

Mooring system analysis of multiple wave energy converters in a farm configuration

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Abstract

Like all other floating structures, wave energy converters (WECs) need to be kept in position by station-keeping systems in order to realize its functionality and ensure its safety. A compliant mooring system is normally applied and survivability is the main concern for mooring system design. However, WECs based on relative motions impose special requirements on their mooring systems to ensure that they do not affect the energy capture significantly. The purpose of this study is to investigate possible mooring systems for the FO3 WEC which extracts wave energy based on the principle of relative motions between a platform and multiple point absorbers. The study focuses on the survivability of the mooring system for one WEC and for multiple WECs in a farm configuration under extreme environmental conditions. Coupled time-domain simulation of the mooring system for a single WEC is used and compared with the frequency-domain analysis. An integrated mooring system for nine WECs connected by lines is designed and the dynamic behaviour of the whole system in random seas is analyzed by the time-domain method. Based on the analyses of configurations investigated, it is found that the individual mooring is more feasible than the integrated mooring.

Keywords: Hydrodynamic modelling, mooring system, time-domain simulation, wave energy converter

1 Introduction

Station-keeping systems are required for floating structures to limit the excursion and orientation of the structures under the action of environmental forces due to waves, currents and wind. Depending upon the principle for providing the restoring force, a station-

keeping system can be a passive (e.g. a mooring system), an active (e.g. a dynamic positioning (DP) system) or a combined active-passive system (e.g. a thruster-assisted mooring system). From an economic point of view, compliant mooring systems are much cheaper and more frequently applied. They are also most relevant for floating WECs.

In the offshore oil and gas industry, design codes for mooring systems already exist, such as DNV OS-E301 [1], API RP-2SK [2] and ISO 19901-7 [3]. Ultimate design check is normally considered. If the structure is moored for 5 years or more, fatigue limit state should be considered. Design check also includes a check when one mooring line fails due to abnormal causes. However, there is no specific design code for mooring systems of wave energy converters. A guideline [4] on applying the existing codes to design and operation of WECs has been published by DNV and Carbon Trust. However, the potential risk associated with mooring failure is lower for WECs, which are normally unmanned. Using the same safety factor on mooring lines as for offshore oil and gas platforms might be too conservative. More work need to be done for choosing a suitable safety level. Industry experiences are valuable and needed for developing such codes.

Some researchers have already pointed out key issues related to mooring system design for wave energy converters, see [5], [6] and [7]. A design approach for WEC moorings is also described in [8, 9]. One of the key design considerations is to maintain the position of the WEC under extreme loading conditions, while allowing efficient conversion of wave energy in operational conditions. Since mooring system could be quite different for motion-dependent and motion-independent WECs, the focus in this paper is motion-dependent WECs.

Various types of mooring systems are envisaged and used for floating structures, including catenary line and taut-line systems, see Fig. 1. In addition, clump weights or buoys can be attached to mooring lines.

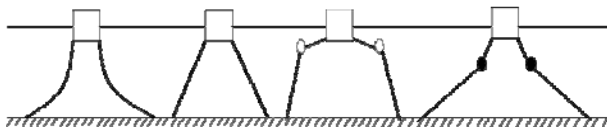


Figure 1: Types of mooring systems (from left: catenary line, taut-line, taut-line with buoys and taut-line with clump weights)

Possible designs of mooring systems for WECs have been discussed in [7] in terms of configurations, components and anchors.

A catenary line system usually consists of chain links and relies on the weight of links or clump weights if attached, to provide horizontal restoring force. If no clump weight is used, a very long mooring line of chain links must be considered to obtain adequate flexibility. Hence, this concept might not be suitable in shallow waters. Moreover, catenary line systems will certainly induce vertically downward loads. This could limit the allowable deck loads for WECs.

A taut-line system is composed of wire or synthetic ropes and is normally highly pre-tensioned. As a result, taut-line systems are usually quite stiff both in horizontal and vertical directions and can significantly reduce vertical motions of the WEC if connected to the sea bottom directly. This feature is certainly not acceptable for a motion-dependent WEC.

In order to limit the influence of mooring systems on vertical motions, the top part of mooring lines, which is directly attached to the WEC, should be kept as horizontal as possible. In such cases, buoys can be attached as shown in Fig. 1. In this configuration, the buoy is attached to the sea bottom by a vertical taut-line and connected to the WEC horizontally. However, in order to provide enough horizontal stiffness to avoid large offset of the WEC, large-volume buoys must be applied.

Many different types of floating wave energy converters have been introduced since the 1970s. A point absorber is the simplest concept, where a strong coupling between mooring systems and WEC motions might be expected since the size of a point absorber is relatively small. The effect of catenary line systems on the surge, heave and pitch motions of a point absorber has been studied in [10, 11]. It was shown that the mooring system can be designed to make its influence on the wave energy absorption small or even such that the energy capture increases as compared with a freely floating absorber. In addition, mooring systems will also introduce a strong damping effect on WEC motions, see [12, 13], which is important to consider for estimating the energy absorption in a realistic manner.

