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Study of the effect of water depth on potential flow solution of the OC4 Semisubmersible Floating Offshore Wind Turbine

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Abstract

This work aims at assessing the influence of water depth on the potential flow solution for a semisubersible floating offshore wind turbine. More specifically, the system developed for the Offshore Code Comparison Collaboration Continuation (OC4) of the International Energy Agency IEA was considered for this paper. This work has been inspired by previous studies concerning the effect of shallow water on Liquified Natural Gas Carriers (LNGC). The influence of water depth on the hydrodynamics of such systems is evident from measurements as well as from simulations, specifically when secondary effects in the wave and flow modelling are addressed. This scenario has motivated the comparative study for the Floating Wind Turbine herein reported, also taking into account second order hydrodynamics (Quadratic Transfer Functions, QTF) as well as low frequency contribution in the incoming wave, due to shallow water (Setdown effect). The simulations were conducted relying on the codes DIFFRAC and aNySIM, developed at Maritime Research Institute of Netherlands (MARIN) and the results are presented for a range of water depth between the nominal value of 200 m and the extreme shallow water of 30 m.

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Keywords: Shallow waters, Floating Offshore Wind Turbines, OC4, Semisubmersible, Quadratic Transfer Functions, Setdown.

1. Introduction

There has been a renewed interest in shallow water effects for the design of Liquefied Natural Gas (LNG) terminals. Many studies looked in details at the behavior of LNG carriers (LNGC) with shallow water mooring systems adapted to the offloading of gas. Such vessels have a hull shape which generally provides little damping in surge, and therefore, any increase of the drift load excitation may result in a large drift motion response and significant increase of the mooring loads. These studies have shown that the effects of the water depth under the assumption of Airy waves become fully visible only when full Quadratic Transfer Functions (QTF) are considered. Also the ratio of the draft over the water depth was identified as a main parameter triggering shallow water effects. In practice, both numerical models and model tests in basins are used to assess accurately the loads on LNGCs moored in shallow water. In the

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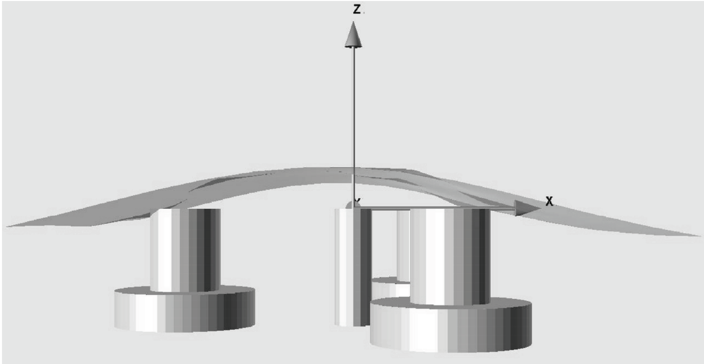

Fig. 1: OC4 Semisubmersible platform.

gas terminal design process, basin effects are usually characterized and simulations of LNGC are run including these effects to obtain more realistic results. Also wave propagation models accounting for the wave frequency and slow frequency components of the wave field, or actual in-situ measurements are recommended to define the shallow water waves used as input for the simulations and model tests of moored LNGC [1], [2]. Floating foundations are commonly considered for water depth greater than 70 m. Although the wave hydrodynamics in shallow water can be analysed in the same way as for gas terminals, the response of a small semisubmersible in shallow water is expected to be significantly different from a LNG carrier. A semisubmersible is more transparent to waves and its hull is not as nicely profiled as a LNGC. The phase II of the Offshore Code Comparison Collaboration Continued (OC4) project, operated under IEA Wind Task 30, has defined the semisubmersible floating system [3] (Fig. 1) for the National Renewable Energy Laboratory (NREL) offshore 5-MW baseline wind turbine [4]. The investigations within the OC4 project [5], as well as more specific works about second order hydrodynamics of this system ([6],[7],[8]), have considered 200 m as water depth for the installation. The relatively small draft of this semisubmersible (20 m), could potentially allow installation at smaller water depth. The present study investigates the influence of water depth on the potential flow solution of the OC4-semisubmersible Floating Offshore Wind Turbine (FOWT). More specifically, setdown effect in the incoming waves as well as low frequency bound waves, have been considered the only contributions characterizing the non-linear hydrodynamics of shallow waters.

