Sea state influence on Design Waves for an M4 WEC

Christine Lynggard Hansen[a], **Hugh Wolgamot**[a], **Paul H. Taylor**[a], **Adi Kurniawan**[a], **Jana Orszaghova**[a,b], **Henrik Bredmose**[c]

a. Oceans Graduate School and Marine Energy Research Australia, The University of Western Australia, WA, Australia.

b. Blue Economy Cooperative Research Centre, Launceston, TAS, Australia

c. DTU Wind and Energy Systems, Kgs. Lyngby, Denmark

Email: christine.lynggardhansen@research.uwa.edu.au

Highlights

- We analyse the measured response of the M4, a hinged attenuator-type WEC.
- The linear hinge angle Design Waves and Design Responses are compared for three different severe sea states with limiting steepness.
- We show that the linear Design Response is essentially sea state independent for responses with natural frequency placed in the high tail of wave spectra of given overall steepness.

1 Introduction

Attenuator-type wave energy converters (WECs) such as the M4 are tuned to respond and absorb wave power in a frequency range matching prevailing conditions at a given deployment site. This resonant behaviour in the wave frequency range makes the response remarkably linear, and they are therefore straightforward to study in the context of Design Waves, i.e. a short wave sequence conditioned to induce the average maximum response of a structure.

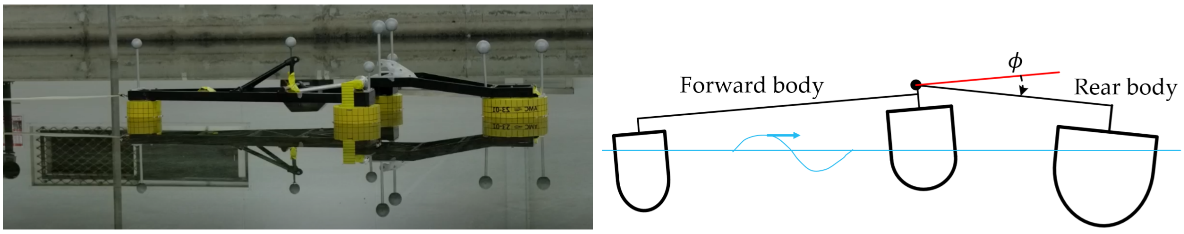
Ocean scale trials with an M4 WEC are planned for 2024 in King George Sound near Albany, Western Australia. In preparation, a model scale experimental campaign was conducted in a wave basin. The M4 WEC consists of three rows of cylindrical floats with rounded bottoms, attached to two beams, which are connected by a hinge (see figure 1). The float diameter and draft increase from the bow to the stern to ensure alignment with the mean wave direction and the variants are labelled by the number of floats in each row; here the 1-2-1 M4 is studied.

On the basis of NewWave theory (Tromans et al. 1991), Santo et al. (2017) conducted a Design Wave analysis for the 1-1-1 M4 using experimentally derived response transfer functions and determined that the wave that induces the averaged largest hinge motion response is distinct from the incident NewWave in both amplitude and phase. A similar analysis was carried out experimentally in a recent work (Hansen et al. 2023), where further Design Wave analysis was presented. The Design Wave signal was found by averaging the incident wave signals occurring around the time of the maximum hinge angles in a severe irregular sea state. Reproducing the Design Wave as as isolated wave packet in the basin showed a good match between the averaged maximum hinge angle instances in the random waves run and the measured response to the Design Wave group. We note that the primarily linear hinge angle response of M4 is affected by dunking - a full submergence of the centre floats, which represents an abrupt change of the system's properties.

The M4 is designed to the wave period of the most commonly occurring sea-states. For storm sea states, this means that the hinge natural frequency f_0 will be located out on the high tail of the wave spectrum. We will show that for a band-limited resonant response mode (like the hinge angle of the M4) in the high tail of a severe sea state, a Design Wave analysis for a given spectral shape and steepness is independent of the peak period. The analysis is conducted with the WEC in survival mode - i.e. with the power take off disconnected.

2 Experimental setup

Experiments at 1:15 scale relative to the Albany demonstrator device were carried out in a wave basin at the Australian Maritime College, the University of Tasmania. Details of the experiments are presented in Howe et al. (2023). The basin is 35m long, 12m wide, with a depth of 0.8m. Long-crested waves were produced by 16 piston-type wave paddles along one short edge and damped by a porous beach at the other end. The M4 device was constructed with fibreglass floats mounted onto carbon fibre frames, and had a full length of 1.6m and maximum



(a) (b)

Figure 1: (a) Photo of the M4 device in still water. (b) Schematic side-view drawing.

