Experimental study on short design waves for extreme response of a floating hinged raft wave energy converter

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1 INTRODUCTION

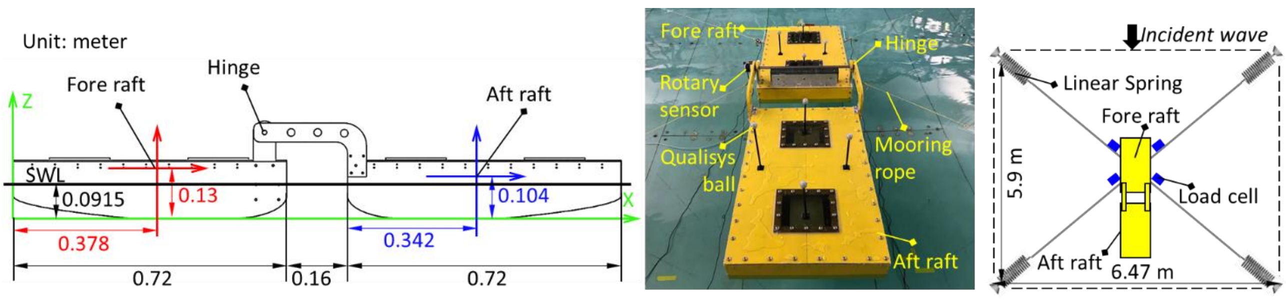
Predicting extreme responses with respect to a long-term return period (e.g., 50-year) is of great importance for the design of an offshore structure. The established method is to conduct a large number of long-duration (1-hour/3-hour) simulations to predict the design loads/responses [1, 2]. If the system response can be well modelled via a linear transfer function, the long-term analysis is easy to achieve. The analysis will be considerably time-consuming if a time-domain nonlinear response model is required and even impractical using a computational fluid dynamics (CFD) method or physical tank testing.

To speed up the design procedure, there has been continuous interest in investigating the potential of using a short design wave (SDW) to replace long-duration irregular wave tests (IR) [3, 4]. Several standards have suggested that SDWs can be applied on fixed offshore structures, while applying SDWs on the design loads of floating offshore structures needs to be verified with further numerical simulations and experimental results before they can become established tools. In present work, four types of SDW are investigated experimentally on a designed 1:50 scale floating hinged raft wave energy converter (WEC): (1) the New Wave (NW) which is a single wave series obtained based on the frequency content of the wave spectrum; (2) the most likely extreme response wave (MLER) which is a single wave series obtained via the frequency content of the response spectrum; (3) the conditioned NW (CNW) which is a group of waves generated by embedding the single NW into a series of short random irregular backgrounds; and (4) the conditioned random response wave (CRRW) which is a group of waves generated by embedding the MLER into a series of random irregular backgrounds. For the CNW and CRRW, 20 wave series are run in this work.

2 EXPERIMENTAL DESCRIPTIONS

2.1 Experiment Model

A designed 1:50 scale two-body hinged raft WEC was built and tested. Its main geometric dimension and the mooring layout are described in Fig. 1 and Table 1. With the constraint of the hinge, the device has 13 degrees of freedom (DOF): 6 DOF (surge, sway, heave, roll, pitch and yaw) for each raft and the relative hinge angle between the fore raft and aft raft. 4 aerial mooring lines were used to secure the device. Each mooring line consists of a stiff rope using polyethylene fibers and a linear spring with calibrated stiffness of 7.35 N/m. The motions of the two rafts were measured by a Qualisys optical tracking system. A rotary sensor was installed to record the relative hinge angle. 4 load cells were used to capture the mooring loads at the fairleads. In this work, response of the relative hinge angle is studied to demonstrate the application of SDWs on this floating structure.



(a) (b) (c)

Fig. 1. (a) Dimensions of the designed 1:50 scale hinged raft WEC. The green, red and blue coordinates represent the global coordinate, the centre of gravity (CoG) of the fore raft and the CoG of the aft raft, respectively. (b) Experiment model. (c) Mooring layout.

Table 1. Main parameters of the 1:50 scale hinged raft model. The order of the inertias is I_{XX}, I_{YY}, I_{ZZ}.