2. First Order Hydrodynamics

Shallow waters have non-negligible effect on the first order potential flow, as already investigated in the above mentioned previous studies [1], [2]. Let us firstly be concerned with dispersive waves, typical of deep waters (*free waves*), which are, by definition, waves such that interact linearly among each other and their wave length is less than four times the water depth $\lambda \leq 4 \cdot h$ (i.e deep water waves), where h is the water depth and λ is the wave length. Also, the *dispersion relation*, for an arbitrary water depth, can be expressed as follows:

$$\omega(k) = \sqrt{g \cdot k \cdot tanh(kh)} \tag{1}$$

where ω, k, g are respectively the wave circular frequency, the wave number ($\lambda k = 2\pi$) and the gravitational acceleration. In Fig. 3 the gravity wave dispersion relation is reported for the water depth $h = 200$ m and $h = 30$ m, which represent respectively the nominal water depth for the OC4 floating wind turbine and the extreme shallow water, being the draft of the OC4 floating substructure of 20 m. In Fig. 3 the solid and dash-dot lines represent respectively the Eq. (1) for 30 m and 200 m, whereas the dashed and dotted lines represent the related *dispersion relation* limits ($\lambda = 4 \cdot h$). The intersection of the curves with the related horizontal lines (limits) draws two regions in which the wave corresponding to a wave circular frequency ω can be considered dispersive (i.e can be seen as deep water wave, whose phase speed is two times the group speed), whereas in the region where the dispersive relation does not hold (e.g the interaction among different frequency waves becomes non-linear) bound waves are created ("bound" to primary wave, the phase speed equal to the group speed). Having indicated in Fig. 3 also with S,P and H respectively the

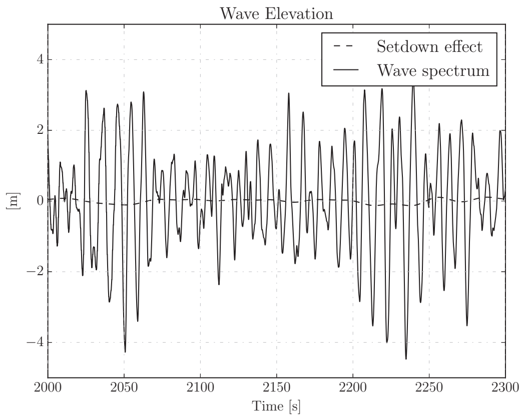

Fig. 2: Setdown associated to primary wave.

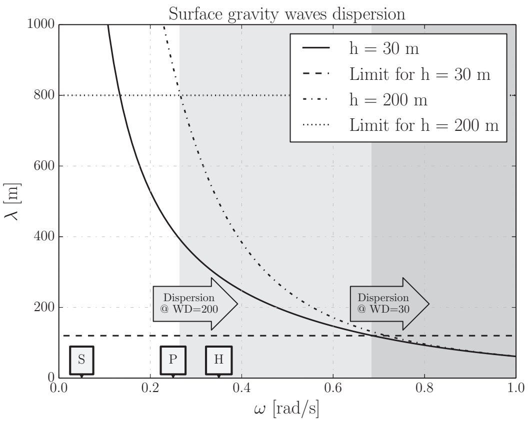

Fig. 3: Surface gravity waves dispersion relations.

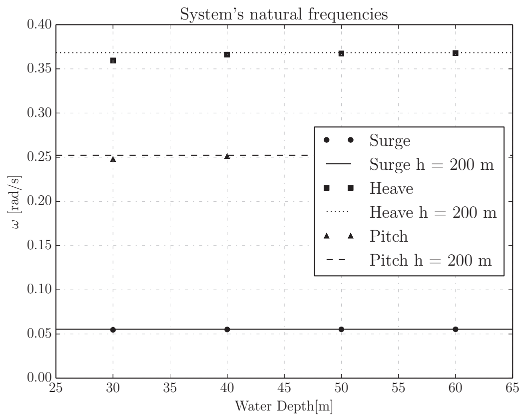

Fig. 4: OC4 Semisubmersible natural frequencies Vs water depth *h*.

degrees of freedom (DoFs) surge, pitch and heave natural frequencies (0.05, 0.25 and 0.35 rad/s) of the OC4 floating offshore wind turbine (FOWT), it is worth noticing that the heave natural frequency is seen as a deep water wave for a water depth of 200 m, whereas it is not for the extreme shallow water of 30 m. In this study, only the previously mentioned DoFs have been considered. From this perspective it can be consistently expected that the most significant changes in the hydrodynamics of this floating platform will affect the heave degree of freedom, as the water depth decreases. Moreover, it is also reasonable not to expect any significant variation in the potential flow solution, varying the water depth, for wave frequencies greater than approximately $1 - 1.2$ rad/s, for which the nature of the waves can be considered the same, both for deep or shallow water (i.e lines overlapped in Fig. 3).

