Hydrodynamic Response of Mocean Wave Energy Converter in Extreme Waves

J.A. Samuel[1], V. Venugopal[2], C.H. Retzler[3], Q. Ma[4]

Abstract— **The design of moored floating wave energy converters (WECs) must take into account extreme responses and mooring line loads in order to ensure their survival and continued wave power generation in the ocean environment. This study focuses on Mocean Energy's Blue Horizon C1 hinged raft WEC and aims to provide a better understanding of its hydrodynamic characteristics in survival wave conditions. To achieve this, a physical model study was conducted on a Froude scale of 1 in 50 at the FloWave Ocean Energy Research Facility, University of Edinburgh. The experiments involved the use of NewWaves focusing of crest and trough at the model hinge location, as well as long crested irregular waves. Motion responses of the fore and aft bodies of the WEC were measured using a Qualisys camera, and single component load cells were used to measure the forces in the 3-point catenary mooring lines. The hydrodynamic characteristics of the WEC were evaluated in terms of response amplitude operators and non-dimensional mooring line loads. Results indicate that the fore and aft bodies of the WEC exhibit similar motion responses, except for the pitch motion. The aft body has a pitch response 2 to 3 times higher than the fore body. Concerning the moorings, the wave load on the mooring line in line with the wave direction was found to be higher than the other two mooring lines which were arranged at an angle to the wave direction. The results will provide insight into the behaviour of the Mocean device in survival wave conditions and will aid with the determination of appropriate design parameters for optimal performance and survival in the ocean environment.**

Keywords— **Hinged raft WEC, Motion responses, Mooring line loads, NewWaves.**

I. INTRODUCTION

AS global energy demand continues to grow, transitioning toward sustainable and renewable energy sources is more pressing than ever. Climate change has urged humanity to mitigate its adverse effects by reducing greenhouse gas emissions and increasing the use of renewable energy resources (IPCC, 2018). Wave energy, a form of ocean energy, has gained significant attention due to its potential to meet these goals and contribute to energy resilience by providing a diversified energy mix (Falcão, 2010).

The world's oceans are vast and powerful, holding immense potential to generate renewable energy from waves (Falnes, 2007). Wave energy converters (WECs) have been developed to harness this potential, with a wide range of designs and configurations available (Cruz, 2008). Research in wave energy has grown steadily, advancing our understanding of wave energy resource characterisation, WEC device optimisation, and the development of efficient energy conversion systems.

Despite progress in wave energy research, ensuring that WEC devices are robust and able to withstand extreme wave conditions, known as survival wave conditions, remains critical. Extreme wave conditions, characterised by high wave heights, long wave periods, and wave steepness, present significant challenges to the successful operation of wave energy technologies. Encounters with extreme wave events may result in structural damage, diminished power performance, or even the catastrophic failure of WECs. Consequently, a comprehensive understanding of the hydrodynamic response of WECs under extreme waves is imperative to ensure their longevity and survivability in real-world marine environments (Holthuijsen, 2007).

Early research into WECs began with the introduction of pioneering concepts, such as Salter's Duck (Salter, 1980), which presented a unique approach to harnessing wave energy through a hydraulic system driven by the motion of the Duck's curved upper surface rising and falling while the flat lower surface remained stable. Falnes (2002) expanded on this foundation by providing a

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comprehensive introduction to various WEC types, including hinged rafts, and discussed their potential benefits and drawbacks.

This study focuses on a particular WEC known as Mocean Energy's Blue Horizon C1 (hereafter 'Mocean Blue Horizon C1') hinged raft WEC. The Mocean hinged raft WEC uses a floating hinged raft with asymmetric hulls to convert the motion of waves into electrical power. The WEC features wave channels that project into the wave flow, and an electromagnetic generator located at the hinge converts the relative motion of the hulls into power. The investigation of the hydrodynamic characteristics of the Mocean hinged raft WEC is conducted through experimental means, aiming to ensure its survival and continued wave power generation in the ocean environment. Additionally, this study aims to support the validation of numerical models for WECs.

In the year 2012, Pelamis Wave Power (PWP) developed the Pelamis P1 and P2 machines (Yemm et al., 2012), which were among the first grid-connected WECs and provided valuable insights into the practical implementation of hinged raft WECs. These machines featured a series of cylindrical segments connected by hinged joints that allowed relative motion, converting wave energy into mechanical energy. McNatt and Retzler (2020) evaluated the motion responses and power generation of the M100 Mocean WEC with and without power take-off (PTO) damping. It was found that the inclusion of PTO damping eliminates the sharp resonant peaks. Caio et al. (2021) studied the motion responses of the M100 Mocean WEC subjected to regular waves through experimental study and found that the motion responses of fore and aft bodies behave the same except for pitch response.