In order to increase the amount of absorbed wave energy, many point absorbers might be grouped and attached to a large-scale floating platform. The WEC considered in this paper is the FO3 WEC, which extracts wave energy based on the relative motions between a platform and twenty-one point absorbers. Heaving plates are installed on the columns of the platform to limit the vertical motion. The mooring

system needs to be designed to have as little influence as possible on platform motions when the WEC is in operation. Considering the relatively large size of the platform as compared with a single point absorber, it is not desirable for mooring system to increase power capture by providing a phase shift. The survivability is the most important issue for mooring design. The wave power capture efficiency is achieved by selecting suitable number and size of point absorbers.

In addition, a system shut-down will be activated in severe sea states. Point absorbers are therefore held in a fixed position or set to move freely along the guide. In the second case, an end stopper must be installed in order to avoid the possibility of impact between the platform and the point absorbers. In this paper, all point absorbers are considered fixed relative to the platform for survival conditions, and the mooring system should survive under the extreme loads acting on the whole system.

Another important issue is related to the farm design. A farm of multiple WECs is normally needed, considering the advantage of smoothing power production based on an appropriate configuration to reduce intermittency and sharing infrastructures to lower the average cost. One issue is what the costs related to mooring lines, electricity cables and anchors will be. Installation of the mooring system including anchors is very costly. However, as shown in [14], the cost of anchor installation depends on the number of anchor points. Therefore, it is preferable to share as many anchors as possible for multiple WECs. A starting point for identifying the system with minimum costs is to study the dynamic behaviour of individual WECs and an integrated system of multiple WECs which are linked together with mooring lines.

This paper deals with wave-induced response of a single and multiple WECs by using both the frequency- and time-domain methods.

2 Methods of mooring analysis

Mooring analysis method has been widely used for floating structures in the offshore oil and gas industry, see [15]. A brief description of the methodology is given herein. As shown in Fig. 2, a moored floating structure will encounter mean forces induced by waves, currents and wind, as well as dynamic loads including the first-order wave forces and the slowly varying wind and wave forces. As a result, both the vessel motion and mooring line tension would have a mean static component plus wave frequency (WF) and low frequency (LF) dynamic components. LF responses are mainly due to the resonance of the whole moored structure. These responses can be predicted by mooring analysis in the time domain or in the frequency domain.

In frequency-domain analysis, the motion response is normally first predicted. Then the tension induced by the motion at the fairlead of mooring lines is estimated. Normally, the stiffness of the mooring system is linearized and used in the LF vessel motion analysis. The damping due to the taut mooring lines considered

herein might be neglected in the frequency-domain analyses both for WF and LF vessel motions.

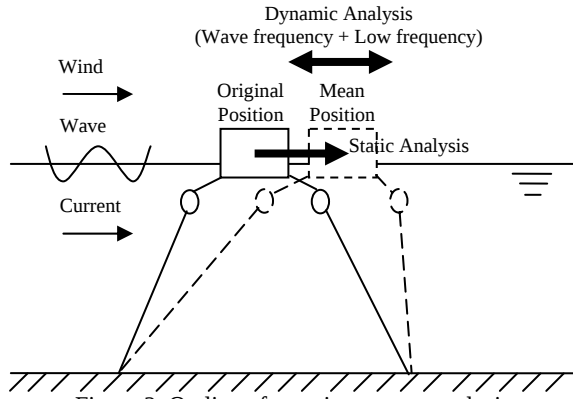


Figure 2: Outline of mooring system analysis

However, the time-domain method considers the vessel and all mooring lines as a whole system and solves both motion and tension responses simultaneously. All effects from the mooring system can be modelled directly. It is usually called a coupled mooring analysis [15]. We focus on the time-domain analysis in this paper.

Mean forces acting on the WEC are wind, current and mean wave drift forces.

Drag-type forces (see Eq. (1)) are used for estimating the mean wind and current forces, based on the evaluation for each component of the platform and the point absorbers. This would result in conservative estimates of the forces.

$$F = \frac{1}{2} \rho * A_e * C_d * V^2 \quad (1)$$

where ρ is the density of air (or sea water), A_e is the exposed area of the component, C_d is the drag coefficient and V is the wind (or current) speed.

Mean wave drift force in irregular sea states are calculated based on the frequency-dependent wave drift coefficients, see Eq. (2).

$$F_{WD} = \int_0^{\infty} 2C_{WD}(\omega) * S(\omega) d\omega \quad (2)$$

where $C_{WD}(\omega)$ is the wave drift force coefficient and $S(\omega)$ is the wave spectrum.

First-order wave forces acting on the vessel are usually calculated by using a hydrodynamic code. HydroD [16] is used in this work. It uses WAMIT [17] as a core approach for hydrodynamic analysis. Rigid-body motions are assumed and linear potential theory is applied. Frequency-dependent excitation, added mass and potential damping forces are obtained.

Slowly varying wave forces are applied herein based on the Newman's approximation [18], by which the quadratic force transfer function is generated only by the diagonal terms, i.e. the frequency-dependent mean wave drift force coefficients. Similarly, the constant (i.e. the frequency-independent) wind force coefficients are applied in the present study to model the slowly varying wind forces.