Sea states	H_s [m]	T_p [s]	γ [-]	$S = H_s/\lambda_z$ [-]
ESS2	0.064	1.29	1	0.050
ESS3	0.077	1.80	1	0.037
ESS4	0.144	2.26	1.5	0.053

Table 1: Model scale sea state properties

width of 0.63m. A photo of the model is shown in Figure 1a. The device was moored by a flexible latex cable to a stationary point, and cable tension was provided by a mass attached to an external pulley system. The rigid-body motions of both the forward (front and centre floats and front beam) and rear (stern float and stern beam) bodies were measured using a Qualisys motion tracking system. The hinge rotation ϕ was defined as the difference between the local forward and rear body pitch responses respectively (positive with the centre float high), and is shown schematically in Figure 1b.

The device was tested in the three different extreme sea states (ESS) shown in Table 1. The sea states are generated from a JONSWAP spectrum (based on Kurniawan et al. (2023)), and represent the steepest measured (H_s, T_p) combinations. Irregular waves were generated in pairs of two phase-inverted 30-minute (lab scale) runs for each sea state. The incident wave signal η used in the following is measured by a wave gauge positioned at $x = 9.53$m distance from the wavemaker, corresponding to the equilibrium position of the centre floats, and offset laterally by 0.5m from the sidewall.

3 Results

Figure 2 shows the power spectral densities of the incident wave and hinge response for the three sea states. The odd (predominantly first order, solid line) and even (predominantly second-order, dashed line) harmonic responses are constructed by phase-based harmonic separation (Walker et al. 2004). The incident wave spectra show that in the high tail, the three sea states have very similar energy levels. As all three sea states represent survival conditions for the M4 machine, the hinge natural frequency, $f_0 = 1.05$Hz is placed in the high tail of the wave spectrum, such that the linear resonant hinge response is very similar for all sea states. The response is remarkably linear with small even harmonic hinge response. The sub- and super even-order harmonic responses at $f < 0.4$Hz and $2f_0 = 2.1$Hz respectively are again at comparable levels for all sea states (as they primarily result from self-interactions of the linear resonant response). However, the second-order sum-frequency response at $f \sim f_0$ increases significantly with the sea state and increasing peak period due to different excitation levels around $\frac{1}{2}f_0$.

The Design Wave is found for all three sea states inspired by NewWave theory. The NewWave, presented in Tromans et al. (1991) describes the most probable linear shape around an extreme wave crest within a sea state. A NewWave in response, with a crest at $t = 0$ can be written as the inverse Fourier transform of the hinge angle spectrum S_ϕ:

$$\phi^{NW}(t) = \alpha_\phi \frac{\mathrm{Re}\left(\sum_n S_\phi(\omega_n)\ \Delta\omega\ \exp(-\mathrm{i}\omega_n t)\right)}{\sum_n S_\phi(\omega_n)\Delta\omega}, \tag{1}$$

with the amplitude of the extreme response crest at the 1 in M level given by $\alpha_\phi = \sqrt{2\sigma_\phi^2 \ln(M)}$, S_ϕ the response spectrum, ω_n the angular frequency and $\Delta\omega$ the frequency discretization. The

