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COMPARISON OF MOORING LOADS IN SURVIVABILITY MODE ON THE WAVE DRAGON WAVE ENERGY CONVERTER OBTAINED BY A NUMERICAL MODEL AND EXPERIMENTAL DATA

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ABSTRACT

The Wave Dragon Wave Energy Converter is ready to be up-scaled to commercial size. The design and feasibility analysis of a 1.5 MW pre-commercial unit to be deployed at the DanWEC test center in Hanstholm, Denmark, is currently ongoing. With regard to the mooring system, the design has to be carried out numerically, through coupled analyses of alternative solutions. The present study deals with the preliminary hydrodynamic characterization of Wave Dragon needed in order to calibrate the numerical model to be used for the mooring design. A hydrodynamic analysis of the small scale model in the frequency domain is performed by the software *HydroD*, which uses *WAMIT* as core software. The quadratic damping term, accounting for the viscous effect, is determined through an iterative procedure aimed at matching numerical predictions on the mooring tension, derived through time domain coupled analysis, with experimental results derived from tank tests of a small scale model. Due to the complex geometry of the device, a sensitivity analysis is performed to discuss the influence of the mean position on the quality of the numerical predictions. Good correspondence is achieved between the experimental and numerical model. The numerical model is hence considered reliable for future design applications.

INTRODUCTION

The Wave Dragon is a floating, offshore Wave Energy Converter of the overtopping type. Incoming waves are focused by two wing reflectors towards a doubly-curved ramp, by which they surge up into a reservoir placed above the mean water level. The power production takes place as the stored water is led back to the sea through a set of low-head hydro-turbines coupled to permanent magnet generators (Figure 1). A commercial unit of Wave Dragon suitable for North Sea conditions (yearly average wave power of 24 kW/m) is a 22,000 tons reinforced concrete structure, occupying an area of around 150x260 m^2. With 4 MW installed power, it can produce up to 12 GWh per year. Scale ratios used in the following are all referred to this North Sea size.

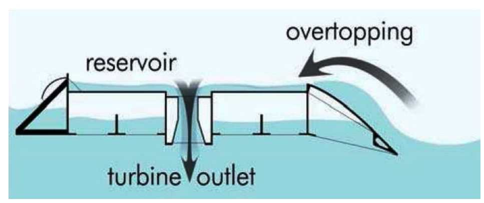


Figure 1. Working principle of Wave Dragon.

Wave Dragon has been developed during more than 10 years, following a Technology Readiness Assessment (TRA) approach in which each new phase of the development is justified by the good results achieved in the previous one. The related research and development has been mainly carried out through physical tests, as suggested by the geometrical complexity of the device, which made it difficult to establish reliable ad-hoc numerical models. Since the early phases the development of Wave Dragon was therefore mainly based on wave tank testing of a 1:51.8 scale model; among these were the proof of concept, geometry optimization, hydrodynamic characterization and preliminary power production assessment [1].

Based on these experimental results, in 2003 a 1:4.5 scale prototype was built and tested in Nissum Bredning, a benign location in Northern Denmark. The extended sea trials program allowed acquiring valuable operational experience in many aspects, as well as validating the analytical models resulting from the previous development phase and testing the Power Take-Off system and control strategy [2].

Currently, Wave Dragon is being up-scaled to commercial size. With regard to this, the structural design of a 1.5 MW pre-commercial unit to be deployed at the DanWEC test site in Hanstholm, Northern Denmark, [3] is being carried out together with the related feasibility analysis. Respect to a 4 MW North Sea Wave Dragon the scale of the envisaged unit is 1:1.5. The up-scaling is largely based on the measurement campaign carried out on the prototype during the sea trials and experimental data acquired in previous phases of development.

For a floating offshore structure such as Wave Dragon, an important part of the design process deals with the mooring system. The conceptual mooring system for Wave Dragon is a circular spread of slack chains anchored to a central buoy, to which the main platform and wave reflectors are connected (Figure 2). This system allows de-coupling the vertical motions of Wave Dragon, which are actively controlled to optimize the power production, from the other modes of motions, which are restrained by the mooring system instead. The catenary solution is a well-known technology capable of absorbing peak loads, hence well adequate for a large floating structure such as Wave Dragon. Other elements of the mooring system are a rear mooring line to prevent excessive rotations and cables between the reflectors to prevent them from opening or closing too much.

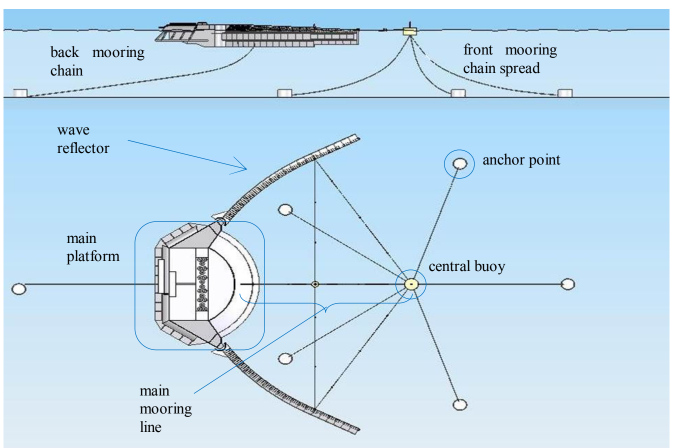


Figure 2. Conceptual mooring system of Wave Dragon.

This general layout needs to be adapted to the local conditions of the DanWEC deployment site and a detailed mooring system has to be designed. Although being a site-specific solution, the result of the design operations would also provide a sound basis for a mooring system suitable for any future deployment, since this is not expected to change substantially.

