is inversely proportional to the mooring restoring force (N^*k_s), instead the damping coefficient is directly proportional to that force.

	Experimental Data (McCormick, 2009)	OpenFOAM data unmoored cylinder	OpenFOAM data moored cylinder
Z_1 (m)	0.22	0.211	0.226
Z_2 (m)	0.17	0.16	0.18
T_d (sec)	2.12	2.08	1.47
ϖ_{dz} (rad/sec)	2.96	3.02	4.28
$\ln(Z_j/Z_{j+1})$	0.258	0.277	0.23
Δz	0.082	0.088	0.072
ϖ_{nz} (rad/sec)	2.97	3.03	4.29
a_{wz} (kg)	3.43	2.09	2.13
b_{cz} (Nsec/m)	207.28	203.26	287.57
b_z (Nsec/m)	16.95	17.83	20.78
b_{rz} (Nsec/m)	1.08	1.14	1.32

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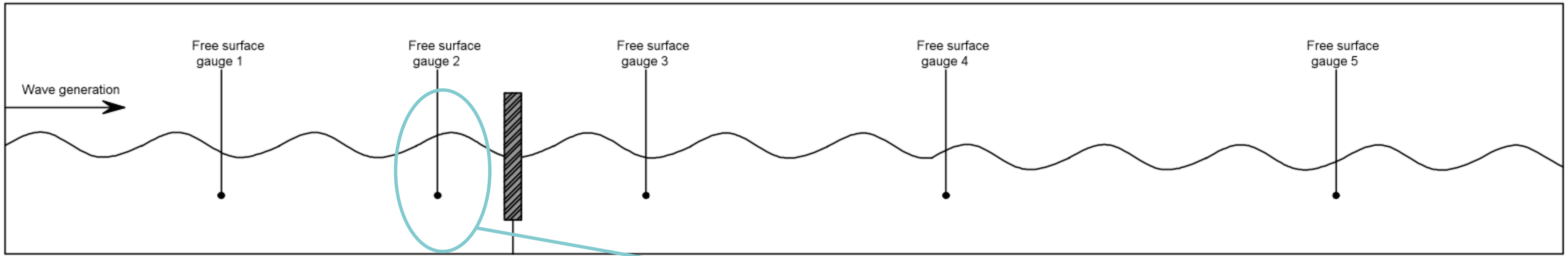
Wave-floating cylinder interaction

Wave-floating body interaction was simulated, including as lateral boundary conditions the free-surface and velocity field as produced by IHFOAM.
The behavior of the floating cylinder hit by a train of regular waves was analyzed.
The body was moored to the bottom, with the same settings of the previous test.

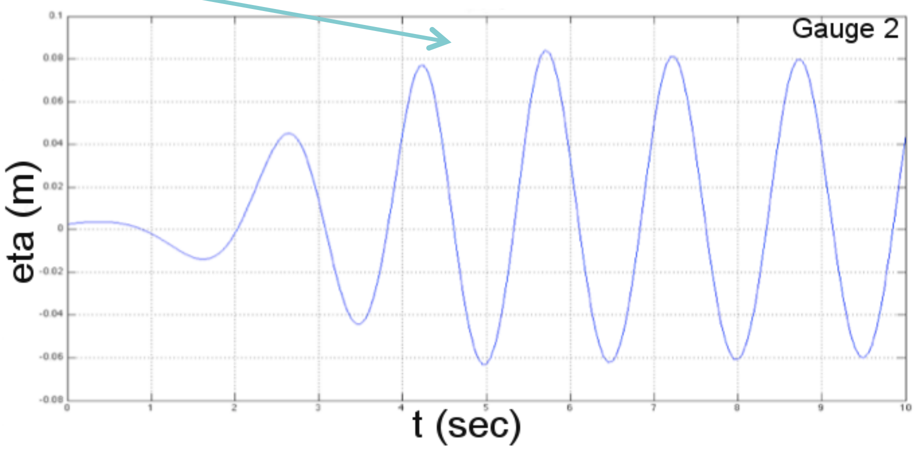


5 numerical gauges were located along the computational channel, in order to capture the radiated waves of the moving object.

