PRELIMINARY DESIGN AND ANALYSIS OF MOORING BUOY FOR AN ARRAYED WEC PLATFORM

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ABSTRACT

This paper presents preliminary design results of a mooring buoy and arrayed Wave Energy converter (WEC) platform producing a total rated power of 1.0 MW. The single point mooring buoy system is configured to moor the WEC platform and buoy itself for the various environmental conditions of design operating, extreme and survival. The system considers permanent connection of the platform to the buoy with hawsers during the service life. The buoy will have a weathervaning capability to allow the WEC platform to rotate 360 degrees around the buoy toward the incident wave directions, which enables consistent power generation. The power produced in the platform is transferred to shore with a cable through the buoy. The platform with V-shape configuration consists of two long slender leg structures with 120 degree opening leg angle. Each leg structure is a truss-shape structure with pontoons, braces, rotors, generators, hydraulic pipes and other appurtenances. Fully coupled simulations of the buoy and WEC platform were carried out for the design load cases to evaluate the dynamic responses of the buoy and platform. The results were validated with the ABS design requirements.

Keywords: Mooring Buoy, Weathervane, Single Point Mooring, Wave Energy Converter, Arrayed WEC, Wave Energy Device, Floating Energy Platform

INTRODUCTION

There are various types of ocean energy platforms that generate power from waves, currents and tides. Among these, Wave Energy Converter (WEC) devices are highly varied in their designs and technologies but can be broadly classified according to the energy capturing method (Titah-Benbouzid and Benbouzid, 2015; Uihlein and Magagma, 2016) such as point absorber, submerged pressure differential, attenuator, oscillating surge, overtopping and oscillating water column (OWC). However, the majorities of these energy conversion devices are stand-alone floating systems and their energy harvesting performances are highly dependent on the wave directionality, water depth and mooring methods. The existing floating energy devices are also primarily focused on the energy capturing device and the mooring design is considered secondary. However, the mooring system is an integral part of the floating energy harvesting system and can improve the overall power production capacity.

There are few concepts proposed to install multiple WEC devices on a single floating energy platform with a long V-shape structure. Pecher et al. (2012) uses Salter's Ducks as rotors whereas Kelley et al. (2013) adopts OWCs to the corresponding V-shape platform. These systems utilize a single point mooring method.

In this study, we are involved in developing a mooring buoy and a multiple arrayed WEC platform composed of two leg truss type structures forming a V-shape. Power production performance of this WEC platform is improved by adopting a weathevaning mooring buoy. Various weathervaning CALM buoys have been applied very successfully over many decades in the oil and gas sectors to moor a vessel and offload oil or gas liquids (Cozijn and Bunnik, 2004; Cozijn et al., 2005; Ryu et al., 2006; Song et al., 2014).

However even though the CALM buoy mooring technology is mature, the buoy to date is only utilized for oil or gas transfer. Thus, the objective of the present study is to develop a 360-degree weathervaning buoy system, to moor the arrayed WEC floating platform. The produced electrical power will be transferred via power cable to shore through the buoy. This paper covers the preliminary design results of the weathervaning buoy and arrayed WEC platform system. The buoy mooring system consists of stationary and rotating parts to allow the WEC platform to weathervane around the buoy. The buoy is moored with six mooring lines whereas the platform is moored with two hawsers to the buoy.

The WEC platform comprises two hull legs making a V-shaped structure platform. Each leg supports ten WECs along the leg longitudinal directions so that a total of 20 WECs are installed to the platform: Total power production is 1.0 MW. The platform is considered to be a truss-type structures. Numerical simulations are carried out to evaluate the performances of the mooring system and WEC platform, under the colinear environments but the non-colinear cases will be studied in the following year studies. The mooring system designs are assessed with ABS design criteria.