Unlike with other components, the mooring design cannot be based on direct experience, as both during the tank testing and the prototype trials the relatively shallow waters did not allow a proper catenary system to be tested. In these cases the device and reflectors were connected to a vertical pile instead. Therefore the mooring design for the up-scaled pre-commercial unit has to be carried out numerically, through systematic analyses of alternative configurations aiming at finding the best solution in terms of reliability and economic feasibility.

In order to do so, coupled analysis of the response of Wave Dragon to mooring and environmental loads typical of the deployment location will be carried out. This will be done by means of the software *SIMO/Riflex* [4], which has been extensively used in the past for coupled analysis of motions and loads on moored offshore structures and ships. However, preliminary to this, hydrodynamic and mooring models of Wave Dragon have yet to be established.

A thorough investigation aimed at the hydrodynamic characterization of Wave Dragon has been carried out and is presented here. The technique used is to validate a numerical model for hydrodynamic analysis with experimental data relative to previous tank tests. A hydrodynamic analysis of the device is first performed in the frequency domain; the value of the quadratic damping coefficient is then determined in order to achieve the best fit on the tension in the main mooring line between the numerical predictions, deriving from a time domain coupled analysis, and the experimental data, obtained after the tank testing of a 1:51.8 scale model of Wave Dragon. The comparison is made at the model scale, however the results can be used for the pre-commercial demonstrator design, as a geometrical similarity is maintained.

In the following the numerical model and the method used for its calibration are described in detail. The results of the calibration process are the hydrodynamic parameters of Wave Dragon, which will be used in the design of the mooring system for the 1.5 MW pre-commercial unit.

A sensitivity analysis is finally also carried out with regard to the influence of the geometric configuration of the device on the hydrodynamic behavior, since it is found that its hydrostatics and hydrodynamics are very dependent on the mean configuration.

Finally, main conclusions are summarized and further work is addressed.

EXPERIMENTAL DATA

In November 2010 a series of tests have been carried out in order to assess the response of Wave Dragon to extreme wave conditions, in terms of extreme forces in the main mooring line and extreme motions. These have been carried out at the Hydraulic and Coastal Laboratories of Aalborg University (AAU) on a 1:51.8 scale model of Wave Dragon [5]. The scaled model used is 5 m wide (from tip to tip of the reflectors), 2.9 m long in its longitudinal cross-section and 0.28 m high (from the bottom base to the crest freeboard). Irregular waves have been tested, representing extreme conditions typical of the Danish part of the North Sea (with return periods of 10, 50 and 100 years, see Table II). The mooring system was represented through linear springs; the main mooring line was horizontally connected to a fixed vertical pile, where the tension was measured through a force transducer (Figure 3a). Different drafts have been tested. Motions of the model in heave, pitch and surge were measured. Experimental data are available as 30 min long time series, acquired at 20 Hz. This same setup has been analyzed numerically.

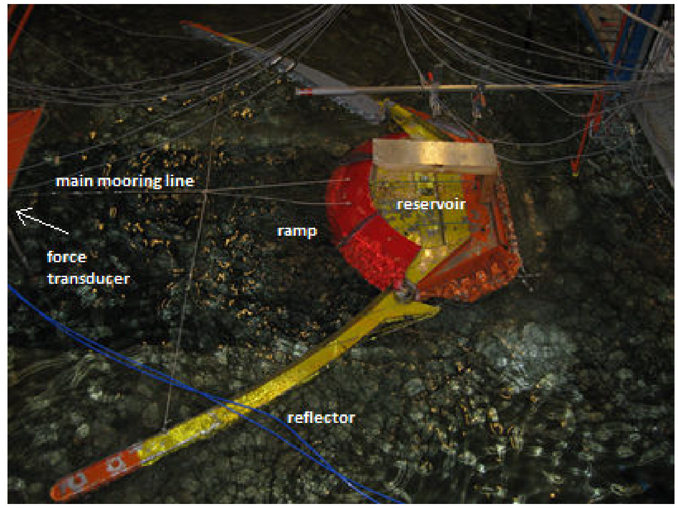
NUMERICAL METHOD

In this study a panel model of Wave Dragon (Figure 3b) is created through the software *GeniE* [6], reproducing the same model geometry and mass distribution used in the tank testing. This panel model is the input for the software *HydroD* [7], used for the hydrodynamic analysis in the frequency domain; this includes the calculation of hydrostatic stiffness, potential damping, added mass and 1st and 2nd order wave excitation forces on the body. Once determined, the hydrodynamic properties will be used in the coupled mooring analysis in time domain, performed through the software *SIMO/Riflex*. Additionally, the viscous term is introduced according to the Morison model. This has been estimated by calibrating the numerical model with data derived from the tank testing of the scaled model of Wave Dragon. The goal is to determine an entry value for the quadratic damping term so that the numerical model is able to reproduce the observed experimental response. An iterative approach has been used to find the best correspondence in terms of tension in the main line of the mooring system, the one connecting the main platform to the central buoy.