Parameters	**Value**
Length of the fore raft [m]	0.72
Length of the aft raft [m]	0.72
Draft of the WEC [m]	0.0915
Width of the WEC [m]	0.435
Mass of fore raft [kg]	25.125
Mass of aft raft [kg]	25.125
Inertias of fore raft [kgm^2, kgm^2, kgm^2]	0.49, 2.06, 2.23
Inertias of aft raft [kgm^2, kgm^2, kgm^2]	0.49, 2.06, 2.23
Spring stiffness [N/m]	7.35
Spring initial pretension [N]	2.5

2.2 Test cases

The Billia Croo site (58.96° N, 3.38° W) at the European Marine Test Centre (EMEC) in the UK, is considered here as the operational site. The hourly reanalysis data of 1979/01/01–present from the European Centre for Medium-Range Weather Forecasts (ECMWF) are used to obtain the extreme sea states related to a long-term return period [5]. The long-term variation of sea states is described by a joint distribution achieved by fitting the signifiant wave height (H_S) distribution via a Weilbull distribution and fitting the peak wave period (T_P) via a H_S conditional log-normal distribution. As a result, the 50-year environmental contour line is obtained and plotted in Fig. 2(a), which gives a set of H_S - T_P to represent the extreme sea states having the largest probablity to generate design reponse.

Table 2. Description of the test cases under 1:50 scale for model testing.

Wave Parameter				**IR**	**SDW**
H_S **[m]**	T_P **[s]**	f_P **[rad/s]**	γ		
0.22	2.2	2.86	1	IR-50year-1	NW-50year-1, MLRW-50year-1, CRW-50year-1, CRRW-50year-1
			3.3	IR-50year-2	NW-50year-2, MLRW-50year-2, CRW-50year-2, CRRW-50year-2
0.05	1.1	5.71	1	IR-R-1	NW-R-1, MLRW-R-1, CRW-R-1, CRRW-R-1
			3.3	IR-R-2	NW-R-2, MLRW-R-2, CRW-R-2, CRRW-R-2

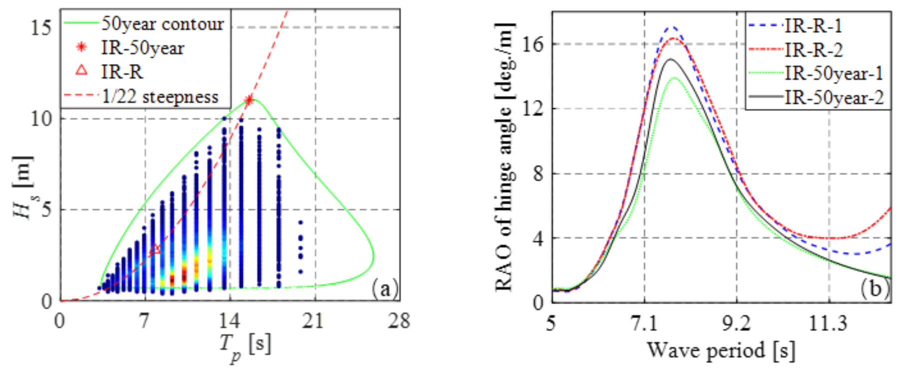


Fig. 2. (a) Schematic of the waves for the EMEC site in full scale. (b) RAOs of the relative hinge angle in full scale.

Considering the linear wave with no breaking, two wave conditions along the 1/22 steepness line are determined to study, as decipted in Fig. 2(a): one is the wave hitting the desired 50-year contour line with the largest H_S, called 50year; another is the wave at the targeted hinge resonance of the device, called R (see Fig. 2(b)). The long-duration IRs are modelled by the JONSWAP spectrum with two different gamma (γ) values. Then, 4 types of SDW are tested on the WEC. The detailed test program is described in Table 2.

3 RESULTS AND DISCUSSION

3.1 Impact of Proceeding Wave Effect and Transient Dynamics

Fig. 3 shows the comparison of the NWs with different γ at the same wave condition and the generated relative hinge angle responses. Clearly, NW-R-1 and NW-R-2 achieve the same focused peak value at 45 second, while they have different proceeding waves before 45 seconds, which leads the WEC to generate different peaks of hinge angle. This may indicate the disadvantage of NW for dynamically floating structures in that the wave with large amplitude is not the only factor to produce extreme response and the proceeding waves before the peak can also be of considerable importance for the extreme response of a dynamically floating structure.
Fig. 4 compares the results from NWs at two wave conditions: R and 50year. As observed, NW-R-1 with much smaller H_S but with targeted response resonance period produces a larger response reaction than NW-50year-1 which has higher H_S. This indicates that NW with large focus amplitude may not generate the extreme response for floating structures and a design wave such as the MLER that considers the transient dynamics of a device (i.e., response RAO) may perform better.