The primary objective of this study is to fill in the research gap of understanding the hydrodynamic response of hinged raft WEC subjected to extreme wave conditions by examining the motion responses and mooring line loads when the WEC is subjected to long crested irregular waves and NewWaves, with wave crest and trough focusing at the model hinge location. Employing experimental methods, this investigation seeks to enhance our understanding of the WEC's behaviour and performance under extreme wave conditions, ultimately informing the design, optimisation, and deployment of wave energy converters. Moreover, the experimental results derived from this study will provide valuable data to support the validation and improvement of numerical models for this type of WECs, thereby contributing to the development of accurate and reliable simulation tools. The details of the experimental model setup and methodology, including the properties of the Mocean hinged raft WEC, wave characteristics, and results and discussion are reported in the following sections.

II. Experimental Investigation

A. *Test facility*

A comprehensive experimental study was conducted in the FloWave facility in Edinburgh, which has a diameter of 25 meters and a depth of 2 meters. The facility is equipped with an annular wave-generating ring, comprising 168 independently controlled wave paddles, each driven by individual electric motors. These paddles operate in a hinged mode to generate regular, irregular, multi-directional and focused waves. The control signal is generated by a personal computer, which controls the servo actuator to operate the wave paddle. This same computer is used for data acquisition from wave gauges, Qualisys cameras, and load cells through an amplifier. The generated wave is dissipated on the other end through an active wave absorption system using wave paddles.

B. *Test model*

A scale model of 1:50 was employed to investigate the extreme motion and mooring line load responses of the Mocean Blue Horizon C1 hinged raft WEC (refer to Fig. 1). The WEC consists of two tubular hulls, both featuring wave channels at their ends, with the forward hull having a notably wider channel. The hulls are connected by a nacelle, which houses a low-friction ball bearing serving as a free hinge with a horizontal axis perpendicular to the long axes of the two hulls. In accordance with the proposed survival strategy of deactivating the PTO system under extreme conditions (i.e., allowing the hinge to move freely), the model did not include a PTO. Mechanical end-stops limited the hinge rotation to ±120°. Qualisys targets were integrated into the hulls for motion capture purposes. The model was fabricated primarily using 3D-printed ABS plastic, enhanced by carbon-fiber sheet reinforcement. Ballast in the form of dense lead metal sheets could be strategically placed using a bolt arrangement beneath each channel for trim correction.

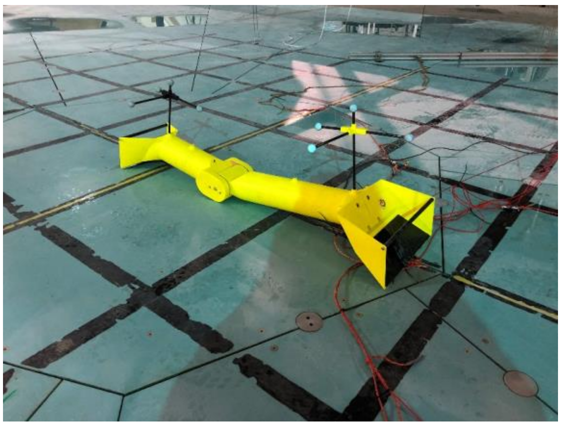

Fig. 1. The view of the Mocean Blue Horizon C1 hinged raft WEC.

The WEC was moored using a three-leg catenary system featuring synthetic ropes that connected ground chains to an attachment point on the model, situated just behind the forward wave channel. The ropes were evenly spaced at 120° intervals around an 8-meter diameter mooring circle.

Two lines extended to the sides of the model, while a third line extended in front of the model, aligned with the principal direction of the incoming incident waves, which were always arranged to propagate from the south and parallel to the long axis of the WEC. Steel hooks secured each line to a fixed structure at the bottom, and the lines were connected to the model via individual carabiners clipped to a stainless-steel ring located at the lower edge of the forward wave channel. The ropes exhibited high compliance, and some pretension was applied to orient the operating point towards the incident wave direction.

C. *Instrumentation*

There are 12 wave gauges (WGs) used to measure the wave surface elevation in FloWave while calibrating the incident waves without the Mocean hinged raft WEC. The details of WG locations during the test runs without the model are given in Fig. 2. The NewWave tests are calibrated by focusing on WG4 (0.81 m, 0 m), which is placed at the model hinge location. Relative to the wave paddle, WG4 is located 11.69 m away. During the test runs with the WEC present, all WGs except WG1 and WG7 are moved 1.5 m away from the centreline of the test facility to avoid interference with the model movements (see Fig. 3). The layout of the wave gauges shown here was used for measuring directional waves, however, directional wave results are not included in this paper. Also, the mooring lines are fitted with single axis load cells, and the Qualisys camera is used to capture the six degrees of freedom responses of the Mocean model.