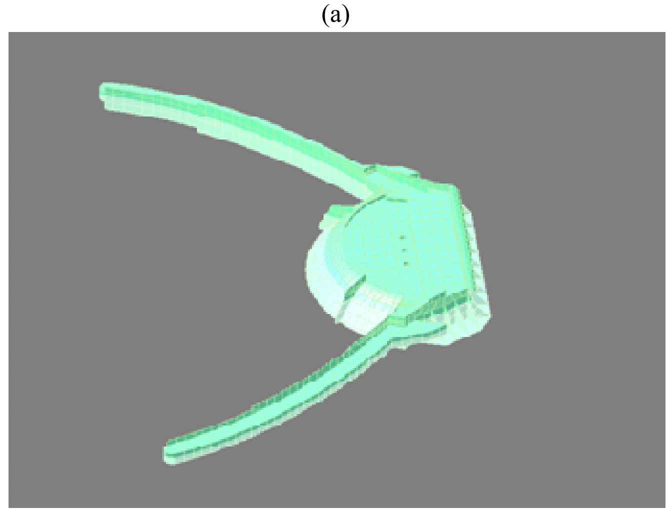
Other non-linear features, such as the overtopping, are disregarded in the analysis; this is not considered a major problem at this stage, as previous studies have shown that in extreme conditions the device should be set to the lowest floating position possible to increase its survivability, a condition in which it is almost totally submerged and the nonlinearities due to the overtopping are very much limited [5].

Three drafts have been considered in the present analysis; these are referred to as low, medium and high draft and corresponds respectively to 0.2 m, 0.24 m and 0.26 m at model scale. Since the hydrodynamic analysis is based on linear theory, for each draft a mean position had to be assumed. In general, this was maintained as close as possible to the average position experienced during the tank tests. More details on this are discussed in the following.

The calibration process was carried out by varying the quadratic damping of the system in surge, in order to reproduce in *SIMO/Riflex* the response observed in the tank tests. Initially free-decaying tests have been considered; this part of the analysis was mainly aimed at identifying the right mean position to be used. However the core of the analysis was represented by the comparison of the results in irregular waves, from which the quadratic damping has been estimated. For each of the 6 experimental test cases considered, 12 different numerical simulations are performed, using 12 different realizations of the same wave condition. From these the distribution of the extreme response in the mooring line could be produced for each case.



(a)



(b)

Figure 3. The experimental setup used in the tank tests (a) and the panel model used in the hydrodynamic analysis (b).

Irregular wave analysis

Once the mean position to be used in the analysis has been assessed based on free-decay tests, the comparison between numerical and experimental response to irregular wave has been carried out in terms of:

- *Statistical analysis* of the whole time series of the tension in the main mooring line (1 experimental and 12 numerical realizations for each case), 30 min long. The comparison considered mean value and standard deviation of the time series.

• *Spectral analysis*, based on: the experimental incident wave component, as derived from 3D wave analysis of the wave measured during the tank tests; the experimental mooring tension recorded in the tank tests; the numerical mooring tension, considering the aggregated time series given by the succession of the 12 simulations for each case considered. A comparison in the wave frequency region aims at assessing the correct representation of the linear part of the system, while the comparison in the low frequency region aims at assessing the behavior in the resonant part of the system.

• *Extreme value analysis* of the tension. The comparison is based on the mean of the extreme value distribution obtained from the numerical simulations and from the experimental results.

The extreme value distributions considered the maxima of time series 5 minutes long (i.e. 6 sub-time series considered for each case) as well as 30 minutes long (i.e. one time series for each case). When 5 minutes long time series are considered, 72 points are available for each numerical case (6 maxima for each of the 12 realizations) and 6 for each experimental case; when 30 minutes long time series are considered, 12 points are available for each numerical case (one for each realization) and 1 point only for each experimental case, corresponding to the absolute maximum. The analysis based on the 5 min long time series is used in order to reduce the statistical uncertainty related to the extreme value estimate based on the experimental data.

RESULTS

Free-decay tests

The hydrodynamic analysis is performed in the frequency domain. This is based on the linear theory, under the assumption of small motions, where a mean position representing the static configuration of the model has to be used as reference in the simulations. Deriving such condition from irregular wave records can be challenging. A first indication on the mean position to use was drawn by referring to the free-decay tests, preliminary carried out in absence of waves. Experimental decay data were available only for the low draft case. The mean trim which better reproduced the free-decay motion time series (in surge, heave and pitch) at that draft was found to be 3.8°, confirming experimental findings which showed a tendency of the model to trim backwards.

To further assess the validity of this floating position, the resulting damping ratio, ζ (-), and natural frequency, ω_0 (rad/s), are also compared with those experimentally determined. In the experimental tests three free-decay realizations have been carried out for each mode of motion. ω_0 and ζ have been derived for each of them and the average value between the three is considered to reduce the uncertainties. With regard to the numerical results, the outcome of the hydrodynamic analysis in *HydroD* including only potential damping is assumed as reference case; from here various possibilities have been tested, such as adding more linear or quadratic damping to account for the drag effect. The best correspondence was achieved by adding some quadratic damping in surge and some linear damping in pitch respect to the reference case. Results are shown in Table I, where also the case of trim = 0° was considered as an alternative.

Table I. Damping ratio and natural frequency in the three modes of motions, from decay tests with trim equal to 0° and 3.8°.

natural frequency (rad/s), ω_0				
		surge	heave	pitch
experimental	1	0.702	3.314	3.329
	2	0.697	3.117	2.884
	3	0.749	3.264	4.287
	mean value	**0.716**	**3.232**	**3.500**
numerical, trim = 0°	potential damping only	0.5956	6.2	6
	potential + viscous term[1]	**0.728**	**6.2**	**6.02**
numerical, trim = 3.8°	potential damping only	0.676	2.67	3.11
	potential + viscous term[1]	**0.73**	**3.19**	**3.32**

damping ratio (-), ζ				
		surge	heave	pitch
experimental	1	0.484	0.194	0.306
	2	0.358	0.196	0.64
	3	0.395	0.196	0.317
	mean value	**0.412**	**0.195**	**0.421**
numerical, trim = 0°	potential damping only	0.0159	0.197	0.146
	potential + viscous term[1]	**0.09**	**0.197**	**0.48**
numerical, trim = 3.8°	potential damping only	0.09	0.017	0.21
	potential + viscous term[1]	**0.15**	**0.2**	**0.31**