The potential flow problem was solved by means of the code DIFFRAC, developed over the last decades at the Maritime Research Institute of Netherland, MARIN. The added mass and damping, as function of circular frequency, have been computed for the DoFs studied. Reporting all the related graphs is beyond the purpose of this paper; nevertheless, the added mass and potential damping of heave is reported in Fig. 5 and Fig. 6. It can be firstly noted that, as previously mentioned, the main difference among various water depth, can be noticed for frequencies lower than $1 - 1.2$ rad/s, since for greater frequencies the difference in the dispersive relation becomes negligible. It can be noted from Fig. 5 that the added mass is increasing, keeping the same trend, as the water depth gets smaller. This also explains the decreasing natural frequency of the system, being the stiffness kept the same as in [6], as the water depth varies, see Fig. 4. This tendency can be noticed for each DoF studied, although for surge the variation in the added mass is quite small.

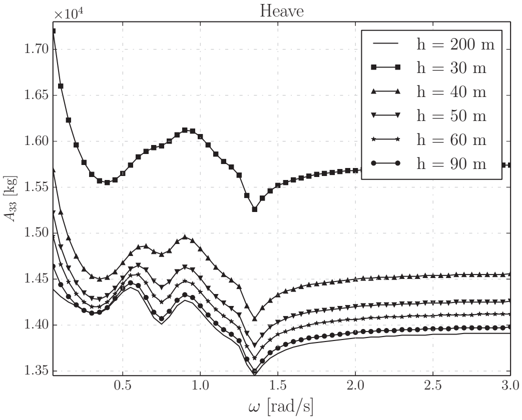

Fig. 5: Heave added mass for different water depth *h*.

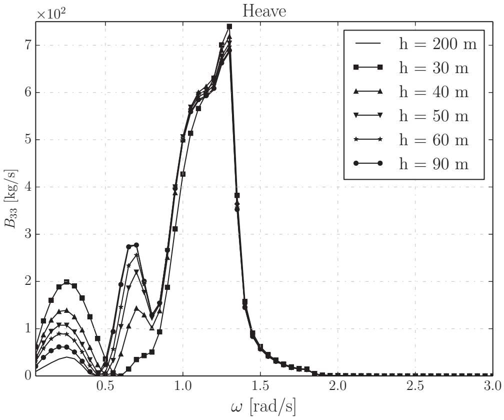

Fig. 6: Heave potential damping for different water depth *h*.

3. Nonlinear contributions: setdown effect and second order hydrodynamics

3.1. Setdown effect (bound incoming waves)

In real operational conditions shallow water waves are characterized by different contributions in the low frequency range. Key role is played by the following contributions: *shaoling effect*, which gives rise to low frequency free waves with their own phase velocity, as the waves approach the shore, the *setdown bound waves* and their reflection, as well as the *edge waves* due to refractive trapping. In this study, the incoming waves have been modelled as *bound waves* due to the *setdown phenomenon* connected to the decrease of water depth.

From theoretical considerations and from results of computations based on three-dimensional potential theory ([9], [10]), it can be shown that mean and low frequency forces associated to shallow water will be higher than in deeper water. These forces will also contain significant effects from pressure contribution which, although in principle also present in deeper water, can in such cases generally be neglected. The increase in mean forces in shallow water relative to the forces in deeper water can in part be explained by the decrease in the wave length in shallow water for the same wave frequency and in part by the modification of the floating platform motion considering low draft over water depth ratio (Fig. 1). In shallow water the irregular incoming waves exhibit the wave setdown phenomenon. This non-linear effect appears as long waves bound to the incoming short waves. Setdown wave elevations are related to second order pressures in the wave field, which in shallow water is dominated by second order potential effects. The incoming irregular waves are characterized by wave grouping, which is a term describing the fact that the waves contained in the train display amplitudes which are relatively slowly varying in time and space, thus giving the impression that waves progress in almost distinct groups. The long waves, which are associated to wave setdown, bound to short waves, generally exhibit wave troughs where the wave group amplitudes are larger and wave crests where wave group amplitudes are smaller, see Fig. 2. Based on potential flow theory, it can be shown that the setdown effect is strongly increased in shallow water. It can also be shown that the setdown effect phenomenon does not contribute to the mean value of the second order forces but only to the slowly varying components. When it comes to modelling the incoming wave time history to also include the setdown effect, with reference to [11], the following equation can be considered:

$$\xi = \xi^{(1)} + \xi^{(2)} = \sum_{i=1}^{N} a_i cos(\omega_i t + \epsilon_i) + \sum_{i=1}^{N}\sum_{j=1}^{N} a_i a_j D(\omega_i, \omega_j, k_i, k_j) cos((\omega_i - \omega_j)t + \epsilon_i - \epsilon_j) \quad (2)$$

where $\xi^{(1)}$ and $\xi^{(2)}$ stand respectively for the wave amplitude due to the wave spectrum contribution and due to setdown phenomenon, a_i and a_j are wave amplitudes, D is a transfer function, properly defined in [11], ω_i and ω_j the wave circular frequencies associated respectively to the phase ϵ_i and ϵ_j. In Fig. 2 the contribution $\xi^{(1)}$ and $\xi^{(2)}$ are plotted separately. As clearly visible in Fig. 8 the second term of the Eq. 2 turns out to give to the wave train a slow varying component, that falls into the frequency range of the slow drift motion. In this range the semisubmersible platforms'

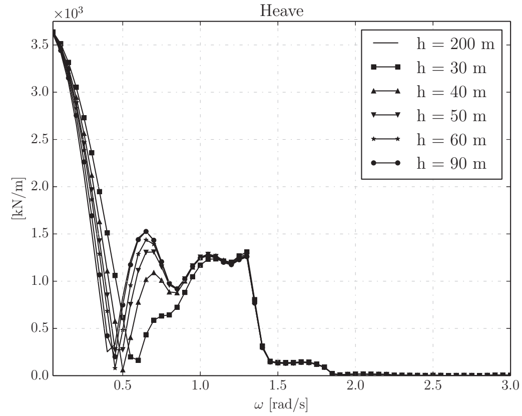

Fig. 7: Heave wave exciting force for different water depth *h*.

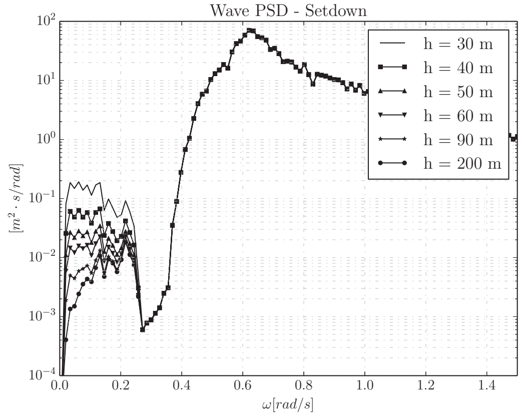

Fig. 8: Setdown Wave PSD for different water depth *h*.

eigenfrequencies usually fall as a design requirement. This effect has also an impact on the exciting forces (Eq. 3), as well as on the QTFs due to different velocity potential. Experimental validation of the setdown wave elevation model, adopted in this study, can be found in [2].

3.2. Second-order hydrodynamics

In this study the formulation of the second order hydrodynamic forces on a floating body suggested by Pinkster [10], that is given as a summation of five contributions derived by direct pressure integration [10], was adopted:

$$
\begin{aligned}
\overrightarrow{F}^{(2)} &= \overrightarrow{F}^{(2)}_{I} + \overrightarrow{F}^{(2)}_{II} + \overrightarrow{F}^{(2)}_{III} + \overrightarrow{F}^{(2)}_{IV} + \overrightarrow{F}^{(2)}_{V} \\
&= -\frac{1}{2}\rho g \int_{WL} \xi^2_{(1),rel} \cdot \overrightarrow{n}_0 \cdot \overrightarrow{dl} + \frac{1}{2}\rho \iint_S \nabla\Phi_{(1)} \cdot \nabla\Phi_{(1)} \cdot \overrightarrow{n}_0 \cdot dS + \\
&\iint_S \rho \cdot X_{(1)} \cdot \nabla \frac{\partial \Phi}{\partial t} \cdot \overrightarrow{n}_0 \cdot dS + \overrightarrow{\Omega}_{(1)} \times M\ddot{\overrightarrow{X}}_{(1)} + \rho \iint \frac{\partial \Phi_{(2)}}{\partial t} \cdot \overrightarrow{n}_0 \cdot dS
\end{aligned}
\tag{3}
$$