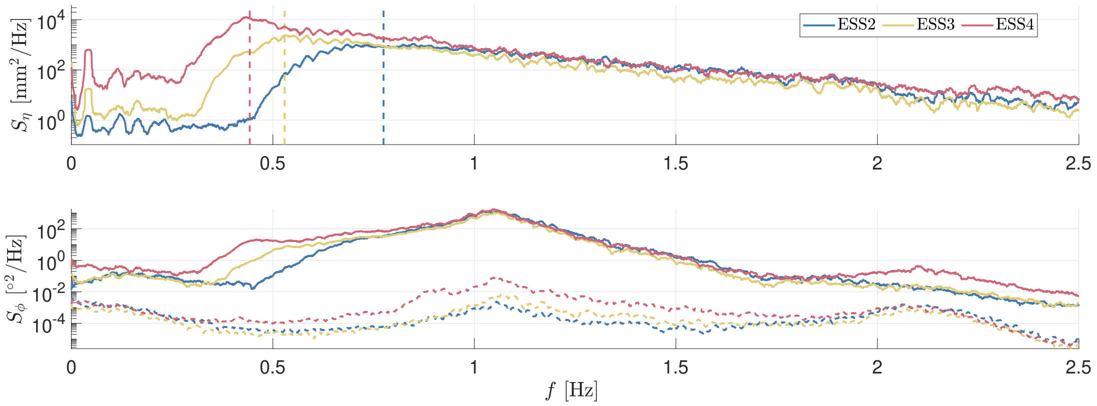


Figure 2: Top: Incident wave spectra. The vertical dashed lines refer to the peak frequency f_p. Bottom: Odd (solid lines) and even (dashed lines) harmonic hinge response spectra.

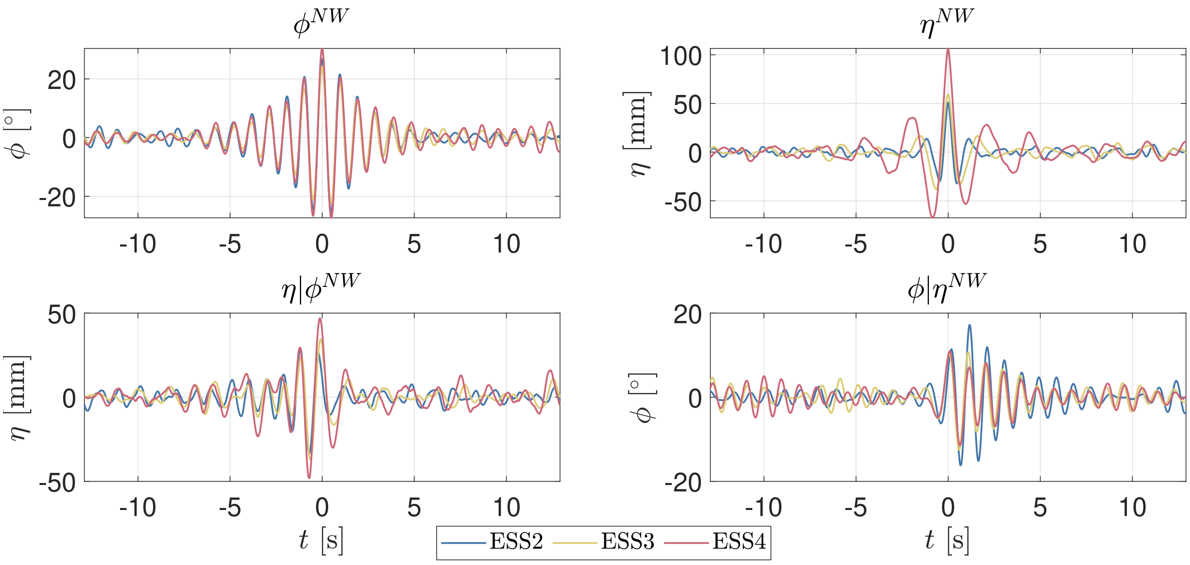


Figure 3: Linear conditioning analysis for 30 min sea state data.

experimental NewWave in response ϕ^{NW} – the average shape of the maximum hinge rotation – is constructed from the measured $\phi(t)$ by cutting out a short time series ($10T_p$ on either side) around each of the N largest linearised crests in $\phi(t)$ and shifting in time, such that the crest is at $t = 0$. We take $N = 30$. To isolate the average η signal that causes ϕ^{NW}, we identify and average short snippets of the $\eta(t)$ time series occurring at the same time as the crests averaged in ϕ^{NW}. We thus construct the conditioned signal 'Wave|NewResponse' ($\eta|\phi^{NW}$). Using the same approach, we identify the incident NewWave η^{NW} and the conditioned response signal 'Response|NewWave' ($\phi|\eta^{NW}$). Figure 3 shows the conditioning process, conducted on the odd harmonic incident wave and response for all three sea states. The upper plots show the conditioning signals, ϕ^{NW} and η^{NW}, and the bottom plots show the conditioned signals $\eta|\phi^{NW}$ and $\phi|\eta^{NW}$. It is clearly seen that the Design Response ϕ^{NW} is very similar for the three sea states, while η^{NW} is highly sea state dependent. There are visible differences between the Design Waves $\eta|\phi^{NW}$ for each sea state, indicating that the Design Wave consists of a narrow-banded part (around f_0) which excites the Design Response, and a sea state dependent part, which does not affect the linear ϕ^{NW}, but might affect higher order responses.