In a coupled mooring analysis, a static equilibrium is first found by a nonlinear static analysis considering only the mean environmental forces. Mean offset and mean mooring line tension are then obtained. Next, the motion of the vessel and the mooring line tension are solved simultaneously under the dynamic wave and wind forces using an appropriate time-integration scheme. DeepC [19] is used for time-domain mooring analysis, while the frequency-domain code, MIMOSA [20], is also used for comparison.

3 The FO3 wave energy converter

The FO3 wave energy converter considered herein is proposed by the Fred Olsen Company. This WEC consists of a four-column platform and up to twenty-one surface-piercing point absorbers. Each cylindrical column of the platform has a submerged heaving plate to provide damping effect. Each point absorber can move along the vertical guide and generates electricity. The WEC model is shown in Fig. 3. The dimensions of columns and point absorbers are also illustrated.

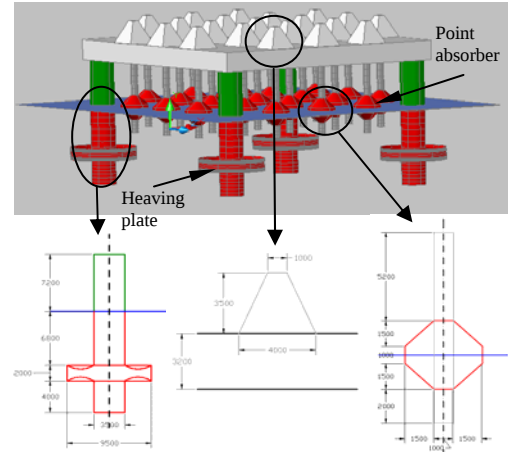


Figure 3: The FO3 WEC model (dimensions in mm)

The WEC has a total mass of 1320 tons, with a platform mass of 1017 tons and a mass of 14.4 tons for each point absorber. The overall length and breadth of the platform are both 36 m and the draft is about 12.8 m. More information of the WEC can be found in [21].

4 Modelling of mean environmental force

Steady wave, wind and current forces as well as first and second-order wave forces have been considered.

The model of current loads has been partly validated by comparison with model tests performed at Marintek, see [22]. This comparison is made for the platform with ring pontoons and listed in Table 1, where the empirical formula uses Eq. (1) to calculate the force with a drag coefficient of 1.0.

In general, the empirical formula overestimates the current load by 20-40%. It also implies that the drag coefficient of 0.75 should be used instead of 1.0 if the empirical formula is applied.

Although the structural components of the present WEC with heaving plates is different from the WEC

with ring pontoons used in the model tests, the empirical formula with a drag coefficient of 0.75 is used in the following analysis. The drag coefficient is chosen herein for the whole structure. A more refined model by considering the force on each component and by accounting for the interaction between components could be pursued in further investigations.

Table 1: Comparison of current load (in kN) between model test and empirical formula for the WEC with ring pontoons (where the relative error means the ratio of the difference between the results of empirical formula and model test to the result of model test)

Current velocity (m/s)	Direction	Model test	Empirical formula ($C_D=1.0$)	Relative error ¹⁾
1.5	Dir. 0	300	423	41%
	Dir. 45	580	753	30%
2.0	Dir. 0	375	475	27%
	Dir. 45	700	844	21%

1) The empirical formula gives larger values.

Moreover, the model of mean wind forces is also based on Eq. (1) and the drag coefficient is simply taken as 1.0.

5 Hydrodynamic modelling for survival conditions

When the mean environmental forces and responses have been determined, the hydrodynamic loads and responses are calculated. The focus herein is the survival condition, which is important for the design of the mooring system. In survival conditions, the wave energy absorption mechanism is assumed to be inactive and the point absorbers can be fixed to the platform either at the still water level or up to the platform deck, see Fig. 4, or let free to move. However, end stoppers would then be needed.

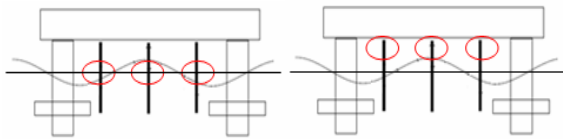


Figure 4: Definition of the location of point absorbers (Left: Condition 1 - fixed at the still water level. Right: Condition 2 - fixed up to the platform deck)

In the hydrodynamic analysis, a water depth of 70m is used and a linear wave theory in shallow water is applied. Heave and pitch motions of the platform are the most relevant quantities for analysis since they are directly related to the wave energy absorption. Natural periods for these two modes are listed in Table 2.

Table 2: Natural period (in s) for heave and pitch motions of the platform without mooring system

	Heave	Pitch
Condition 1	6.2	10
Condition 2	13	55

It is noted that the natural periods of both heave and pitch motions are very low when the point absorbers are fixed at the still water level. This is consistent with the fact that the point absorbers increase the water plane areas and therefore increase the hydrostatic stiffness for both heave and pitch modes and lead to a decrease in natural periods. For instance, the heave natural period is 6.2s as calculated by

$$T_N = 2\pi \sqrt{\frac{M + A}{K}} \quad (3)$$

where M , A and K denote the mass, added mass and hydrostatic stiffness, respectively.

Moreover, the vertical position of the centre of gravity of the platform is decreased by moving the point absorbers down to the still water level. This also causes an increase in the stiffness of the pitch motion since the metacentric height increases.