the terms denoted by "(1)" and "(2)" refer respectively to first and second order, ρ is the water density, g is the gravitational acceleration, $\xi_{(1),rel}$ is the relative wave elevation, n_0 is the outward pointing normal vector with respect to the surface element dS of the platform, dl is the element of the water line contour, Φ is the velocity potential, X is the vector containing the degrees of freedom of the platform and Ω the related angular velocity . The terms I -IV are quadratic contributions of the first order velocity potential, whereas the term V involves the second order velocity potential that in DIFFRAC, the MARIN code adopted for this study, is approximated by considering only the contribution of the undisturbed incoming wave to the wave exciting force kept at the second order [10]. Without loss of generality, for each of the DoFs considered in this study, the pitch QTFs are reported in Fig. 9 and Fig. 10. Consistently with the first order results, it can be noted in Fig. 9 that the sum of all the five contributions (Eq. 3), related to the main diagonal $\omega = \omega_i - \omega_j = 0$, show negligible difference in terms of magnitude for frequency higher than 1-1.2 rad/s approximately, as the water depth decreases from 200 m to 30 m. Nevertheless, observing the difference on the 5th diagonal ($\omega = \omega_i - \omega_j = 5 \cdot d\omega$, where $d\omega$ is the frequency resolution) of the second order forces (Fig. 10), it can be noted that this difference is present also for higher frequencies, since, for off-diagonal terms, the second order forces do not depend only on the first order velocity potential (I-V quadratic terms), but also on the second order velocity potential (V term). Moreover, the contribution V of the second order forces depends on the second order velocity potential that, in shallow water, turns out to be affected also by the water depth.

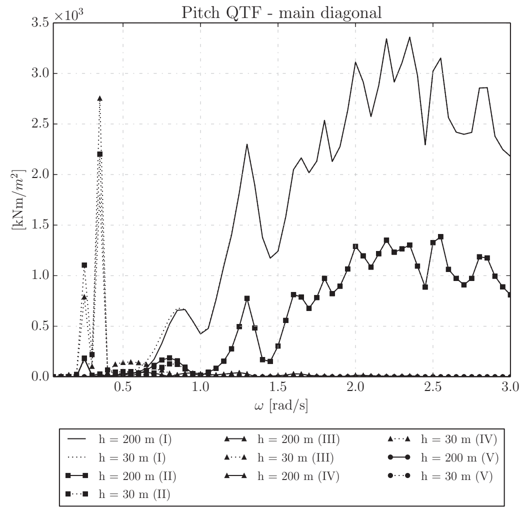

Fig. 9: Pitch second order forces:
main diagonal QTFs for different water depth h.

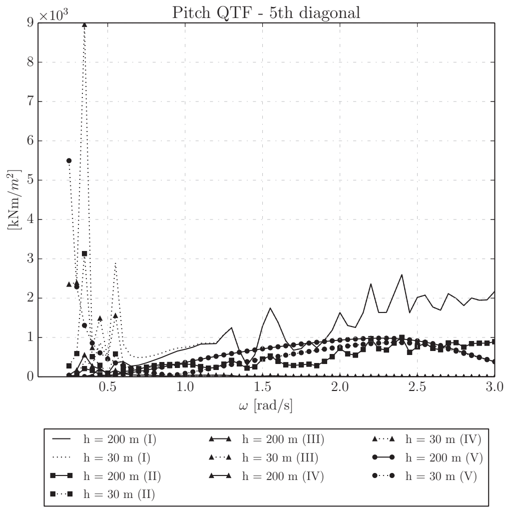

Fig. 10: Pitch second order forces:
5th diagonal QTFs for different water depth h.

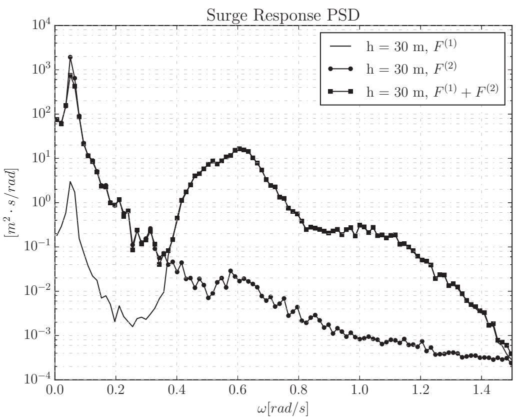

Fig. 11: PSD of the Surge response for different force contribution:
no wave setdown effect, water depth h = 30 m.