[1]Quadratic damping for surge, linear for pitch

The case with trim = 3.8° matches well the experimental results, showing substantial differences only on the surge ζ (see the discussion for more details). Overall, it is considered as the best alternative between the two considered and therefore is taken as first attempt mean position. Nevertheless, the following analysis based on irregular wave tests showed that by assuming 3.8° trim the mooring line tension was significantly overestimated. This is in agreement with the experimental findings. As the main objective of this comparative analysis is to well represent the mooring line tension, it is finally decided to use trim equal to 0° as mean position, which determined more comparable results in terms of tension for all the cases considered (when referring to other drafts too). When assuming 0° trim as mean position a good correspondence is kept on the ζ in heave and pitch, as well as on the ω_0 in surge. ω_0 in heave and pitch get almost the double of the ones experimentally determined instead, while the ζ in surge is still lower compared to the one experimentally determined. This point is further discussed in the sensitivity analysis and discussion below.

Irregular wave tests

From the available experimental database 6 cases have been selected for comparison, including different wave conditions and drafts. All waves have been generated from a JONSWAP spectrum with peak-enhancement factor of 3.3, and $\cos^{2s}$ spreading function with s = 20, representative of long crested waves. All 3 values of drafts have been considered here.

From the numerical simulations 12 different time series each 30 minutes long have been obtained for every case; the experimental results refer to only one realization for each case, also 30 min long. They all refer to steady state conditions. All data are acquired at 20 Hz.

All cases examined refer to a target stiffness of the main mooring line of 460 N/m, as derived from the spring calibration, with a pre-tension of 12 N. However for case 1 the actual stiffness during the tests, derived by plotting the recorded forces against the deformation, was revealed to be 300 N/m. In this case the numerical stiffness was set accordingly to the actually tested value.

As stated above, in all numerical cases the mean pitch is assumed to be zero. During the tank tests the draft actually tested differed from the target value, due to the fact that in dynamic conditions the mean heave was in general lower than zero (especially in the case of large drafts). This phenomenon has also been confirmed in the numerical simulations, and could be explained by the fact that at high and medium drafts the water-plane area becomes very small, providing almost no hydrostatic restoring force in heave; therefore the device tends to get submerged, even though maintaining enough buoyancy to float. In order to reproduce the experimental conditions as much as possible, the draft used in the numerical setup always corresponds to the draft actually measured during the tank testing rather than to the target value.

Table II gives an overview of the test cases, showing incident wave conditions (H_s and T_p) and return period (T_R), as well as values of the target draft (*dr*) and the one actually tested.

The best agreement in the mooring tension between numerical results and experimental data is pursued by varying the quadratic damping of the system in surge, in order to represent the viscous/drag term in addition to the potential damping estimated in hydrodynamic analysis. This is the one significant phenomenon which cannot be accounted for with linear theory indeed. The best correspondence is found for a quadratic damping coefficient Cd^* = 500 kg/m for cases 3 to 6, in which the body is totally submerged in its mean dynamic position. The quadratic damping coefficient can be described by the formula

$$Cd^* = \tfrac{1}{2}\,\rho\, Cd\, Ac \qquad (1)$$

where ρ (kg/m^3) is the water density and A_c (m^2) is the measured projected wet surface normal to the surge direction, which is proportional to the draft of the device (*dr*).

Using Eq. 1, *Cd* (-), which is the surge non-dimensional drag coefficient, can be calculated for cases 3 to 6 (for which Cd^* has been previously determined). Due to this the surge *Cd* for the WD model is found to be 0.726. Based on this value, Cd^* can be estimated also for cases 1 and 2, considering the respective projected wet surface area, resulting to be 357 kg/m.

Table III and Figure 4 are overviews of the results of the statistical and extreme values analyses for all the cases considered, shown respectively in absolute and relative terms. The latter shows the ratio between numerical and experimental results for each case, related respectively to the mean and standard deviation of the tension and to the extreme values of the tension. All results are shown at model scale.

Figure 5 shows the spectral analysis for 3 representative cases, in which the numerical extreme values resulted to be respectively the lowest (a), the highest (b) or very similar (c) with respect to the experimental ones.

Sensitivity analysis

As indicated above the mean floating position is subjected to significant uncertainties, influencing the hydrodynamic parameters. Therefore a sensitivity analysis has been carried out with respect to the draft and trim of the device.

The influence of the mean trim position has already been discussed above. By adding quadratic damping to the system, as representative of viscous term, ω_0 in surge gets closer to the experimental value, being 0.728 rad/s. The surge ζ is also increased to the value of 0.09, however still quite distant from the one experimentally determined during the free-decay test.

With respect to the draft, Figure 6 shows how the normalized hydrostatic restoring force in heave and water plane area vary with it; Figure 7 shows their variation for different trim mean positions; Figure 8 and Figure 9 show respectively variations of the normalized added mass and normalized potential damping in the three modes of motions for different drafts in the frequency domain. The normalizing factors used here are $(\rho \cdot V \cdot g)/L$ for the heave hydrostatic restoring force, $\rho \cdot V$ and $\rho \cdot V \cdot L^2$ respectively for translational and rotational added mass, $\rho \cdot V \cdot (g/L)^{0.5}$ and $\rho \cdot V \cdot L \cdot (g/L)^{0.5}$ for the translational and rotational potential damping; here g (m/s^2) is the gravity acceleration, V (m^3) is the displaced volume and L (m) is a characteristic length, set to 100 m.