DESIGN CONDITIONS AND REQUIREMENTS

Metocean Conditions

The WEC platform will be installed to the west offshore of Jeju Island, South Korea at a water depth 80m. Metocean conditions for the wave dominant events is presented in Table 1. Two different operating conditions are considered: normal design operating (DOC) and 1-yr operating (DOC 1-yr). Design Extreme Condition (DEC) considers a return period of 50-yr but 100-yr condition is used for the survival condition (SVC). The associated surface currents and winds to the dominant wave events are determined from each independent event using the factors recommended in API 2MET (2007). The irregular waves are presented with JONSWAP spectra. The currents and winds are at the surface and 10 m above the surface, respectively.

Table 1 Metocean Conditions (Wave Dominant)

Wave Dominant	Hs (m)	Tp (s)	Gamma	Current (m/s)	Wind (m/s)
Operating (DOC)	2.0	6.65	2.2	0.40	6.0
Operating (DOC 1-yr)	5.74	10.81	2.2	0.95	19.38
Extreme, 50-yr (DEC)	9.72	13.98	2.2	1.07	41.24
Survival, 100-yr (SVC)	11.32	15.10	3.0	1.14	45.99

Mooring System Design Criteria

The Design Load Cases (DLCs) considered in the buoy and WEC platform response analysis are based on the guidelines in ABS FPI (2013), API 2SK (2005) and SPM Rule (2013). Codirectional environments are assumed. The mooring system design shall comply first with the requirements specified by ABS FPI (2013), API RP 2SK (2013) and ABS Guidance (2011) as the WEC platform and mooring buoy shall stay connected even during the extreme and survival storm events, except the disconnected cases for the platform maintenance. Design life of the mooring systems is 25 years. The Factors of Safety (FoS) of the mooring and hawser lines are summarized in Table 2 and Table 3, where the FoSs are for the dynamic analysis of the mooring lines. In addition, Single Point Mooring (SPM) design requirements of mooring lines and hawsers shall be complied with ABS SPM Rule (2014) as the buoy mooring can be considered as a SPM. Table 4 summarizes the design requirement of the SPM buoy mooring. When the platform is disconnected (buoy alone, SPM mooring case), 100-yr condition is DEC for the buoy mooring.

Table 2 Mooring Line Safety Factors (WEC Platform Connected)

Design Conditions	Mooring Conditions	Platform-Buoy	Analysis Method	FoS
50-yr (DEC)	Intact	Connected	Dynamic	1.67
	One Broken Line (at New Equilibrium Position)	Connected	Dynamic	1.25
	One Broken Line (Transient)	Connected	Dynamic	1.05
100-yr (SVC)	Intact	Connected	Dynamic	1.05

Table 3 Mooring Hawser Safety Factors (WEC Platform Connected)

Design Conditions	Hawser Conditions	Platform-Buoy	Analysis Method	FoS
DOC	Intact (One Line case)	Connected	Dynamic	1.67
	Intact (Two or more lines case)	Connected	Dynamic	2.5

Table 4 Single Point Mooring Line Safety Factors

Design Conditions	Mooring Conditions	Platform-Buoy	Analysis Method	FoS
DOC	Intact	Connected	Dynamic	3.0
100-yr (DEC)	Intact	Unconnected	Dynamic	2.5

MOORING BUOY AND WEC PLATFORM CONFIGURATIONS

Mooring Buoy

The weathervaning mooring buoy consists of turn table, buoy hull with skirt, fairleads, main bearings, power cable swivel (slip ring), power cable connectors and Appurtenances. In this study, various mooring buoys were sized and configured but one of them was finally selected for the present analysis, based on the preliminary results of the buoy responses and mooring tensions of each buoy option. The particulars and 3D shape of the buoy selected are shown in Table 5 and Figure 1. The details of the buoy components in the figure are not presented due to intellectual properties. The buoy has a single diameter hull with skirt at the keel of the buoy hull. There is a moon pool with a diameter 1.0 m used for the power cable.