However, a realistic sea state contains waves with a period of 5s-25s (i.e. wave frequency of 1.26rad/s to 0.25rad/s). An example of JONSWAP wave spectra are shown in Fig. 5.

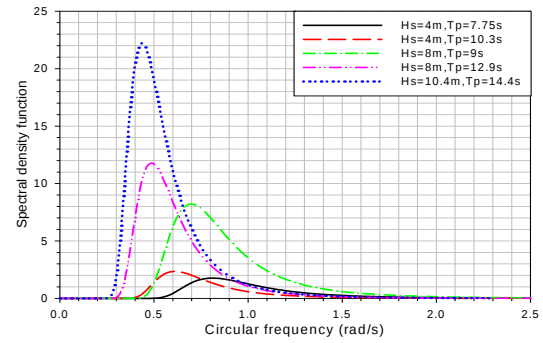


Figure 5: JONSWAP wave spectra of different sea states (where H_s and T_p represent the significant wave height and the spectral peak period, respectively)

Floating structures are normally designed so that the natural period of motion is outside of the range of wave energy to avoid possible resonance. Therefore, it should be noted that the WEC in Condition 1 will experience strong motion resonance since both natural periods of heave and pitch motions are close to wave periods. This is not acceptable for the WEC in the survival condition. Therefore, in the following mooring analysis for survival conditions, we consider only the situation when the point absorbers are fixed up to the platform deck, i.e. Condition 2 in Fig. 4. Moreover, this condition also implies reduced surge forces.

Heave and pitch motion response amplitude operators (RAOs) are obtained for these two locations of point absorbers, see Figs. 6 and 7, respectively. The present study uses a single-body hydrodynamic analysis, while the hydrodynamic analysis based on the generalized modes developed by Taghipour and Moan [21] is also included for comparison. The single-body analysis and the generalized-mode analysis show similar hydrodynamic properties of the WEC. As shown in Fig. 6, strong resonance occurs in the pitch mode when the point absorbers are fixed at the still water level. When the point absorbers are fixed out of

water, the natural period will increase due to smaller stiffness and be away from the waves with most of the energy.

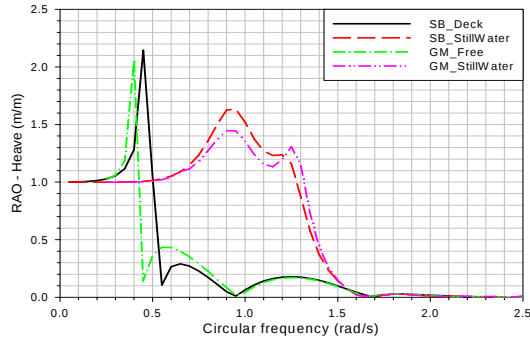


Figure 6: Heave motion RAO of the platform (Dir. 0) (In the figure, SB and GM represent the single-body and the generalized-mode analysis, Deck and StillWater denote that the point absorbers are fixed up to the platform deck and at the still water level, respectively and Free means that the point absorbers can freely move along the guides.)

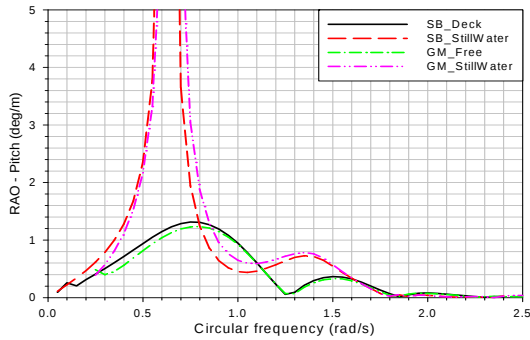


Figure 7: Pitch motion RAO of the platform (Dir. 0)

In reality, the motion of the platform also depends upon the damping mechanism, including potential damping (radiation damping), viscous damping and power take-off damping. The potential damping of the WEC is relatively small and in the survival condition, there will be no damping due to power take-off. The viscous damping on surge or sway motion is easy to model since the cross-section of the columns are circular. However, for heave and pitch (or roll) motions, the viscous effect is very difficult to quantify due to the presence of heaving plates along the platform columns. Experimental study is usually carried out. Herein, the effect of viscous damping on, for example, heave motion RAO is studied by assuming 5%, 10% and 30% of critical damping, see Fig. 8. It is clearly shown that the viscous damping has an important effect at the resonance of heave motion, while at higher frequencies, the effect is limited. A damping coefficient of 10% of critical damping is chosen in this study.

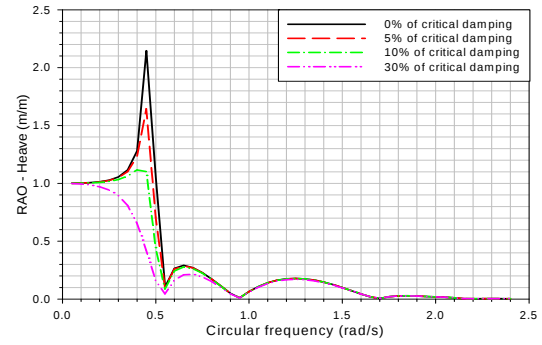


Figure 8: Heave motion RAO of the platform considering different level of viscous damping (Dir. 0)

6 Mooring analysis of a single WEC

A mooring system for a single WEC is illustrated in Fig. 9. Four polyester mooring lines with attached buoys have been considered. The fairlead of each mooring line is located at the bottom of each column of the WEC. This might not be preferable since large bending moment could occur at the column-deck connection due to mooring line loads. If this is a concern for structural design of the platform, the fairleads of mooring lines could be located at a point higher up on the columns.