In these tests, two waves propagate over 1.5 m of water depth:

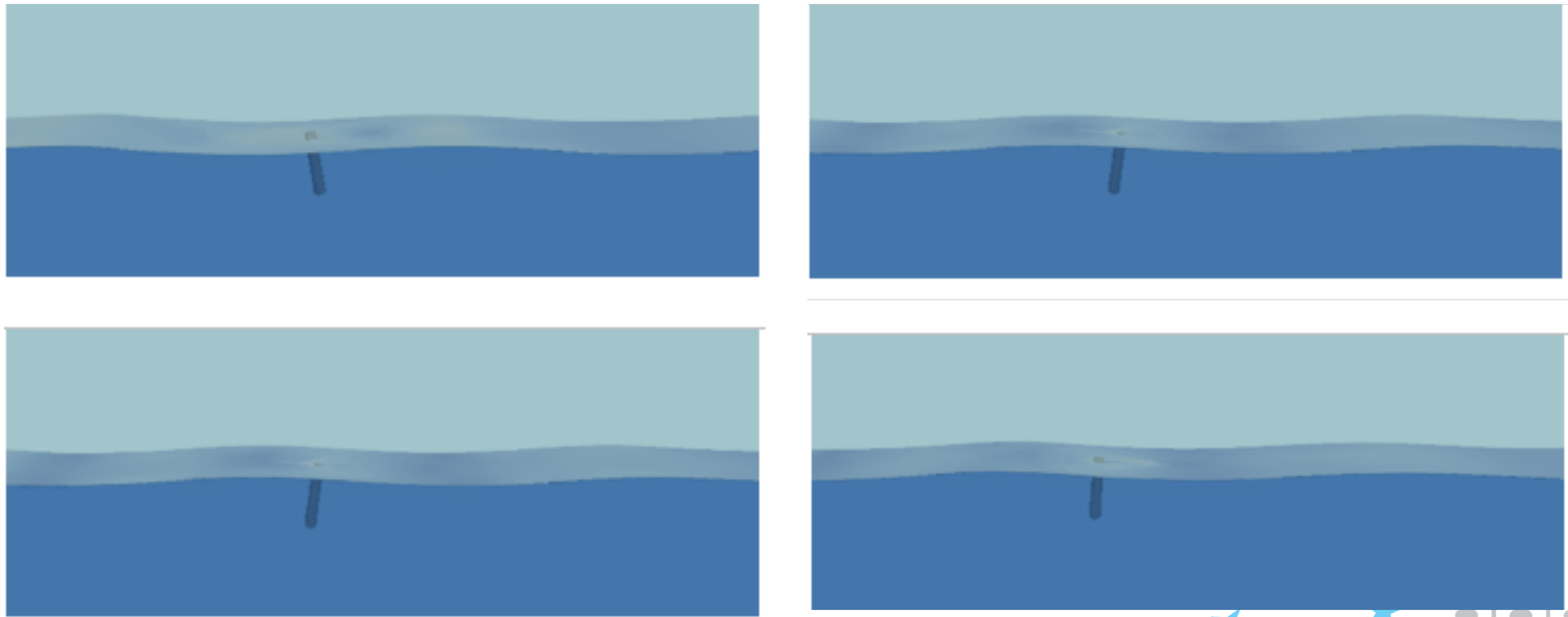
-Wave1: H=0.25 m, T=1.5 sec

-Wave2: H=0.3 m, T=2 sec



Wave-floating cylinder interaction

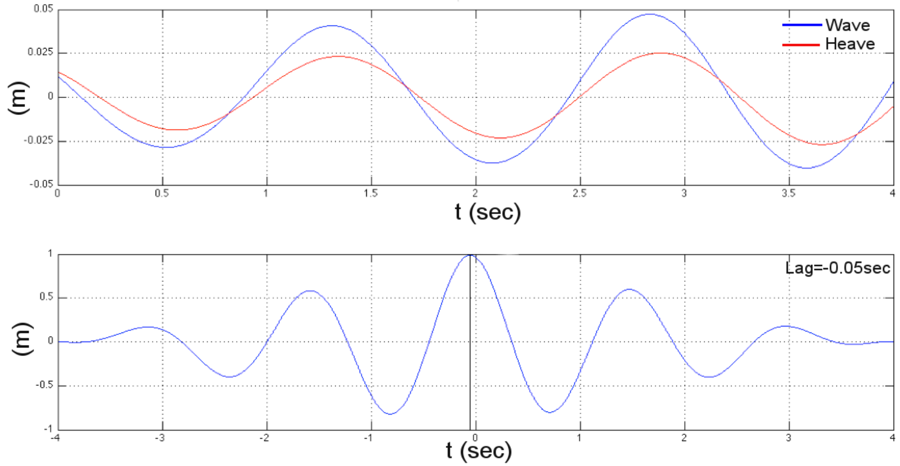
A snapshot series from Wave1 simulation shows an example of the interaction between the propagating wave and the moored floating cylinder.



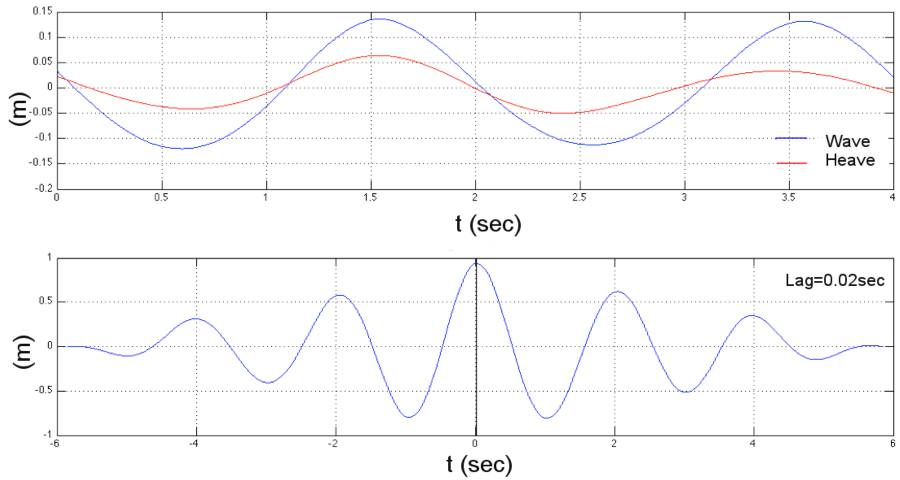
Wave-floating cylinder interaction

Difference responses of the moving cylinder were observed under i) a wave with a period equal to its natural damped period (Wave1) and ii) a wave with a greater period (Wave2). The interaction between the floating cylinder and waves was evaluated in terms of the Response Amplitude Operator (R.A.O.) and phase lag between the two oscillating signals (wave and heave).

Wave1



Wave2



	H (m)	T (sec)	R.A.O.	Phase lag (sec)
Wave1	0.25	1.5	0.584	-0.05
Wave2	0.3	2	0.375	0.02

Conclusions

The aim of this work was to preliminary investigate OpenFOAM® capability in simulating wave-floating structures interaction, a topic for which this code was not implemented yet.

The comparison between numerical results and experimental data shows a good agreements of the performed free decay tests.

OpenFOAM®, with the inclusion of the wave generation tool IHFOAM, is deemed to be a valid and reliable instrument to model interaction between floating bodies and waves.

This innovative application with OpenFOAM® represents the first step to develop a numerical wave tank where it is possible to study wave-floating structure interaction, as an extra input or a full alternative to the experiments in design process.

Thanks for your attention!