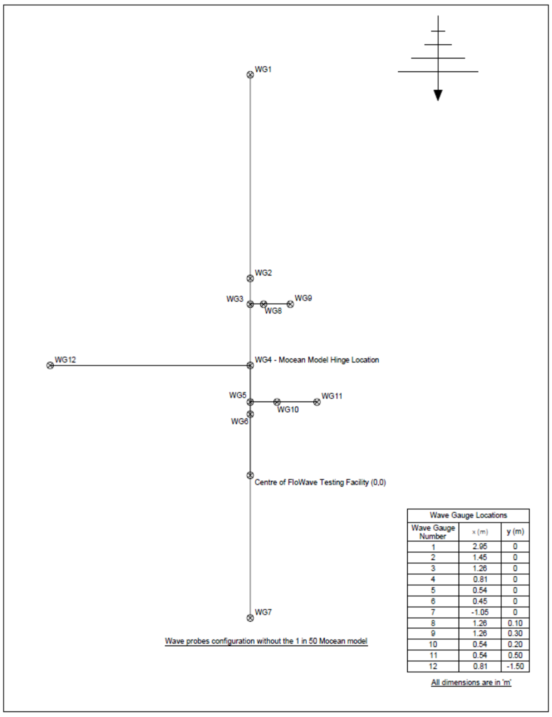

Fig. 2. Wave gauge locations during the tests without the model.

D. *Wave Conditions*

The physical model study involves testing the Mocean hinged raft WEC with regular, irregular, and focused waves (using NewWave theory). The water depth during the test was 2 meters. Details of wave conditions are given in Tables I, II, and III, respectively.

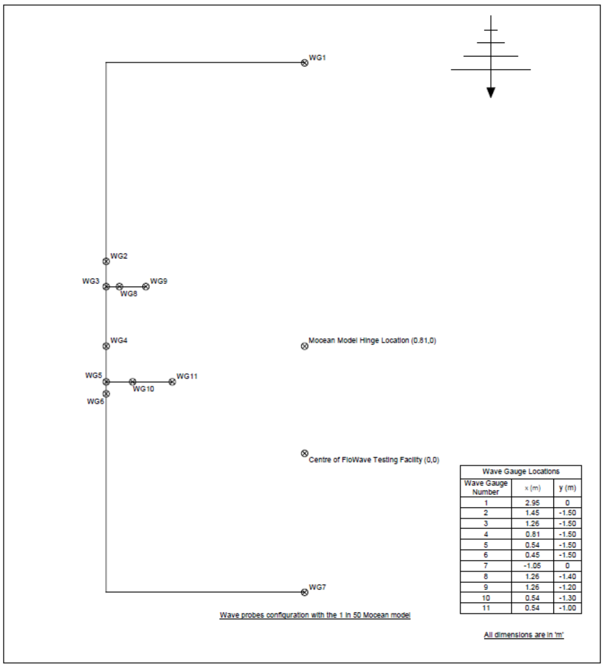

Fig. 3. Wave gauge locations during the test runs with the model.

TABLE I
DETAILS OF REGULAR WAVE CONDITIONS TESTED

Wave period, T (s)	Wave height, H (m)
0.95	0.11
1.1	0.15
1.25	0.15
1.5	0.15
1.75	0.15
2	0.15
2.25	0.15
2.5	0.15
2.75	0.15

TABLE II
DETAILS OF IRREGULAR WAVE CONDITIONS TESTED

Peak wave period, T_P (s)	Significant wave height, H_{m0} (m)
0.95	0.06
1.1	0.09
1.25	0.12
1.5	0.18
2	0.22

TABLE III
NEWWAVES CONDITIONS TESTED FOCUSING ON CREST AND TROUGH

Peak wave period, T_P (s)	Significant wave height, H_{m0} (m)
0.95	0.08
1.1	0.11
1.25	0.14
1.5	0.20
1.75	0.27
2.00	0.31
2.25	0.30
2.50	0.25
2.75	0.18

III. RESULTS AND DISCUSSION

E. *Responses in regular incident waves*

To comprehend the influence of wavelength and wave height on the responses of the Mocean hinged-raft WEC, the model was subjected to regular incident waves with constant wave height and varying wave periods. The incident waves were calibrated to achieve the target wave heights at the WEC hinge location through wave field measurements without the model. The results of motions, mooring line loads, and flex response discussed in this section are derived from the time-domain analysis of the recorded measurement signals.