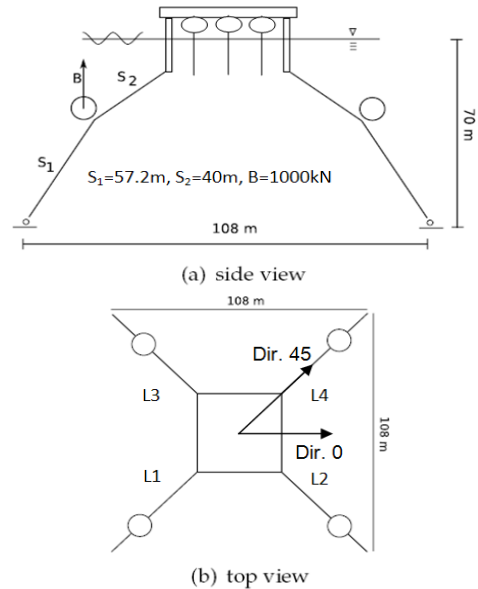


Figure 9: Mooring system configuration for a single WEC

A water depth of 70m is considered. The length of mooring lines and the size of the buoy are also shown in Fig. 9. Two environmental directions are considered and waves, currents and wind are assumed collinear.

Two sea states are defined in Table 3, one corresponds to the operational condition and the other is the survival condition. The survival condition used herein is severe and in reality, metocean data related to the site of consideration needs to be collected and a sea state with a return period of 100 years can be obtained and used in the mooring analysis.

Table 3: Environmental sea states

	Hs (m)	Tp (s)	Mean wind speed (m/s)	Current velocity (m/s)
Env. 1	4	7.75	10	0.5
Env. 2	10.4	14.4	29	2

Mooring analysis is carried out using both the frequency-domain (F-D) and time-domain (T-D) methods, where the F-D analysis does not consider the effect of mooring system on WF motion responses and the mooring stiffness is linearized for LF motion responses. The comparison of these two methods in terms of surge, heave and pitch motions is made in Table 4. Only the operational condition (Env. 1) is listed herein. Standard deviation and 1-hour extreme values are shown.

Table 4: Comparison of dynamic motions of the WEC based on the T-D and F-D analyses (where the F-D results are shown in parentheses)

Env. 1		WF std.	1-h WF max	LF std.	1-h LF max	1-h total max
Surge (m)	Dir. 0	0.33 (0.31)	1.27 (1.15)	0.30 (0.21)	1.04 (0.70)	2.05 (1.57)
	Dir. 45	0.23 (0.22)	0.71 (0.80)	0.23 (0.18)	0.95 (0.58)	1.33 (1.16)
Heave (m)	Dir. 0	0.16 (0.15)	0.62 (0.57)	0.003 (NA)	0.025 (NA)	0.62 (0.57)
	Dir. 45	0.15 (0.15)	0.48 (0.53)	0.004 (NA)	0.025 (NA)	0.48 (0.53)
Pitch (deg)	Dir. 0	1.07 (0.98)	3.76 (3.61)	0.48 (NA)	1.55 (NA)	4.44 (3.61)
	Dir. 45	0.62 (0.57)	2.20 (2.09)	0.40 (NA)	1.48 (NA)	2.30 (2.09)

There is no significant difference in motion responses, especially not in WF heave and pitch motions, obtained by the F-D and T-D methods. It means that the F-D method can be used for mooring analysis in the operational condition and the mooring system does not affect the motion behaviour of the WEC. This is because the wave- and wind-induced dynamic motions of the WEC in the operational conditions are limited and the stiffness and damping of the mooring system are too small to affect the WEC motions.

However, in the survival condition, the pitch motion will be strongly influenced by the mooring system. This is because the windward mooring lines will be more stretched when mean environmental force becomes larger in severe sea states, and the contribution to the total stiffness increases. As shown in Fig. 10, the natural frequency in pitch increases with the stiffness of the mooring system.