Table II. Overview of the tested conditions in each case considered (values at model scale).

case		T_R (y)	H_s (m)	T_p (s)	target *dr* (m)	actual *dr* (m)
1	test06_k300_Cd*357	50	0.173	1.896	0.2	0.2
2	test11_k460_ Cd*357	100	0.201	1.969	0.2	0.2
3	test17+_k460_ Cd*500	10	0.145	1.829	0.24	0.29
4	test27#_k460_ Cd*500	100	0.184	1.896	0.24	0.29
5	test30+_k460_ Cd*500	10	0.167	1.829	0.26	0.34
6	test35+_k460_ Cd*500	50	0.168	1.969	0.26	0.34

Table III. Overview of the results from the statistical and extreme values analyses, in absolute terms (values at model scale).

case			TS mean (N)	TS std (N)	max (5 min dist) (N)	max (30 min dist) (N)
1	test06_k300_ Cd*357	num.	15.60	12.64	58.59	65.25
		exp.	17.21	8.68	67.24	83.39
2	test11_k460_ Cd*357	num.	16.40	18.00	88.24	101.18
		exp.	21.68	16.8	98.95	113.9
3	test17+_k460_ Cd*500	num.	13.48	13.8	68.08	81.01
		exp.	18.98	10.9	67.43	77.79
4	test27#_k460_ Cd*500	num.	13.4	16.4	83.46	97.7
		exp.	24.74	13.8	79.41	88.83
5	test30+_k460_ Cd*500	num.	11.95	12.4	57.31	63.4
		exp.	17.67	10.3	55.89	67.79
6	test35+_k460_ Cd*500	num.	12.24	13.3	61.99	69.05
		exp.	17.45	11.5	65.15	71.36

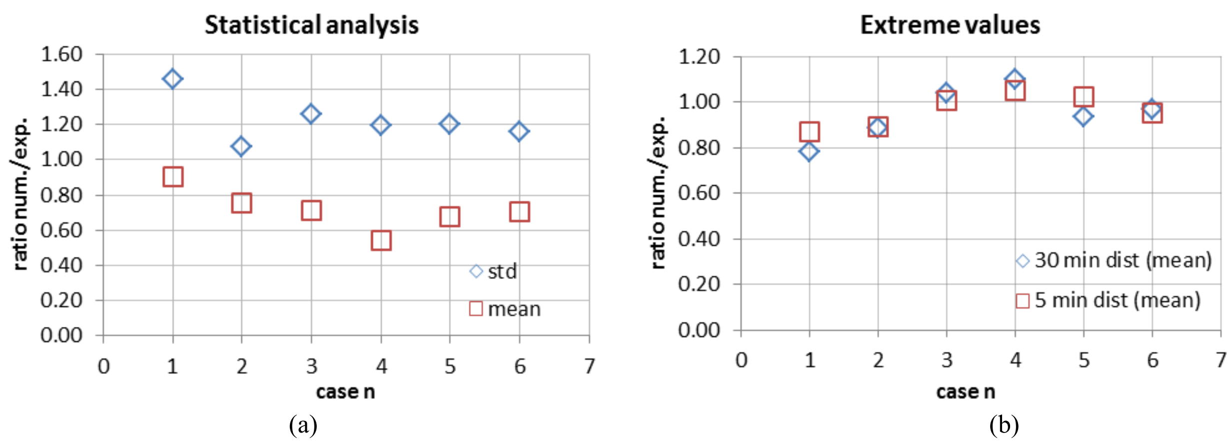
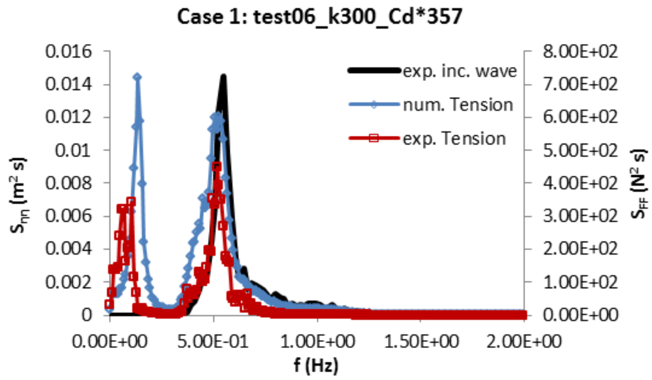
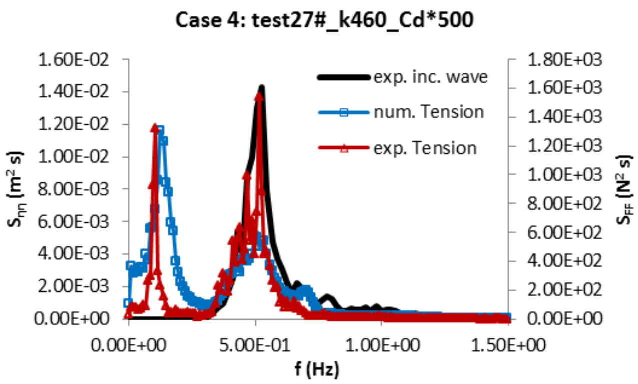


Figure 4. Comparison of mooring line tension obtained as (a) response statistics and (b) extreme values, shown as ratio between numerical and experimental values.