1) *Motions*

The six-degree-of-freedom responses of the Mocean hinged raft WEC for both fore and aft bodies are shown in Fig. 4, for a regular wave of height 7.5 m. Because the two bodies are joined by the single-degree-of-freedom hinge, they are constrained to move identically in each degree of freedom other than in pitch; and within the limits of experimental error, this is observed to be the case. The surge response is found to increase with the wave period due to large orbital motion of longer wave periods. Conversely, the heave response is found to decrease with an increase in wave period and achieves a maximum heave response of 1.5 times the incident wave height at the low wave period. The sway response is found to be negligible. Likewise, the roll and yaw responses are found to be less than 1.5 degrees and 0.3 degrees per meter of incident wave height, respectively.

The effect of asymmetric body mass distribution is evident in the pitch response. In contrast to other hinged-raft WECs, the Mocean hinged-raft WEC is designed with a larger fore body length to increase stability compared to the aft body. This design choice contributes to the difference in pitch response. The pitch response of the aft body is found to be three times that of the fore body. The most significant difference in pitch response between the fore and aft bodies is observed at the low wave period region (at around T = 10 seconds). The difference in pitch response of the fore and aft body is defined as the flex angle. A larger flex angle results in greater wave power generation. This relationship is evident in the results discussed later in the section on flex response.

2) *Mooring line loads*

The mooring line loads on the Mocean hinged raft WEC, with their magnitudes obscured for commercial confidentiality, are shown in Fig. 5. It is observed that the west and east mooring line loads are similar (as would be expected from their mirror symmetry around the wave principal direction) and several times lower than those of the south mooring line. The difference is explained by the drift forces undergone by the WEC (steady in regular waves, unsteady in irregular waves) that bias the mooring downwave, thus tending to stretch the foreward (south) mooring line and slacken the aftward moorings. The excitation of the mooring lines by the WEC motion then produces larger load excursions on the forward line than the aft. The WEC motion is enhanced at lower periods, and this gives rise to a corresponding increase in the forward mooring loads.

3) *Flex response*

The flex response of the Mocean hinged raft WEC is a critical parameter in understanding the WEC's performance, and it is illustrated in Fig. 6. This response exhibits a pattern that is analogous to the pitch response, indicating a strong correlation between these two dynamic behaviours.

The WEC has been designed to have an amplified flex response for increased power generation, a critical aspect of the WEC's overall performance. The resonant wave period of the system is a key factor, as both the flex response and mooring line loads exhibit maximum values near this period. The system's design and operational parameters need to be considered to ensure optimal performance and minimise potential stresses on the mooring lines.

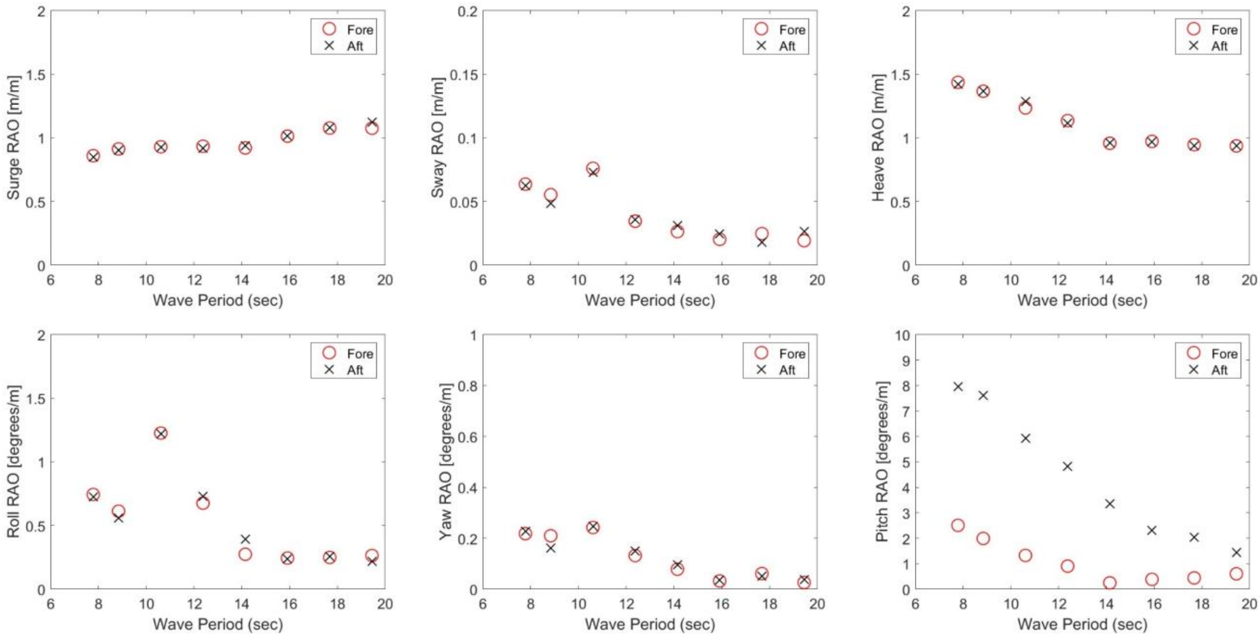

Fig. 4. Six-degree-of-freedom responses of the Mocean hinged raft WEC in full scale subjected to regular waves (H = 7.5 m).