Table 5 Mooring Buoy Particulars

Displacement	tonnes	467.7
Height overall	m	6
Draft	m	4
Hull diameter	m	12
Moonpool diameter	m	1
Skirt diameter	m	16

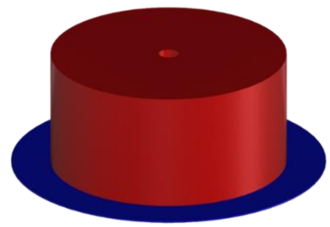

Figure 1 Weathervaning Buoy (Buoy Hull and Skirt)

Mooring Line Properties

A total of 6 lines with 500 m long each were selected, based on the pre-analysis of various mooring combinations. The mooring lines consist of three groups of two lines with 10-degree separation between lines in the same group. Properties of the mooring and hawser lines are shown in Table 6. Each mooring line consists of a single chain system. Pretension of each mooring line is 251 kN. A proper corrosion allowance was applied to the nominal diameter of the chain for the present mooring strength analysis. Two synthetic ropes of a 50 m long each were used for hawsers.

Table 6 Mooring and Hawser Line Properties

Items	Unit	Mooring Line	Hawser
Type	-	R4 studless	Synthetic rope
Diameter	mm	111	227
Dry Weight	tonnes/m	0.246	0.035
MBL	kN	11,856	17,261
Length	m	500	50
No. of Lines	-	6	2

Arrayed WEC Platform and WEC Type

The arrayed WEC platform with a rated power of 1.0 MW consists of various main components: two truss type hulls (pontoons, brace members, appurtenances), twenty WEC assemblies (rotor, pump, shaft), four generators and electrical equipment, marine systems, power cables between WECs, hawser fairleads and power cable connector, as illustrated in Figure 2. The platform particulars are summarized in Table 7

A cylinder type rotor (WEC) with a rotating center off its center was considered in this study, but other rotor configuration like Salter's duck is also being studied. The rotor has been designed by another working group of the present study. Each rotor is designed to generate 50 kW under the design waves of Hs 2 m and Tp 6.65 s (Table 1).

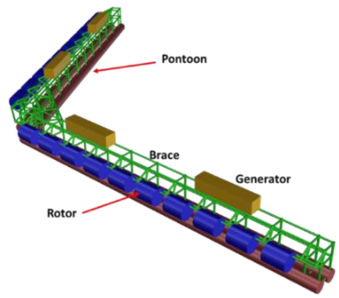

Figure 2 Arrayed WEC Platform Configuration

Table 7 WEC Platform Particulars

Total Power Rate	MW	1.0
Displacement	tonnes	2,800
Draft	m	5.8
Platform Leg Length (each)	m	86.0
Platform Height	m	8.8
Pontoon Length (each)	m	86.0
Diameter	m	2.8
Spacing (c-c)	m	4.0
Numbers per leg	ea	2
Generator: Length per Unit	m	14.0
Numbers per leg	ea	2
Rotor Diameter	m	5.0
Length	m	5.0
Numbers per Leg	ea	10
Angle Between Legs	deg	120

NUMERICAL MODELING AND MOORING LAYOUTS

Mooring and WEC Platform Layouts

The coordinate reference origin is located at the buoy center on the mean waterline. The origin is depicted in the mooring layout (Figure 3), where the mooring line numbers (ML# 1 ~ 6) are presented. Separation angle between lines in the same group is 10° so that angle between groups is 120°. Figure 4 shows also the layouts of mooring buoy, WEC platform, mooring lines and hawsers (green lines) along with the power cable (red lines). All headings are referred to the direction which the wave/wind/current flow.