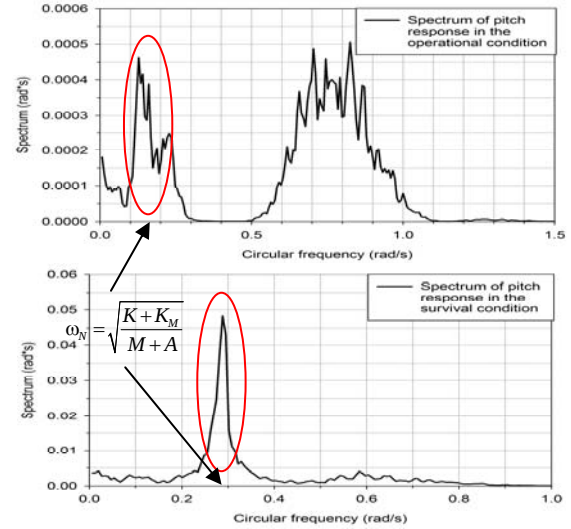


Figure 10: Comparison of pitch motion spectra in the operational and survival conditions (Dir. 45) (where ω_N is the natural frequency in pitch and K_M is the stiffness of the mooring system)

Mooring line loads in both the operational and survival conditions are mainly induced by the surge (or sway) motion of the platform, which is not important for wave energy absorption. As an example, the spectra from the T-D analysis for surge motion and tension of the mostly-loaded line in survival condition are plotted in Fig. 11. Similar frequency components are observed. WF responses dominate in this case, but slowly-varying components also show in both responses. However, in lower sea states, depending on mooring configuration, LF response might be dominating.

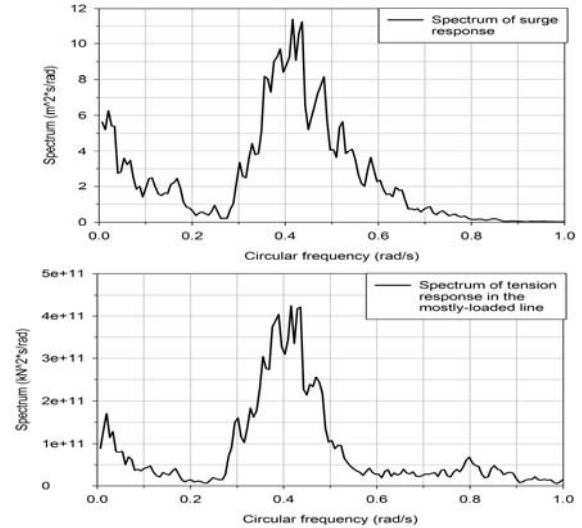


Figure 11: Comparison of surge motion spectra and mooring line tension responses (Env. 2, Dir. 45)

Mooring line tension behaves differently in the operational and survival conditions. In Fig. 12, time series of mooring line tension are shown for these two conditions. Compared with the operational condition, the tension in the survival condition is highly nonlinear due to stretching of mooring lines. Higher values of

skewness and kurtosis are also expected for tension in these conditions, which implies higher extreme values. This also indicates that the F-D method will underestimate the extreme tension in the survival condition since a linearized mooring system is usually applied in the F-D analysis.

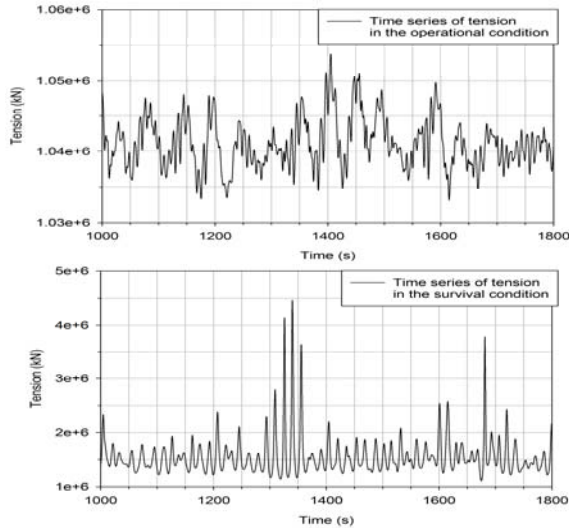


Figure 12: Comparison of tension time series in the mostly-loaded line in the operational and survival conditions (Dir. 45)

In order to reduce the possible stretching of lines, mooring systems should be designed to be soft even in the survival condition. A sensitivity study has been carried out, which assumes different horizontal position of anchors defined in Fig. 13. The sensitivity of the surge motion and mooring line tension to the mooring configuration are shown in Table 5, in terms of 1-hour extreme values. Increasing the footprint of anchors from 54m to 126 m could decrease the extreme tension by 50%. Hence, it is preferable to increase the footprint of anchors in order to reduce the size of buoys in the mooring system.

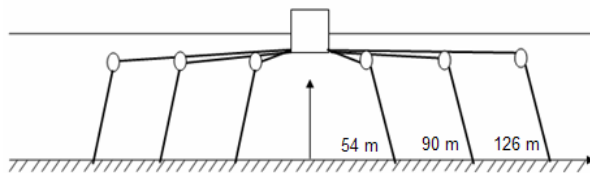


Figure 13: Definition of horizontal position of anchors

Table 5: Comparison of surge motion and mooring line tension with different horizontal position of anchor

Env. 2 Dir. 45	Buoyancy=1000 kN		Buoyancy=500 kN	
Position of anchors	1-h max surge (m)	1-h max tension (kN)	1-h max surge (m)	1-h max tension (kN)
54 m	20.4	3312	24.4	8455
90 m	21.0	2143	26.2	5804
126 m	21.1	1878	26.7	4460

7 Time-domain mooring analysis of nine WECs in a farm configuration

An analysis of moored multiple WECs is carried out based on an integrated configuration where nine WECs are linked by horizontal mooring lines and connected by vertical lines to the sea bottom through buoys, see Figs. 14 and 15. The horizontal distance between two adjacent WECs is equal to 72m, i.e. two times the length of the WEC. The distance between two adjacent anchors is 108m. This is the same distance for anchoring the single WEC. The length of mooring lines and the size of buoys are similar to those used for the single WEC.