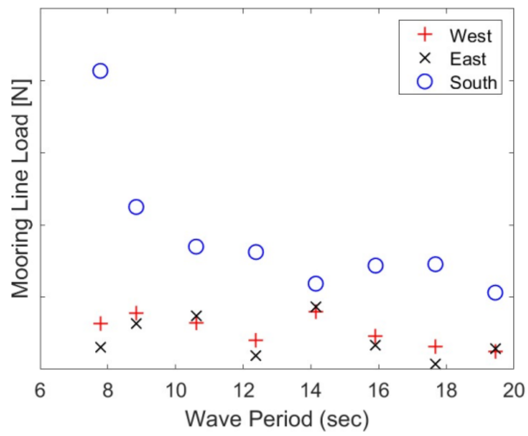

Fig. 5. Mooring line loads subjected to regular incident waves.

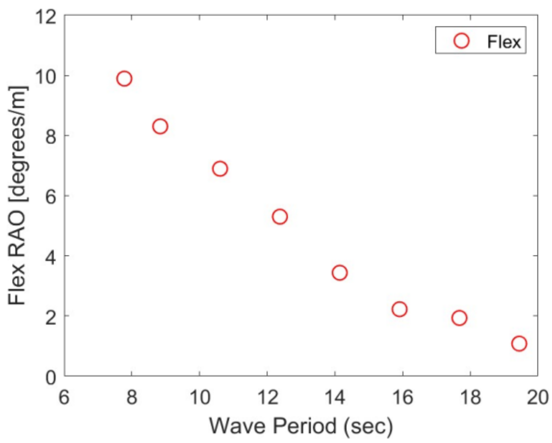

Fig. 6. Flex response of Mocean hinged raft WEC subjected to regular incident waves.

F. Responses in irregular incident waves

The irregular waves, representative of the extreme sea states for EMEC Billia Croo as described in Table II, were examined by measuring the motions, mooring line loads, and flexural responses of the Mocean hinged raft WEC. These sea states were scaled to a duration of 1 hour and realised with a wave count ranging from 252 to 512, based on the peak period, T_P. Unless otherwise specified, these sea states were long-crested waves.

1) Motions

The non-dimensional motion responses of the Mocean hinged raft WEC subjected to long irregular waves, compared to regular wave measurements, are depicted in Fig. 7. For irregular waves, the motion responses are calculated by dividing the significant response of the motions by the significant incident wave height. Considering that the fore and aft bodies exhibit similar behaviour across all motion responses except pitch the results displayed are limited to the fore bodies in order to avoid redundancy. However, in the case of pitch responses, a crucial parameter, the data for both the fore and aft bodies are presented to provide a comprehensive understanding.

An important observation is the general convergence of motion responses derived from irregular and regular wave measurements when conducted under comparable wave test conditions. This convergence highlights the consistency in the system's responses regardless of the wave type being investigated. The maximum deviation between regular and irregular measurements occurs in the low period region, which should be noted as primarily due to this particular low-period region not being investigated through regular wave measurements.

The maximum pitch response is identified as 15 degrees per incident wave height, providing valuable information for the design and operation of such WEC systems. In line with prior observations, model responses are found to be maximum in proximity to the resonant wave period