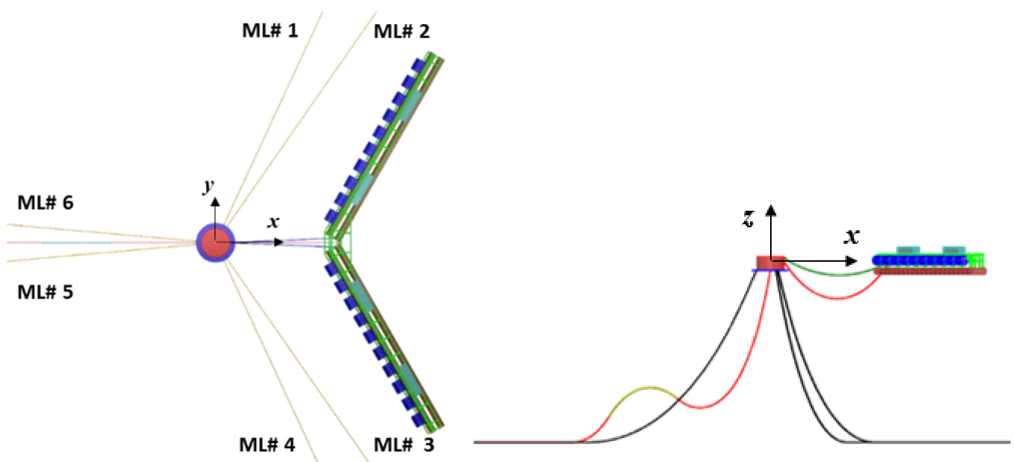

Figure 3 Buoy and WEC Platform Layouts (2-D)

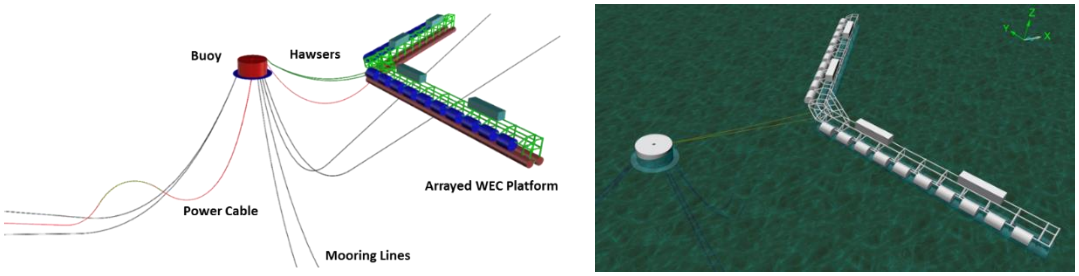

Figure 4 Buoy and WEC Platform Layouts (3-D)

Hydrodynamic Coefficients

The complex truss-shape WEC platform was split into two parts for hydrodynamic modeling purposes; primary member with relatively large dimensions and secondary member (small braces). Panel meshes were generated only for the primary members. Potential based hydrodynamic coefficients estimated with WAMIT were imported to Orcaflex model for the analysis. But the small braces were included in the Orcaflex model as Morison elements. In this numerical model, the viscous effects of the primary members were also presented by implementing Morison elements. Here the drag contributions of the primary members only were taken into account as the added masses were included in the WAMIT results.

Wind forces of the WEC platform were estimated using ABS FPI (2013) and the longitudinal and lateral force coefficients (CFx and CFy) are presented in Figure 5. But the mooring buoy wind effects were neglected in the present study due to small windage area compared to the WEC platform. Current forces were modeled with Morrison elements, instead of inputting current force coefficients to the numerical model. These coefficients will be calibrated further with the results of the model tests.

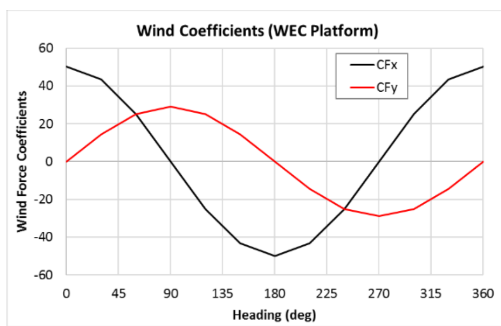

Figure 5 Wind Force Coefficients of WEC Platform

NUMERICAL RESULTS AND DISCUSSIONS

Restoring Forces

Restoring forces of the entire mooring system of the buoy estimated at three directions of 0°, 90° and 180° are compared in Figure 6. The offset directions of 0° and 90° are toward the +x and +y axis directions as presented in Figure 3. Nonlinear behaviors of the mooring stiffness are seen at the higher offsets (excursions).