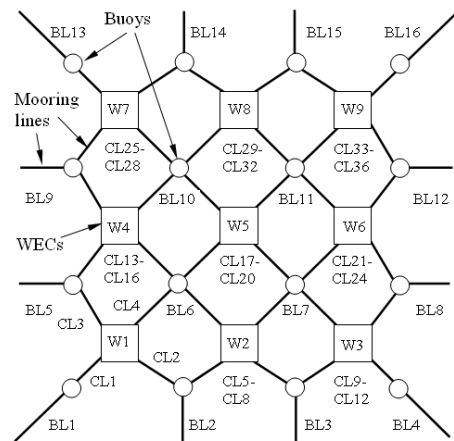


Figure 14: Mooring system configuration for a farm of 3*3 WECs (top view)

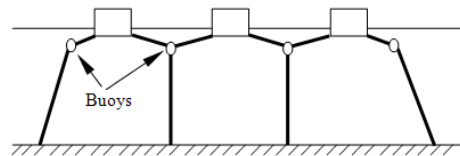


Figure 15: Mooring system configuration for a farm of 3*3 WECs (side view)

In Fig. 14, all WECs and mooring lines are numbered. For such a mooring system grid, time-domain simulation is the only available tool. In the following analysis, only the results of selected WECs and mooring lines are compared with the results for the single WEC.

The environmental loads acting on the WECs in the farm are calculated without accounting for the effect of upstream platforms on the downstream ones. For instance, diffracted and radiated waves due to the presence of the upstream platforms are not considered as a part of incident waves to the downstream ones. However, the correct phasing between the dynamic responses of the WECs due to waves is considered in the mooring analysis. Moreover, conservative estimates of mean current and wind forces are expected by neglecting this interaction effect.

The analysis of the operational condition shows that there is no big difference in the heave and pitch motions of the WECs in this farm configuration as

compared with the responses for a single WEC. For example, the heave motion spectra in the operational condition for one WEC and three typical WECs in a farm configuration are plotted in Fig. 16. The differences in the frequency component and in the motion variance are limited. Therefore, in terms of motion characteristics, it is not different if the WECs are moored individually or in a group.

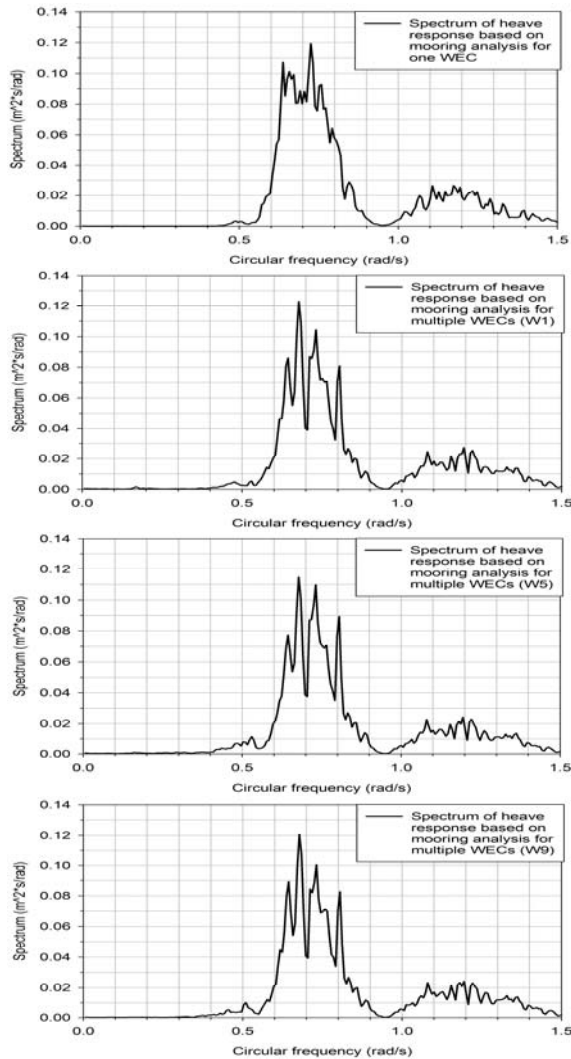


Figure 16: Comparison of heave motion spectra for single WEC and different WECs in the farm configuration (Env. 1, Dir. 0)

However, in the survival condition, large mooring line tension in horizontal lines is observed (see Fig. 17) due to a contribution at high frequencies and the reason is clarified that when the dynamic motions of two adjacent WECs caused by waves with a certain wave length have a phase difference of 180 degrees (see Fig. 18), large mooring loads can be induced in the horizontal lines associated with the relative opposite WEC motions.