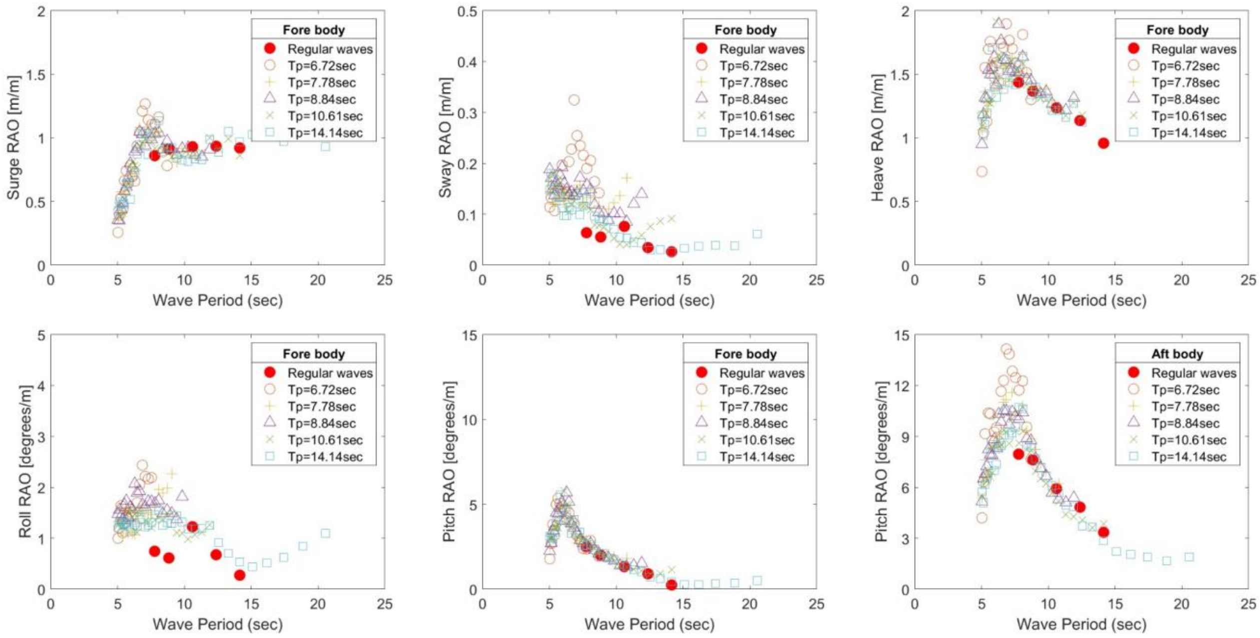

Fig. 7. Six-degree-of-freedom responses of the Mocean hinged raft WEC in full scale subjected to irregular waves.

system. This finding re-confirms that the system exhibits heightened sensitivity and responsiveness near the resonant wave period, which can have implications for the WEC's overall performance and efficiency.

2) *Flex response*

Fig. 8 presents a comparison of the flex response of the Mocean hinged raft WEC when subjected to long irregular waves and regular waves. It is observed that the WEC's flex response when exposed to irregular waves is notably higher, ranging from 15% to 25% more than the response observed during regular wave measurements. As the wave period increases, the flex response of the WEC gradually decreases. This trend can be attributed to the fact that the WEC's design is optimised for specific wave periods, and its response decreases when subjected to wave periods that deviate from its optimal range.

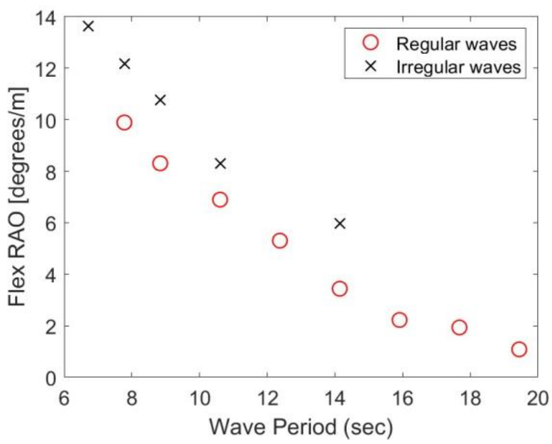

Fig. 8. Flex response of Mocean hinged raft WEC.

G. *Survival tests*

The extreme wave interactions with the Mocean hinged-raft WEC are studied using NewWaves, focusing on the crest and trough at the hinge location of the model. The NewWave sea states are selected as similar to long irregular sea states, and the wave conditions are described in Table III. This section provides insight into the motions, mooring line loads, and flex response subjected to NewWaves.

1) *Motions*

The non-dimensional motion responses of the Mocean hinged raft WEC subjected to NewWaves are shown in Fig. 9. This analysis reveals a comparable trend in motion responses between NewWaves with regular waves and irregular waves. However, a notable distinction is observed in the magnitudes of the NewWaves, which are found to be greater than the regular wave measurements and closely resemble the long irregular wave measurements.