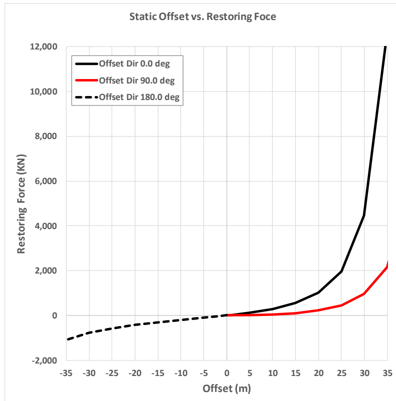

Figure 6 Mooring Buoy Restoring Force Curves

Free Decay Simulations of Mooring Buoy

Free decay simulations of the mooring buoy with the mooring lines were conducted for surge, heave and pitch and the results are presented in Figure 7. Here the simulations were the cases that buoy was disconnected to the WEC platform. Table 8 summarizes the natural periods of the mooring buoy, estimated from the decay results.

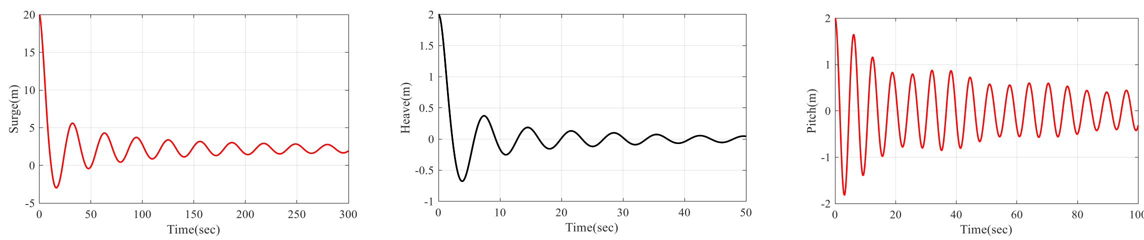

Figure 7 Mooring Buoy Surge Decay Time Histories

Table 8 Natural Periods of Mooring Buoy

Motion	Period (sec)	Frequency (Hz)
Surge	31.2	0.032
Heave	7.1	0.141
Pitch	6.4	0.156

Motion and Tension RAOs

Motion and mooring tension RAOs of the mooring buoy and WEC platform were estimated using white-noise waves with Hs 4.0 m. Due to the weathervaning platform around the buoy, a single heading of zero degree (0^o) was selected for these simulations.

Figure 8 compares the motion RAOs of surge, heave and pitch for 0^o heading. Here “Coupled” or “Buoy only” represents the buoy-platform connected or disconnected buoy to the platform. The surge motions of the buoy-platform connected show similar responses to each other due to coupled effects by connection. However, the heave motion RAOs of the buoy indicate that the buoy is most likely decoupled to the platform whether the buoy is connected or disconnected to the platform. This effect is clearly seen near the platform heave resonance. As shown, the pitch responses of the connected buoy are, however, strongly coupled to the platform over the wave periods up to about 20 seconds. Also, the disconnected buoy pitch resonance period is shifted to the platform pitch period due to the coupled effects.