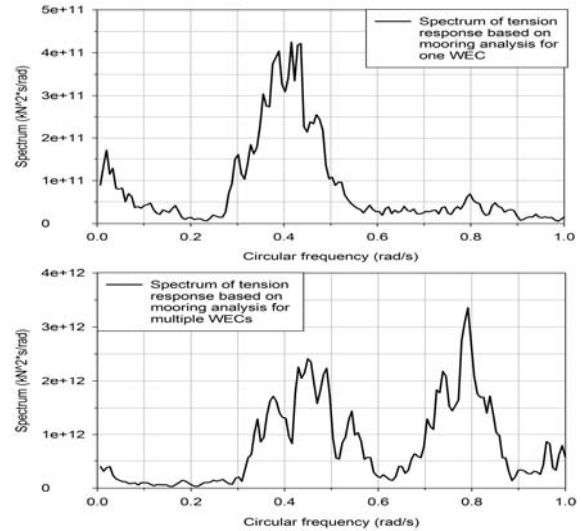


Figure 17: Comparison of tension spectra based on mooring analyses for one WEC (L1 in Fig. 9) and multiple WECs (CL17 in Fig. 14) in the survival condition (Env. 2, Dir. 45)

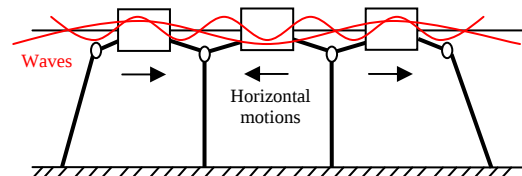


Figure 18: Illustration of relative horizontal motion between two adjacent WECs

This kind of phenomenon is unique for the WECs moored in a farm configuration and sharing horizontal lines. We do not observe such situation in the tension analysis of the single WEC, since no mooring line is used to link two WECs. It is also found that extreme mooring line tension in the horizontal lines is larger than that in the vertical lines. The 1-hour extreme tension in the mostly-loaded line in the farm configuration is about two times the extreme tension in the mooring system for one WEC. A large capacity of mooring lines might be required in order to carry these loads.

However, if the WECs are connected by mooring lines of sufficient length or attached with clump weights instead of buoys, the mooring line tension can be reduced as long as the first-order horizontal relative motions are not restricted by the connecting lines. However, one should also simultaneously consider the mean environmental forces on the WECs inside the farm which have to be carried by these lines.

8 Conclusions and recommendations about future work

Considering the restrictions imposed on the mooring system design by relatively shallow water conditions, small footprint of anchors and working principle of the WEC, a taut-line mooring system with buoys is analyzed for the FO3 WEC. A single WEC and a farm of nine WECs have been analyzed by means of coupled time-domain simulation tools.

The main findings in the study of the mooring system for a *single WEC* are as follows.

- Hydrodynamic properties of the platform are sensitive to the location of the point absorbers in survival conditions. Strong resonance might occur when the point absorbers are fixed at the still water level. However, when the point absorbers are fixed out of water, the natural period will increase due to smaller stiffness and be away from the waves with most of the energy.

- Analysis of mooring system using buoys shows that heave and pitch motions in the operational condition are not influenced by the stiffness of mooring system. However, since the damping effect due to power take-off is not modelled herein, the motion characteristics of the WEC would be different if this effect is considered. In the survival condition, large dynamic pitch motions are observed when the mooring stiffness contributes significantly to the total stiffness of the pitch mode.

- Mooring line loads in both operational and survival conditions are mainly induced by the surge (or sway) motion of the platform.

- Viscous damping due to heaving plates along the platform columns is important to decrease the platform heave and pitch motions in severe sea states since other damping mechanisms are limited.

- A sensitivity study of mooring configuration suggests to increase the footprint of anchors in order to reduce mooring line dimensions and buoy size.

- The frequency-domain method can accurately predict the motion and tension responses in the operational condition, while it will underestimate the responses in the survival condition.

The following conclusions can be made from the analysis of *nine WECs moored in a farm* configuration.

- In the operational condition, there is no big difference in terms of heave and pitch motions for a single WEC and for multiple WECs moored in a farm. However, the radiation and scattering effect due to hydrodynamic interaction between the WECs is not considered herein. This could change the motion characteristics of the WECs in the farm.

- Large mooring line tension in horizontal lines is observed when the dynamic motions of two adjacent WECs caused by waves with a certain wave length have a phase difference of 180 degrees. In such a case, the demand on mooring line capacity might be very high. Therefore, the individual mooring is more feasible than the integrated mooring system. However, increasing the line length and using clump weights can reduce the tension of mooring lines in the farm.

There are still many *remaining challenges* related to mooring system of this particular structure and WECs in general.

- The primary design principle for floating structures is to choose the natural period away from main wave input periods to avoid resonant motions. Further design study needs to be done to optimize the size of the platform with this issue in mind.

- Viscous damping will play an important role on motion responses in survival conditions and a refined analysis of viscous effect is needed.

- The mooring system considered in this paper is very expensive due to large buoys. The performance of other mooring system layouts, for instance, using clump weights, need to be studied.

- Only extreme response is considered in this paper. In reality, fatigue damage also needs to be considered, especially in mooring lines and mechanical components of the energy absorption system.

- Cost evaluation of a WEC system needs to be analyzed considering mooring systems including mooring lines and anchors, together with other systems, like mechanical and electrical systems. The final goal is to reduce the cost per kwh considering the life cycle of the WECs.

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