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Use of constrained focused waves to measure extreme loading of a taut moored floating wave energy converter

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ABSTRACT

This paper concerns experimental measurements of the interaction of a taut moored floating body, representing a point absorbing wave energy converter in survivability mode, with extreme waves. The extreme waves are modelled in four ways. NewWave theory is first used to generate focused wave groups of varying steepness. Steepness is shown to have negligible effect on peak mooring loads, but causes significant differences in the resulting motion. The NewWave group is then constrained into both regular and irregular background wave trains so that the floating body has a load history caused by previous waves when interacting with the focused wave group. It is shown that an independent focused wave group is insufficient to properly model the extreme response of the floating body. However differences between the target and measured constrained time series due to non-linear wave-wave interaction limited the potential benefits of this approach. Finally the results from these tests are compared with measurements taken using irregular waves without any deterministic focused wave groups present. This comparison found cases where the floats response was greater than during any of the constrained NewWave tests, indicating that the assumption made that NewWave will generate the largest response was incorrect in this case.

1. Introduction

Floating wave energy converters must be designed to withstand the largest waves experienced during storms of magnitude equal to their design condition. This forms part of a wave energy device's survivability criterion, part of the dual requirements of any marine energy device: the ability to extract energy in small to moderate seas, while surviving more extreme conditions (Barstow et al., 2008 p. 52). Achieving an understanding of the response to these extreme waves is important. Large degrees of uncertainty in the expected loads often lead to the use of conservative assumptions which can negatively influence the commercial viability of a device (O'Neill et al., 2006).

Most floating offshore wave energy converters are being designed to deploy in arrays. Spacing between individual devices within an array depends on many factors, including maximising power generation, provision of maintenance access and achieving an acceptable collision risk. For this last point it is important to be able to also predict the maximum expected displacement of devices during extreme events.

Both experimental and numerical techniques are used to model a device's response to extreme waves. In both cases a deterministic focused wave group based on NewWave theory is often used to generate a time series of an extreme wave. NewWave theory, as described by Tromans et al. (1991), models the statistically most probable surface elevation shape associated with the occurrence of an extreme wave crest with a specified exceedance probability (Pinna and Cassidy, 2004). NewWave theory has the advantage that it generates an extreme event within a relatively short time series when compared to relying on randomly occurring extreme events in an irregular time series of the sea state in question. The short time series means, in a correctly designed experiment, that all important wave-structure interactions occur before any significant influence from wave reflections from basin walls occur. The wave group generated by NewWave theory propagates into calm water. This and again the relatively short time series involved, means that NewWave focused wave groups are well-suited for proving validation data for computationally expensive computational fluid dynamic (CFD) models.

These advantages of using NewWave focused wave groups to measure extreme wave interactions have led to the approach being used in a wide number of applications. In the offshore environment extreme wave impacts on fixed cylinders relevant to a wide range of structures have been assessed both experimental and numerically using NewWave theory (Walker and Eatock Taylor, 2005; Ransley et al., 2013; Zang et al., 2010),

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while Stallard et al. (2009a) measured the forces on a vertical cylinder moving through a stationary fluid with a motion devised from NewWave theory. Rozario et al. (1993) successfully compared the loads predicted by NewWave on a North Sea oil platform with simulations of random seas. Westphalen et al. (2014) conducted Volume of Fluid and SPH CFD simulations of NewWave wave groups interacting with the Manchester Bobber wave energy device, comparing results to those from 70th scale experimental measurements (Stallard et al., 2009b; Weller et al., 2013). More recently NewWave theory has been used to investigate the impact of extreme waves in the coastal environment. Borthwick et al. (2006) measured wave kinematics of NewWaves impacting on a 1:20 beach plane, while Whittaker et al. (2017) measured wave runup of a plane beach.