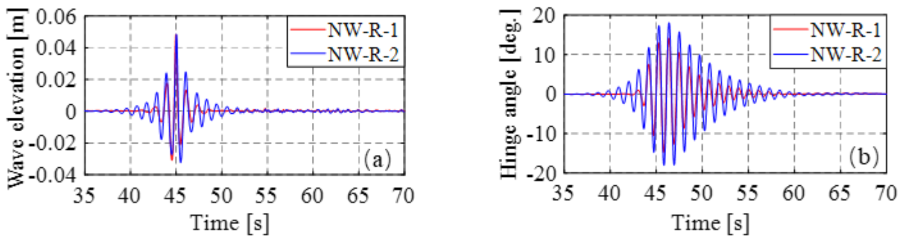


Fig. 3. Examples of proceeding wave effect on this floating hinged raft WEC under wave conditions of NW-R-1 and NW-R-2. (a) Wave elevation. (b) Hinge angle response.

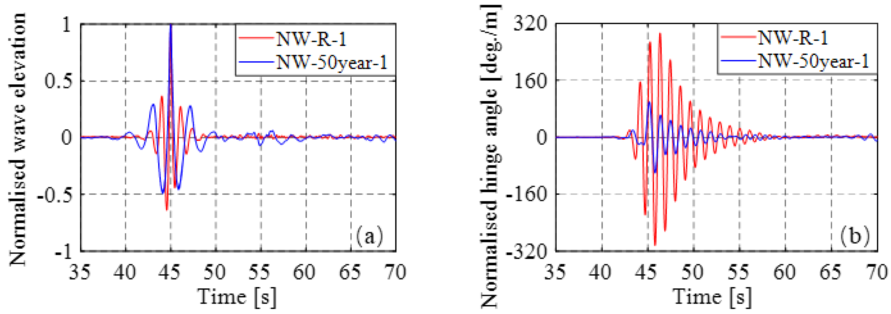


Fig. 4. Examples of transient dynamics effect on this floating hinged raft WEC under wave conditions of NW-R-1 and NW-50year-1. (a) Normalised wave elevation. (b) Normalised hinge angle response.

3.2 SDWs for Extreme Response

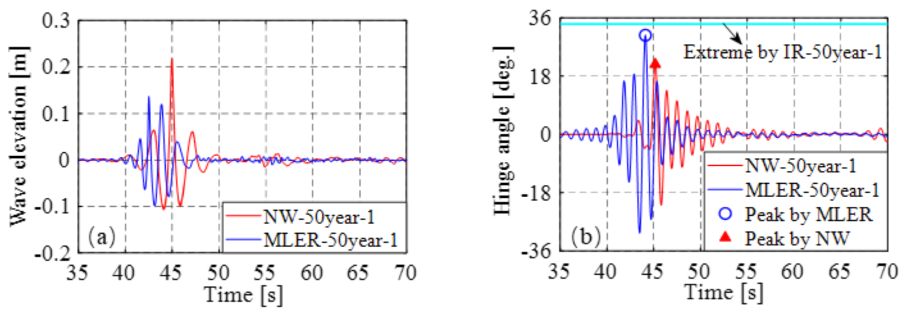


Fig. 5. Comparison of NW and MLER under wave condition of 50year-1. (a) Wave profiles of NW-50year-1 and MLER-50year-1. (b) Hinge angle responses generated.

Fig. 5 shows the physically measured results from NW and MLER under wave condition of 50year-1. As seen, the wave profile MLER with consideration of the response RAO is totally different from the profile of the NW. Furthermore, the MLER with smaller peak amplitude leads to a larger hinge angle of 31 degree, which is quite close to the extreme target of 34 degree through long-duration IR wave, compared with that from NW.
Fig. 6 shows the probability distributions of the hinge angle for different sea states tested. The presented distributions are obtained by physical model testing under IR waves with the Rayleigh distribution based on

the zeroth spectral moment of the hinge angle response. For comparison, results from 20 CNWs, 20 CRRWs, a single NW and a MLER are also shown. The design response studied here is that with exceedance probability of 10^{-2}. Clearly, the physically obtained distributions more or less fit well those from the Rayleigh distribution. This states that the hinge angle response is mainly linear under the sea states studied. Then, the figure shows that using response conditioned SDWs such as MLER and CRRW produce hinge angles at lower exceedances compared with wave based SDWs such as NW and CNW. Using MLER generates hinge angles fitting well with the target 10^{-2} exceedance probability, while NW considerably underpredict the extreme response. With consideration of random backgrounds, both CNW and CRRW could generate hinge angle reaching exceedance probability of 10^{-2}, while a considerably higher percentile is required for CNW and the hinge angles predicted from CNWs have greater variations.