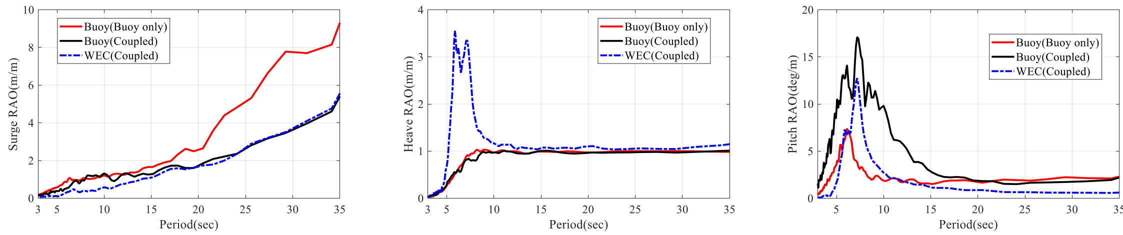

Figure 8 Surge, Heave and Pitch Motion RAOs: Disconnected and Connected Buoy to WEC Platform Cases, Heading 0º

Figure 9 compares the mooring line and hawser tension RAOs for the connected and disconnected buoys. Here mooring line M#6 (or #5) which was the most loaded line under the wave heading 0º, was selected. The mooring line tension RAOs of the connected buoy are greater than the values of the unconnected case due to coupling with the platform. Both case RAOs increase as the wave period increase. The hawser tension responses (H#2) show much different behaviors from the mooring line tensions. Stronger effects in the wide range of wave periods up to around 20 seconds exist due to the influence of the platform motions.

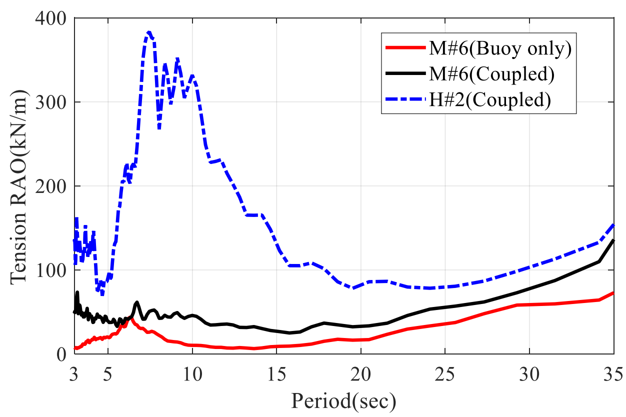

Figure 9 Mooring Line and Hawser Tension RAOs: Unconnected and Connected Buoy to WEC Platform Cases, Heading 0º

Mooring Buoy Motions

Numerical simulations were run for 3 hours each case excluding an initial ramp time for the environment heading of 0º. The wind, wave and currents were assumed con-directional. The maximum values of motions and tensions were estimated using Rayleigh extreme method. For the mooring line damage case, mooring line ML #5 which was the most loaded line in the 0º heading was assumed damaged. A mooring line sudden failure was excluded in the present study but will be considered in the future work. Motions of the buoy and WEC platform were measured at the buoy origin (0, 0, 0) and platform leg intersection location on mean waterline, respectively.

Mean, standard deviation (STD), maximum values of excursions, heave and pitch of the mooring buoy connected to the WEC platform are summarized in Table 9 and Table 10. It is observed that the excursions for the extreme and survival conditions exceed 50% of the water depth (WD). There are significant motions in heave and pitch of the buoy under the extreme and survival events due to the connected platform effects. These will be further investigated with modifications of the mooring buoy and WEC platform configurations in the following year work.

Table 9 Buoy Excursion (Platform-Buoy Connected)

Design Condition	Mean (m)	STD (m)	Max (m)	%WD
DOC	5.7	1.4	12.1	15.1
DOC (1-yr Operating)	18.5	2.4	29.6	37.0
DEC (50-yr Extreme, Intact)	22.5	3.4	38.5	48.2
DEC (50-yr Extreme, Damage)	28.2	3.4	44.0	55.0
SVC (100-yr Survival, Intact)	23.3	3.8	40.9	51.2

Table 10 Buoy Motions (Platform-Buoy Connected)

Design Condition	Heave			Pitch		
	Mean (m)	STD (m)	Max (m)	Mean (deg)	STD (deg)	Max (deg)
DOC	-0.2	0.3	-1.7	0.8	4.1	21.1
DOC (1-yr Operating)	-0.5	1.1	-5.7	3.6	7.5	40.3
DEC (50-yr Extreme, Intact)	-0.7	2.1	-10.7	7.4	7.2	42.6
DEC (50-yr Extreme, Damage)	-0.2	2.2	-10.6	11.2	7.0	45.8
SVC (100-yr Survival, Intact)	-0.6	2.5	-12.4	9.1	7.4	45.5