(a)



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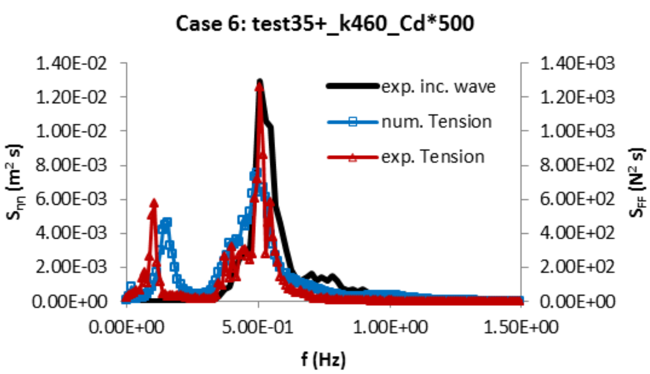

(c)

Figure 5. Results from the spectral analysis showing: experimental incident wave spectrum (η), spectrum of the numerical mooring tension (F) as simulated, spectrum of the experimental mooring tension (F) as measured.

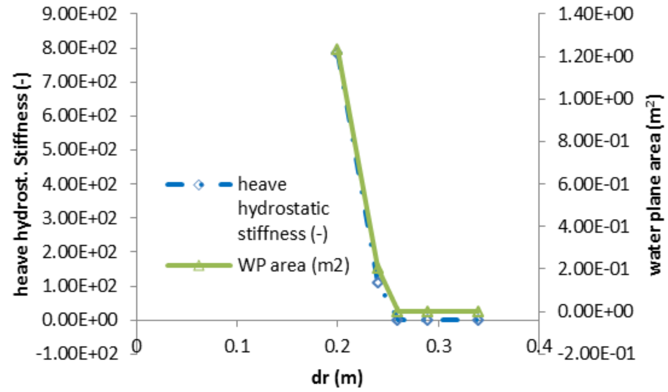

Figure 6. Normalized hydrostatic restoring force in heave and water plane (WP) area for different mean drafts.

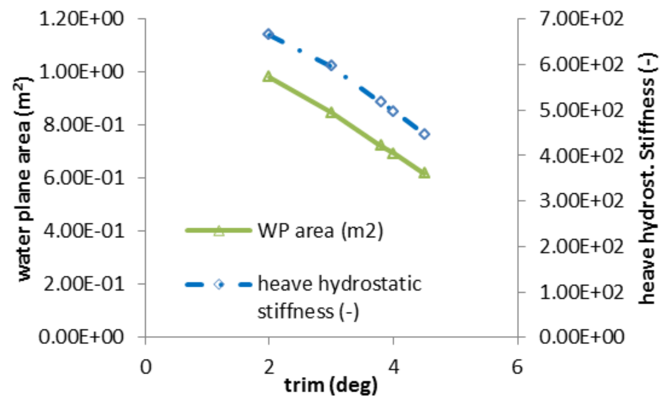

Figure 7. Water plane (WP) area and normalized hydrostatic restoring force in heave for different mean trim static positions.

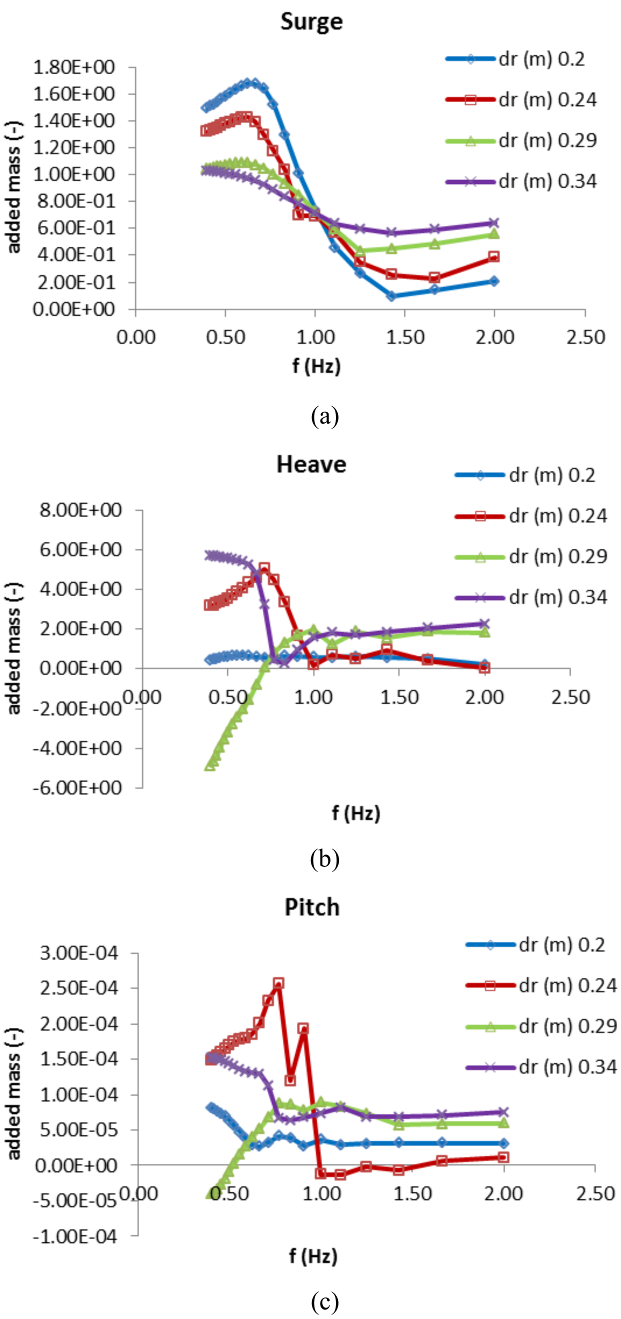

Figure 8. Normalized added mass in surge (a), heave (b), pitch (c) in the frequency domain, for different drafts.