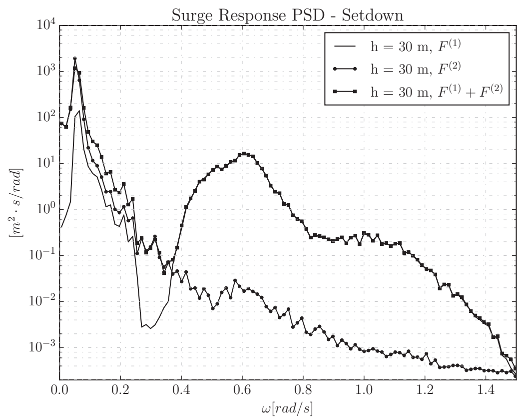

Fig. 12: PSD of the Surge response for different force contributions:
wave setdown effect, water depth h = 30 m.

4. Results

The results reported in Fig. 11 - 16 show Power Spectrum Densities (PSD) of the time histories of the response (Fig. 11 and Fig. 12) or force (Fig. 13, Fig. 14 and Fig. 16), for surge and heave, acting on the OC4 floating offshore wind turbine, with or without setdown slow-varying components included in the generation of the wave train. For each simulation the irregular sea-state taken as reference is a Jonswap spectrum with a significant wave height H_s of 6 m and peak period of T_p 10 s, which is also referred to as the load case *LC2.2* of the OC4 exercise [5]. The tools adopted for this aim is aNySIM, developed at MARIN for taking also into account the wind turbine properties as well as the mooring system. In Tab. 1 the statistics of the response is reported, as the water depth varies. As it can be noted from Tab. 1, the highest standard deviation is associated to surge, especially for the extreme case water depth of 30 m, as it can be expected also looking at the related PSD, Fig. 12. More specifically, looking at the Fig. 13, Fig. 14, it is clear how the second order forces, both quadratic contributions (F^{2Q}, I to IV) and total contribution (F^{2Tot}, I to V), are not negligible in the range of surge natural frequency (Fig. 13), in which they are summed to the first order forces, whose contribution has nearly the same order of magnitude when setdown phenomenon is also

Tab. 1: Statistics of the responses.

Load case ($F^1 + F^2$)	Type	Surge Mean [m]	Surge Standard Deviation [m]	Heave Mean [m]	Heave Standard Deviation [m]	Pitch Mean [deg]	Pitch Standard Deviation [deg]
h = 30 m	No Setdown	1.75	2.017	0.031	0.183	0.006	0.584
	Setdown	1.802	2.616	0.031	0.205	0.006	0.556
h = 40 m	No Setdown	1.473	1.514	0.032	0.203	0.027	0.619
	Setdown	1.495	1.769	0.032	0.207	0.026	0.603
h = 50 m	No Setdown	1.396	1.405	0.031	0.227	0.032	0.647
	Setdown	1.409	1.507	0.031	0.228	0.032	0.636
h = 60 m	No Setdown	1.371	1.358	0.030	0.246	0.034	0.663
	Setdown	1.380	1.412	0.030	0.246	0.034	0.653
h = 200 m	No Setdown	1.371	1.334	0.030	0.275	0.036	0.682
	Set Down	1.373	1.338	0.030	0.274	0.036	0.677

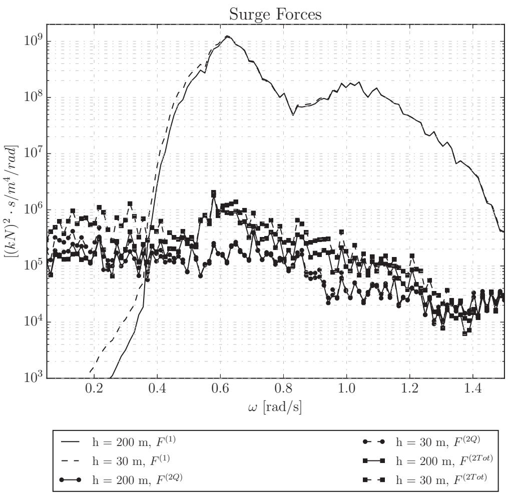

Fig. 13: Surge PSD of different force contributions: no wave setdown effect.