A more comprehensive examination indicates that the motion responses of the trough-focusing waves (NWt) generally surpass those of the crest-focusing waves (NWc). This finding highlights the significance of considering NewWaves that concentrate on troughs at the model hinge location of the Mocean model. Within the subset of trough-focusing NewWaves, the NWt-Crest – which represents the division of crest measurement of the motion responses with the trough value of the NewWaves – is found to display a more pronounced pitch response compared to other test conditions. In concordance with earlier observations, the heave and pitch responses exhibit maximum values near the resonant period of the WEC. Moreover, a detailed comparison of the pitch responses

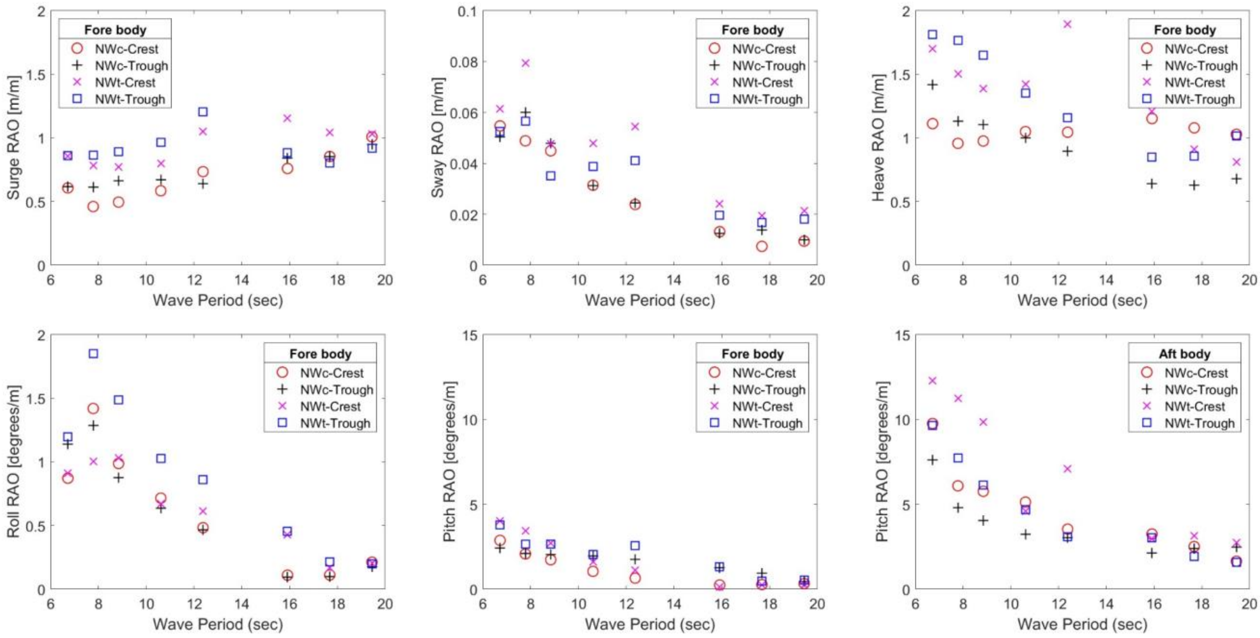

Fig. 9. Six-degree-of-freedom responses of the Mocean hinged raft WEC in full scale subjected to NewWaves.

reveals that the aft body exhibits greater values than the fore body.

2) Mooring line loads

The mooring line loads acting on the Mocean hinged raft WEC when subjected to NewWaves are illustrated in Fig. 10. In the vicinity of the resonant period of the WEC, which is approximately T = 10 seconds, it is observed that the mooring line load due to NewWaves focusing on the trough reaches a high value. This suggests that during this specific period, the trough-focused NewWaves have a considerable impact on the mooring line loads.

On the other hand, as the wave period extends, the NewWaves that are focused on the crest demonstrate higher mooring line loads. This finding underscores the importance of thoroughly investigating both wave-focusing techniques, trough-focused and crest-focused NewWaves, in order to better understand their respective effects on the mooring line loads and the overall performance of the WEC.

In addition, a consistent observation emerges with regard to the mooring line loads' distribution. As expected, the loads on the south mooring line which is in line with the principal wave direction are notably higher than the loads experienced by the west and east mooring lines, and provision must be made for this in any practical mooring.

3) Flex response

The flex response of the Mocean hinged raft WEC when subjected to NewWaves is depicted in Fig. 11. It is observed that the flex response of the NewWaves, with a focus on the trough at the WEC hinge location, is higher than that of the NewWaves focusing on the crest. Additionally, the NWc-Trough, which represents the division of trough measurements by the crest of NewWaves concentrating on the crest, is found to be higher than the NWc-Crest.