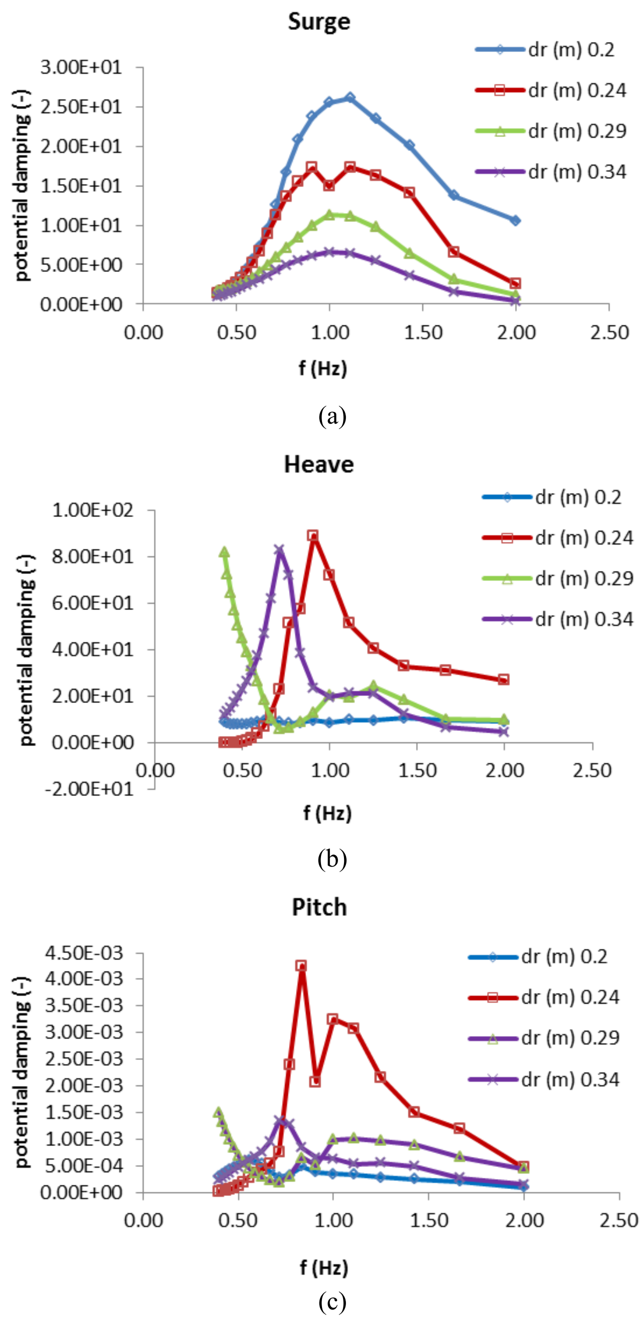

Figure 9. Normalized potential damping in surge (a), heave (b), pitch (c) in the frequency domain, for different drafts.

DISCUSSION

It should be noted that the numerical model is based on the 1st and 2nd order wave forces, while other non-linearities might have been experienced in the tank testing of the model, such as the afore-mentioned water plane area variations.

The statistical analysis shows that in general the mean value is numerically underestimated, while the standard deviation is slightly overestimated, respect to the experimental results. The former can be explained as the increased draft experienced in dynamic conditions, due to the low heave restoring force, might have added some extra pre-tension to the system, whereas in the numerical simulation this did not happen since the target draft was already set as mean position. The mean tension values are however relatively small in absolute terms, so that even small differences from experimental and numerical values are reflected by a large differences in terms of ratio (Table III).

In Figure 5 the low frequency peak in the tension spectrum corresponds to the surge natural frequency of the system, while the higher frequency peak corresponds to incoming wave frequency. The tension spectral analysis shows that the wave frequency regime is very well represented numerically, while in the resonant part a slight shift in the low peak frequency can be observed. However, it is considered the best match achievable due to the uncertainties related to the numerical modeling and experimental results. It's worth mentioning that a great improvement in the correspondence of the low frequency peak was observed as quadratic damping was added to the system, accounting for the 2nd order drag forces (Table I).

The extreme value analysis shows that the numerical predictions are within 80-110% of the experimental values for the 30 min long time series distribution, and within 90-105% on the 5 min long time series distribution (Figure 4b). When 30 min long time series were considered only one experimental realization was available, only one maximum being therefore available for the comparison. By basing the extreme value analysis on 5 min long time series, statistical uncertainty is reduced. Here the number of realizations available for the analysis increased by a factor of 6, allowing respectively 72 numerical and 6 experimental maxima to be used for each case. Moreover, the maxima considered are distributed along the whole time series, not being locally concentrated due to wave groups. Overall, the comparison can be therefore considered more sound.

With regard to the static mean position used, this has revealed to be critical in the analysis. Due to the complex geometry of the device - mainly made of opened-bottom chambers - the distribution of the buoyant elements on the device plays a key role in the determination of the water-plane are A_w. Due to this, even small changes in the model floating position (*dr*) or trim position had a significant influence on the water plane area, A_w. As *dr* was increased to the medium or high level, for which the water free surface was close to or above the top of the buoyant element, A_w dramatically reduced indeed (Figure 6); the same happened when trim occurred (Figure 7), even for small values barely noticeable to the naked eye (e.g. around a 30% decrease in A_w for just 2° trim difference).These variations in A_w in turn affected the hydrostatic stiffness (as $c_{33} = \rho \cdot g \cdot A_w$, being c_{33} the heave hydrostatic stiffness) and, in cases where respectively the added mass and the potential damping were almost constant, also the natural frequency of oscillation ω_0 and the damping ratio, ζ. This is what happened in the case of low draft, which the free-decay tests refer to. In this case both added mass and potential damping in heave, and partly in pitch, were almost constant (Figure 8, 9); this, combined with a significant increase in A_w caused by even small trim differences, determined ω_0 to increase and ζ to decrease. These effects are particularly evident on ω_0 in heave and pitch (Table I).