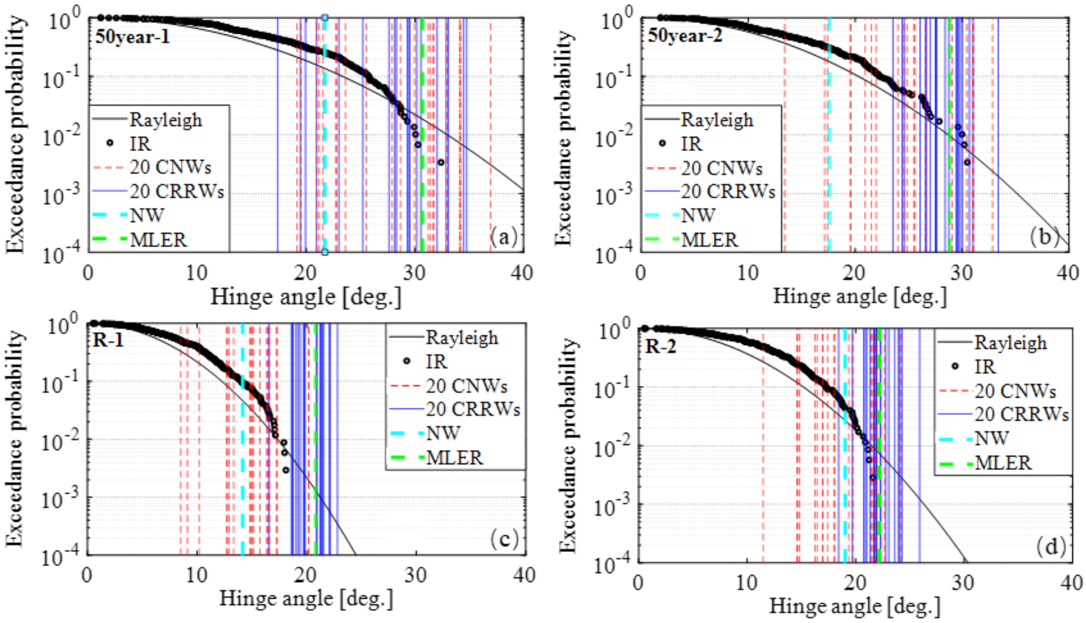


Fig. 6. Comparison of IR, CNW, CRRW, NW and MLER for relative hinge angle response. The theoretical probability distributions are described by the Rayleigh distribution. (a) Under 50year-1. (b) Under 50year-2. (c) Under R-1. (d) Under R-2.

4. Conclusion

This study has carried out a series of physical model tests to investigate the application of SDWs for generating extremes on a 1:50 scale floating hinged raft WEC. It has been found that response conditioned design waves such as the MLER and CRRW have better performance than wave conditioned SDWs such as NW and CNW for generating extremes on a floating structure. Other design responses are worth investigating, such as mooring load, bending moment, etc., in future work. Application of SDWs under wave conditions with high nonlinearity and even wave breaking is also of interest to study.

ACKNOWLEDGEMENT

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REFERENCES

[1] NORSOK STANDARD: N-003. Actions and action effects. 2007.
[2] IEC, Marine energy - Wave, tidal and other water current converters - Part 2: Design requirements for marine energy systems. Technical Specification IEC TS 62600-2. 2016.
[3] Hansen, P.F. and L.P. Nielsen, On the New Wave model for the kinematics of large ocean waves. Ocean Waves, 1995.
[4] P.H. Taylor, P. Jonathan, and L.A. Harland. Time domain simulations of jack-up dynamics with the extremes of a Gaussian process. in 14th Int Conf Offshore Mech Arct Eng.
[5] ECMWF. https://www.ecmwf.int/.