WEC Platform Motions

Maximum heave and pitch motions of the platform connected to the mooring buoy are summarized in Table 11. In general, the heave motions are greater than the values of the buoy, but the pitch motions are smaller than the buoy motions. However, the platform pitch exceeds 30º except during the design operating condition (DOC). As such, the modifications of the platform configuration are recommended to avoid the excessive motions in the extreme sea states to minimize the damages to the rotors.

Table 11 Platform Motions (Platform-Buoy Connected)

Design Condition	Heave			Pitch		
	Mean (m)	STD (m)	Max (m)	Mean (m)	STD (m)	Max (m)
DOC	-0.2	1.2	-6.0	0.4	3.5	17.5
DOC (1-yr Operating)	0.1	2.2	10.6	0.8	6.1	30.3
DEC (50-yr Extreme, Intact)	0.6	3.1	15.4	1.4	7.0	35.6
DEC (50-yr Extreme, Damage)	0.6	3.1	15.5	1.4	7.1	35.7
SVC (100-yr Survival, Intact)	0.7	3.3	16.7	1.6	7.0	35.5

Mooring and Hawser Line Tensions

Tensions at the fairlead of the mooring and hawser lines were summarized in Table 12 and Table 13. It is shown that the mooring lines and hawsers comply with the design requirements for the considered DLCs except the mooring line damage case under 50-yr extreme event. According to the hawser results, there is an opportunity to optimize the hawser size.

Table 12 Buoy Mooring Tensions (Platform-Buoy Connected)

Design Condition	Mean (kN)	STD (kN)	Tmax (kN)	FoS (est.)	FoS (req.)
DOC	305	29	459	22.3	3.0
DOC (1-yr Operating)	646	289	2,168	4.71	3.0
DEC (50-yr Extreme, Intact)	1,024	947	5,832	1.75	1.67
DEC (50-yr Extreme, Damage)	1,926	2,110	12,330	0.83	1.25
SVC (100-yr Survival, Intact)	1,159	1,179	7,049	1.45	1.05

Table 13 Hawser Tensions (Platform-Buoy Connected)

Design Condition	Mean (kN)	STD (kN)	Tmax (kN)	FoS (est.)	FoS (req.)
DOC	67	90	536	32.2	2.50
DOC (1-yr Operating)	361	504	2,916	5.92	2.50
DEC (50-yr Extreme, Intact)	717	1,127	6,352	2.72	(1.67)
DEC (50-yr Extreme, Damage)	750	1,242	6,960	2.48	(1.25)
SVC (100-yr Survival, Intact)	851	1,436	7,973	2.17	(1.05)

SUMMARY AND RECOMMENDATIONS

Preliminary design and analysis of a weathervaning buoy to moor the arrayed WEC platform were completed. The buoy was designed to accommodate the power cable to transfer the power from the platform to shore. Also the platform was configured to install multiple WECs to harvest the energy from the waves up to 1.0 MW. The platform has a V-shape hull with two truss hull legs with 120º leg open angle and configured with various components of rotors, generators and structural members. DLCs for the analysis were taken considering that the buoy and platform stay connected even during the storm events.

Uncoupled and fully coupled analysis of the buoy and platform were performed for the sea states of operating, extreme and survival conditions. Significant coupling effects to the heave and pitch of the buoy were observed in the extreme and survival conditions. It was also seen that there were considerable motions of the platform in storm seas. The preliminary designs of the buoy mooring and hawser lines were validated with ABS requirements.

The responses of the buoy will be further assessed in following studies with modifications of the buoy and mooring configurations, along with platform shape optimization to take the smaller wave loadings and implementation of platform motion dampening structures.

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