It is quite difficult to assume univocally one value for the experimental static trim position; this was possibly not exactly 0° all the time, any difference affecting the results by determining an overall lower A_w with the mentioned consequences on ω_0 and ζ.

However, for the sake of mooring tension analysis, the most important mode of motion is surge, which is far less affected by variations in A_w. Due to this, 0° trim could be reasonably assumed since it provided a good overall correspondence on the mooring tension in all the 6 cases considered in the analysis.

Here it also emerged that ω_0 seems to be more important than ζ in characterizing the hydrodynamic behavior of the device; a good correspondence on ω_0, such as the one achieved by adding quadratic damping, allowed to reproduce the experimental response very well indeed, although ζ was still quite different from the one experimentally determined. With regard to this, it has to be mentioned that, being the system highly damped in surge, only a few oscillations were available to estimate ζ both in the experimental and numerical case, increasing the uncertainties related to it.

It has to be mentioned here that a commercial unit of Wave Dragon would be built differently respect to the small scale model considered in this study, which was designed for the purpose of preliminary tank testing only. On a commercial unit the buoyancy elements would be distributed more uniformly throughout the main platform, limiting significantly the hydrodynamic sensitivity to the draft and mean trim position.

It is also worth noting that Wave Dragon is designed so that the added buoyancy provided by closed compartments is enough for it not to sink in any condition, always allowing a minimum R_c. This can be already observed at the model scale, where in order to test the lowest R_c needed for survivability mode some external weight had to be added on top of the platform deck.

Therefore, the only case in which the device can get significantly submerged is by consciously entering the survivability mode in extreme waves. This would be due to the combination of extremely low R_c and dynamic loads originated from very high waves (resulting overall in a low heave restoring force) rather than to a lack of buoyancy. By effect of this, as operational conditions are re-established the device would naturally float back to the desired R_c.

Finally, in figure 8 it can be observed how the added mass in heave and pitch is negative for low frequencies in the case of dr = 0.29 m, while the same is positive for either higher or lower drafts. This phenomenon takes place only as the body has a very low submergence (the total height of the model is 0.28 m) and has been previously described by many hydrodynamic researchers. For a more detailed description, which is out of the scope of this paper, the reader should refer to [8].

CONCLUSIONS AND FURTHER WORK

The hydrodynamic characterization of the Wave Dragon has been carried out. A numerical model has been developed and validated with experimental results derived from tank tests of a small scale model, being ready for future use. Added mass, linear and quadratic damping, hydrostatic stiffness and excitation force have been derived for different drafts.

The numerical results obtained for the tension in the main mooring line are matching very well the experimental ones. The numerical model can be therefore considered well calibrated and reliable for future use.

The validity of these parameters can be extended to larger scale devices as long as a geometrical similarity is maintained; therefore they will be used in the future coupled analysis aimed at designing a suitable mooring for a 1.5 MW Wave Dragon to be deployed in Hanstholm, at the DanWEC test site.

A deeper understanding on the hydrodynamic behavior of Wave Dragon is also a result of this study, especially with regard to the influence of its static mean position on the natural frequency of oscillation, the damping ratio and hence the mooring line tension. Results are in agreement with previous experimental findings, and will be very valuable for the implementation of the control strategy on large-scale devices.

Future work will include the use of the software *SIMO/Riflex* to analyze the response of the Wave Dragon to environmental and mooring loads for extreme wave conditions at the DanWEC deployment site. Different mooring layouts will be assessed and the best option chosen based on criteria of reliability and economic feasibility.

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REFERENCES

[1] Frigaard P., Hald T. *Forces and Overtopping on 2nd generation Wave Dragon for Nissum Bredning*. Hydraulic and Coastal Engineering Laboratory, Aalborg University. Technical Report. Phase 3 project, Danish Energy Agency. Project no: ENS-51191/00-0067

[2] Soerensen H. C., Friis-Madsen E. *Sea Testing and Optimisation of Power Production on a Scale 1:4.5 Test Rig of the Offshore Wave Energy Converter Wave Dragon*. Final Technical Report, PROJECT N°: NNE5-2001-00444, CONTRACT N°: ENK5-CT-2002-00603.

[3] DanWEC – Danish Wave Energy Center, Hanstholm c/o Hanstholm Havneforum, http://www.danwec.com

[4] Riflex Manual. http://www.sintef.no/Home/Marine/MARINTEK/Software-developed-at MARINTEK/RIFLEX/

[5] Parmeggiani S., Kofoed J.P., Friis-Madsen E. *Extreme Loads on the Mooring Lines and Survivability Mode for the Wave Dragon Wave Energy Converter*. Proceedings from the World Renewable Energy Congress, 2011.

[6] DNV GeniE User Manual, program version 5.3.

[7] DNV HydroD user manual – program version 1.1-01,2004.

[8] Newman J.N., Sortland B., Vinje T. *Added Mass and Damping of Rectangular Bodies Close to the Free Surface*. Journal of Ship Research, Vol. 28, No. 4, Dec. 1984, pp 219-225.