It was shown in Santo et al. (2017) that the conditioned incident wave $\eta|\phi^{NW}$ and the conditioned response $\phi|\eta^{NW}$ show reciprocity, given a linear response mechanism:

$$\eta(t)|\phi^{NW} = \frac{\alpha_\phi}{\alpha_\eta}\frac{\sum_n S_\eta(\omega_n)}{\sum_n S_\phi(\omega_n)} \cdot \left(\phi(-t)|\eta^{NW}\right) \approx \frac{\sigma_\eta}{\sigma_\phi}\left(\phi(-t)|\eta^{NW}\right). \quad (2)$$

Reciprocity - similarity of the shape of the conditioned wave signal with the scaled and reversed (in time) response to NewWave signal - was shown experimentally for ESS2 in Hansen

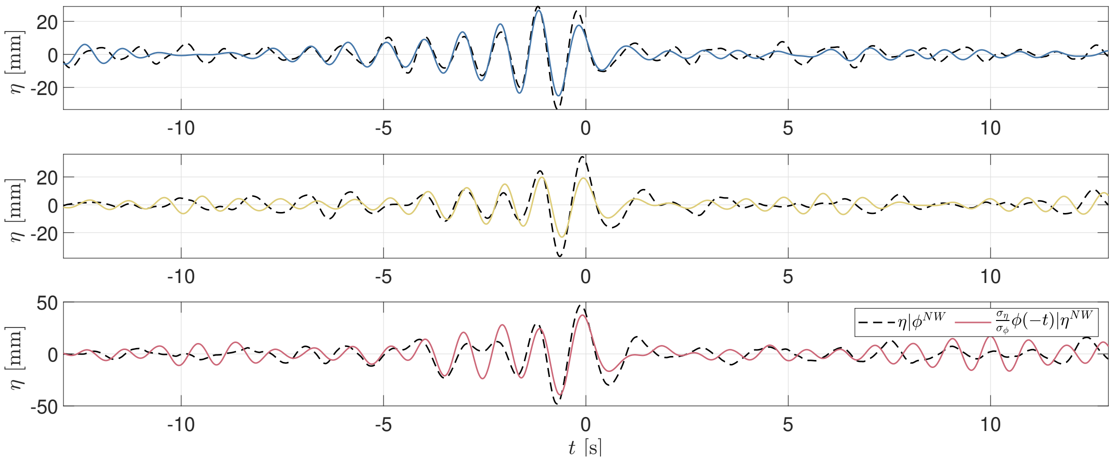


Figure 4: Reciprocity of the conditioned odd harmonic signals for ϕ (reversed in time and scaled) and η. Top: ESS2. Middle: ESS3. Bottom: ESS4

et al. (2023). Figure 4 shows the Design Wave and the response to NewWave, scaled and reversed in time for all three sea states. The reciprocity fit worsens progressively from the top to bottom plot, presumably mainly due to the wave energy found outside of the band-width of the hinge response. We can show that by band-pass filtering η to a narrow frequency range $[0.7f_0; 1.2f_0]$ before applying the conditioning procedure, reciprocity holds reasonably well for ESS4, and the ESS4 $\eta|\phi^{NW}$ signal is now very similar to that for ESS2.

4 Discussion

We have found that the linear NewWave in response – the Design Response – is constant for the hinge rotation in three severe sea states of approximately equal steepness, and that the Design Wave causing it is a narrow-banded wave signal embedded in a sea state dependent background wave. It should be noted that there is a distinct Design Wave for each response mode, and that this universality of the Design Response is expected to be a feature of the band-limited response seen for self-reacting modes in WECs. For a response mode such as surge, which is predominantly driven by subharmonic second-order forcing, these would look significantly different. Further results on Design Waves will be reported at the workshop.

Acknowledgements

This work was supported in part by the Australian Research Council (ARC), Early Career Fellowship DE200101478 and by Marine Energy Research Australia, jointly funded by The University of Western Australia and the Western Australian Government, via the Department of Primary Industries and Regional Development (DPIRD). The support of the Blue Economy Cooperative Research Centre through the project 'Seeding Marine Innovation in WA with a Wave Energy Deployment in Albany' (grant number CRC-20180101) is gratefully acknowledged.

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