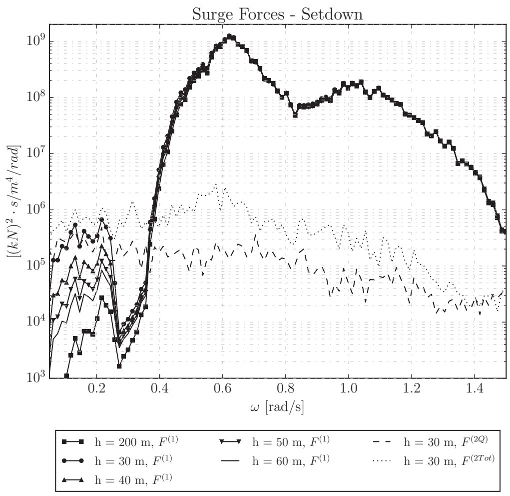

Fig. 14: Surge PSD of different force contributions: wave setdown effect.

included (Fig. 14). These slow-varying contributions, due to drift forces and setdown effect, exciting the surge natural frequency, are responsible of considerable displacement, as reported in Tab. 1 and in Fig. 11 and Fig. 12; therefore, these low-frequency secondary effects must inevitably taken into account in the design of the mooring system. In the same frequency range, as it can also be seen from Fig. 16, the effect of the setdown phenomenon greatly affects the heave degree of freedom, for which the magnitude of the first order forces becomes also greater than the second order forces. It is also interesting to notice from Fig. 16 that the first order heave force shows two set of peaks, one just after heave natural frequency and one at higher frequencies, in the wave spectrum range. With regard to the latter, looking also at the trend of the first order wave exciting force for heave Fig. 7, it is clear how this decreases as the water depth decreases. This can be explained considering that the overall characteristic dimension of the semisubsmersible is about 70 m (Fig. 1). Considering the peak's frequency at the nominal water depth of 200 m, which is approximately of 0.65 rad/s, and by solving the related dispersion relationship (Eq. 1, Fig. 3), it turns out to be associated to a wave length of λ = 140 m (two times the OC4-semi characteristic dimension). This means that for this wave length the OC4-Semi's columns are accidentally excited in phase, as qualitatively reported in Fig. 1, which is a very specific phenomenon occurring in this specific condition (water depth, wave frequency and substructure dimensions). This effect decreases for lower water depth since, for the same wave frequency, the related wave lengths are smaller, so that the synchronization in forcing the OC4-Semi's columns is lower (as in Fig. 7). By comparing the heave wave exciting force (Fig. 7), computed through the potential flow theory, and the related time-tracked heave force PSD (Fig. 16), as well as the corresponding response (Fig. 15), one can notice basically the same consistent trend.

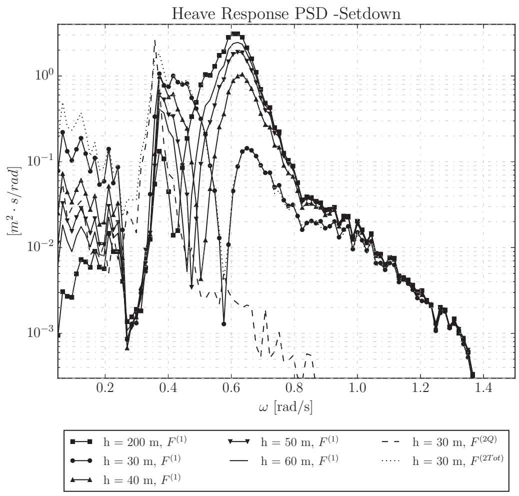

Fig. 15: PSD of the Heave response for different force contributions: wave setdown effect, different water depth *h*.

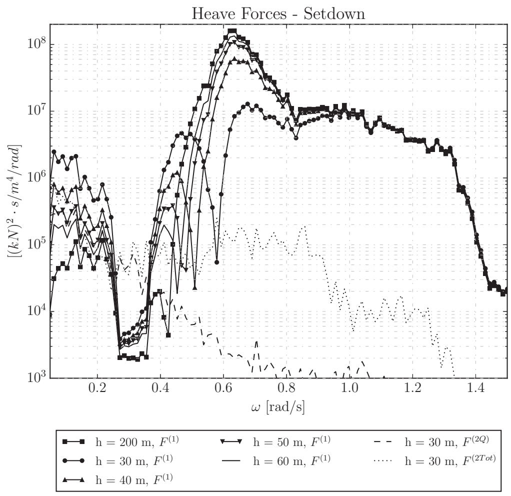

Fig. 16: Heave PSD of different force contributions: wave setdown effect, different water depth *h*.