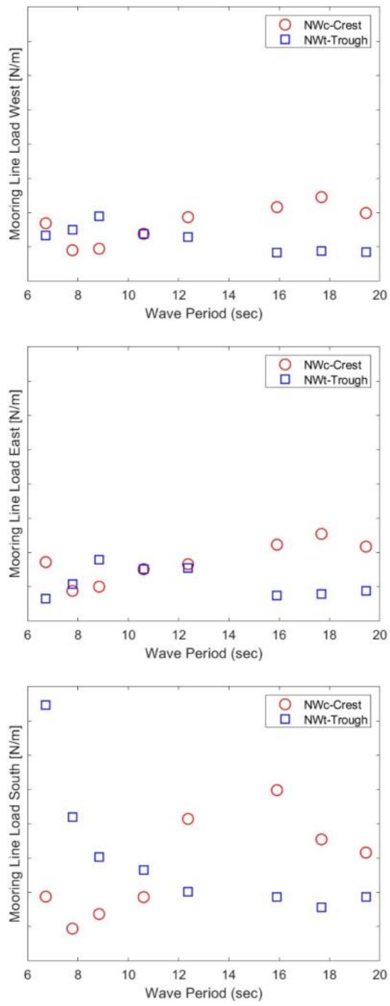

Fig. 10. Mooring line loads on Mocean hinged raft WEC subjected to NewWaves.

The maximum flex response recorded is 14 degrees per meter of the incident wave, a result consistent with observations made when analysing long irregular waves. This finding highlights the fact that utilising NewWaves can effectively replicate the responses of the Mocean hinged raft WEC, offering a more time and cost-efficient alternative to testing with long irregular waves. However, it should be noted that considering long irregular waves with a greater number of waves than those used in the present study of between 252 to 512 could potentially yield even higher results. This suggests that while NewWaves may be an adequate substitute for some testing scenarios, further investigation may be necessary to explore the full range of possible wave conditions and their impact on the Mocean hinged raft WEC's performance.

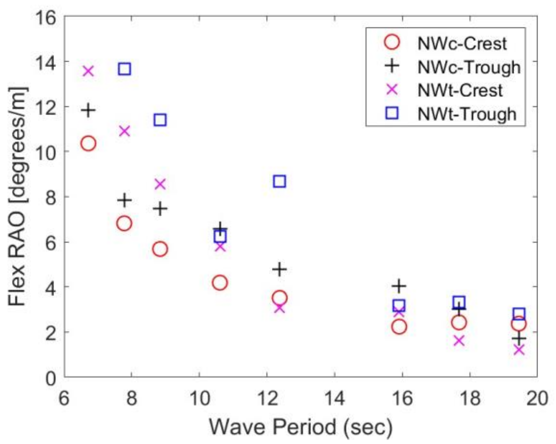

Fig. 11. Flex response of Mocean hinged raft WEC subjected to NewWaves.

IV. Conclusion

This study aimed to investigate the hydrodynamic behaviour of the Mocean hinged-raft WEC by examining its motions, mooring line loads, and flex response under various wave conditions, including regular waves, long irregular waves, and NewWaves. Key findings from this study are summarised below, providing valuable insights into the behaviour and performance of the WEC.

In regular waves the motion responses of the fore and aft bodies of the WEC were found to be similar, except for pitch response, which was influenced by the asymmetric body mass distribution. The pitch response of the aft body was generally several times that of the fore body. The flex angle, the difference between the pitch responses of the fore and aft bodies, had a maximum flex response of 10 degrees per meter of incident waves.

The mooring line loads were affected by the resonant wave period, with all lines experiencing increased loads as they approached this period. The south mooring line, located in line with the incident wave, consistently bore higher loads than the west and east mooring lines, which are located at an angle to the incident waves. This finding underscores the need to design the mooring system to take account of the wave directionality at the chosen deployment site. The study also highlighted the importance of the WEC's resonant period, as both flex response and mooring line loads exhibited maximum values near this period.

In the long crested irregular wave tests, the non-dimensional motion and flex responses were found to be consistent with those obtained from regular wave tests. However, the flex response of the WEC in irregular waves was notably higher, ranging from 15% to 25% more than the response observed during regular wave measurements. The maximum pitch response was identified as 15 degrees per incident wave height.

The analysis of the Mocean hinged-raft WEC subjected to NewWaves yielded similar motion responses and flex responses as those observed in long irregular wave testing. This result indicates that NewWaves can serve as an efficient and cost-effective alternative for assessing the WEC's performance under certain conditions, although further investigation may be necessary to explore the full range of possible wave conditions and their impact on the system. The trough-focused NewWaves had a more significant impact on the mooring line loads and flex response in the vicinity of the resonant period, while crest-focused NewWaves demonstrated higher mooring line loads at the longer wave periods beyond the resonant wave period.

Overall, the study highlights the need for careful consideration of the WEC's design and operational parameters to ensure optimal performance and minimise potential stresses on the mooring lines. While the use of NewWaves provides a time and cost-efficient alternative to testing with irregular waves, further investigation may be necessary to explore the full range of possible wave conditions and their impact on the Mocean hinged-raft WEC's performance.

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