5. Conclusions

The motivation of this work was strongly influenced by previous studies regarding the dynamics of Liquefied Natural Gas Carriers (LNGC) in shallow water mooring systems and, more specifically, whether the same conclusions about the effects of water depth on such system could be also extended to floating offshore wind turbines. For this case study, the OC4-Semisubmersible floating platform, developed as a benchmark under the IEA task 30, was considered. This work gives emphasis on how the potential flow solution is affected by the water depth that ranges from the nominal value of 200 m to the very shallow configuration of 30 m. For limiting the variables and making the understanding of the results more clear, only the potential flow has been considered, and the system's stiffness and viscous damping were kept constant varying the water depth, although it is reasonable to expect that these parameters vary for sea levels as well as the typical viscous-related phenomena can occur (e.g vortex shedding due to the cylinders of the OC4-Semi). Moreover, from studies on LNGC, it is clear how decreasing the water depth has a great impact on the low frequency motion of these platform, due to a variety of complex and combined phenomena related to the different nature of waves compared to deep waters (e.g setdown effect, free and bound waves, directional spreading waves and edge waves). This requires to assess the response of the floating platform according to the offshore engineering approach of measuring the full wave spectrum. In this study first and second order potential flow were solved as function of water depth and also non-linearities, in terms of setdown effect, were taken into account in the generation of the incoming wave time histories. The surge, heave and pitch degrees of freedom (DoFs) were considered for this study. Consistently with the expectation, the results have shown that the most noticeable differences are given for heave, whose OC4-Semi natural frequency corresponds to a wave length which increasingly looses its dispersive property moving to shallow waters. Despite what one would have been expected from LNGC bibliography, surge degree of freedom is not as much influenced, by decreasing water depth, as the heave actually is; although this influence is also moderate. A reasonable explanation for this is that the OC4-Semi is more "transparent" to waves than a typical LNGC, which is also streamlined and whose little potential damping (i.e surge) makes it greatly sensible to forcing conditions.

References

[1] van Essen S., van der Hout A., Huijsmans R., Waals O., "Evaluation of Directional Analysis Methods for Low-Frequency Waves to Predict LNGC Motion Response in Nearshore Areas", *International Conference on Ocean, Offshore and Arctic Engineering, OMAE2013-10235*, Nantes, France, 2013.

[2] Naciri M., Buchner B., Bunnik T., Huijsmans R., Andrews J., “Low frequency motions of LNG carriers moored in shallow water”, *24th International Conference on Offshore and Arctic Engineering*,12-17 June, 2005, Halkidiki, Greece. OMAE2004-51169.

[3] Robertson A., Jonkman J, Masciola M., Goupee A., Coulling A., Luan C., “Definition of the Semisubmersible Floating System for Phase II of OC4”, *NREL/TP-5000-60601, National Renewable Energy Laboraory, Golden, CO.*, Sept., 2014.

[4] Jonkman J.; Butterfield S.; Musial W., Scott G., “Definition of a 5-MW Reference Wind Turbine for offshore System Development”, *NREL/TP-500-38060, National Renewable Energy Laboraory, Golden, CO.*, Feb. 2009.

[5] Robertson A.; Jonkman J.; Musial W., Vorphal F., Popko W., “Offshore Code Comparison Collaboration, Continuation: Phase II Results of a Floating Semisubmersible Wind System”, *NREL/CP-5000-60600,Golden, CO. National Renewable Energy Laboratory*, Nov. 2013.

[6] Gueydon S., Duarte T., Jonkman J., Bayati I., Sarmento A., “Comparison of second order loads on a semisubmersible floating wind turbine”, *NREL/CP-5000-61162, National Renewable Energy Laboraory, Golden, CO*, March 2014.

[7] Bayati I., Jonkman J, Robertson A., Platt A., “The effects of second-order hydrodynamics on a semisubmersible floating offshore wind turbine, *Journal of Physics: Conference Series*, 524, 2014.

[8] Coulling A., Goupee A., Robertson A. Jonkman J., “Importance of Second-Order Difference- Frequency Wave-Diffraction Forces in the Validation of a FAST Semisubmersible Floating Wind Turbine Model”, *International Conference on Ocean, Offshore and Arctic Engineering, OMAE2013-10308*, Nantes, France, 2013.

[9] Bowers, E.C., “Long period oscillation of moored ships subject to short seas”, *Proceedings of the Royal Institute of Naval Architecture*, 1975.

[10] Pinkster J.A., “Low Frequency Second Order Wave Exciting Forces on Floating Structures”. *PhD thesis*, Delft, 1980.

[11] Voogt A., Bunnik T., Huijsmans R., “Validation of an analytical method to calculate wave setdown on current”, *24th International Conference on Offshore and Arctic Engineering, OMAE2005-67436*,12-17 June, 2005, Halkidiki, Greece.