Focused wave groups such as those generated by NewWave theory are used to represent the design load case for fixed structures (Stallard et al., 2009b). Their use as design cases for dynamic structures and devices is questionable however. When dynamic response to waves is expected, the response to a specific extreme wave will depend not only on the load induced by the wave, but the load history caused by the previous wave train (Pinna and Cassidy, 2004). This dependency is not investigated when testing with a single focused wave group. The device or structure in question has a stationary initial state and only interacts with the deterministic wave crests and troughs that made up the initial part of the focused wave group before interacting with the extreme central crest.

Constraining (or embedding) the NewWave within a random background sea state is an approach which allows the effect that a device or structures load history has on that device or structures response to a deterministic extreme event to be investigated. Introduced by Taylor et al. (1997), a Constrained NewWave (CNW) consists of a NewWave group which is constrained into an irregular background sea state with the same characteristic spectrum, such that the resulting time series is statistically indistinguishable from a randomly occurring wave train. The impact of the device's load history variation and the resulting distribution of the responses to the extreme wave can then be investigated by conducting multiple simulations or experiments with the focused wave group constrained into different random background time series.

Various numerical studies have concluded that using the CNW technique is a viable alternative to conducting simulations with random irregular wave time series. For example Cassidy (1999) and Cassidy et al. (2001) demonstrated the use of CNW to determine the short-term extreme response statistics of a Jack-up structure, using 5 NewWaves each constrained into 200 random backgrounds. Their results were found to be comparable to those found from 100 3 h simulations of random seas. Pinna and Cassidy (2004) conducted similar simulations on a fixed monopod platform using 100 CNW cases while Enderami et al. (2010) modelled the extreme response of a Jacket offshore platform using 200 CNW, both with ABAQUS. Both compared results with simulations of 3 h long irregular sea states and found that the maximum response were of a similar magnitude.

Bennett et al. (2012) report what they believed to be the first experimental use of CNW. They compared the use of an independent NewWave, CNW and an ‘optimised sea state’ to model the rigid body motions of a travelling ship in abnormal waves, where the optimised sea state requires an iterative adjustment of the phases in a random sea state so that a target extreme wave occurs. The three different approaches to generating ‘abnormal’ sea conditions were tested for three JONSWAP sea states with increasing significant wave height. Discrepancies between the target and generated wave were reported for the CNW, which was considered to be potentially due to the combination of two wave spectra. Göteman et al. (2015) constrained NewWave into regular waves when measuring the wave load on a point-absorbing wave energy device. The focused wave was constrained into different phase locations within regular waves with four different periods, resulting in 32 cases in total. A correlation between wave height and measured mooring force is reported.

This paper presents a systematic study into the experimental use of independent NewWave and CNW in the investigation of a moored floating body's response to an extreme wave. Results from four sets of experiments are reported and compared. In the first series the interaction of the moored floating body with an independent NewWave focused wave group was measured, along with the interaction with three other focused groups of increasing steepness. In the second series 24 constrained NewWave cases were tested within two regular background waves. In the third series the NewWave was constrained into 180 unique irregular wave backgrounds. The final experimental series consisted of two 3 h long irregular wave time series, without any NewWave group present. A single sea state, representing a 100 year return period at Wave Hub, a wave energy test site of the North Cornwall Coast (UK) was used throughout. The differences between the maximum mooring loads and surge measured during the four set of experiments are specific to the float geometry, mooring arrangement and wave conditions tested here. However by comparing the results from the four different sets of experiments conclusions are drawn and recommendations made about the application of independent and constrained NewWave to the experimental determination of the extreme response of a moored floating body.

2. Experimental methodology

The floating body tested was the same as used in Hann et al. (2015), but with an altered mooring arrangement (Fig. 1). It is a 0.5 m diameter floating body, consisting of a hemisphere and 0.25 m high cylinder, with a dry mass of 43.2 kg and made from steel with a concrete ballast. The floats centre of mass was about the central axis of the float, 0.319 m from the top of the cylinder. Moments of inertia were $I_{xx} = I_{yy} = 1.61$ kg m^2 and $I_{zz} = 1.25$ kg m^2. A single taut mooring was used consisting of 1.38 m of 3 mm diameter Dyneema® rope (spring constant, $k \approx 35$ N/mm) in series with a 12.5 mm diameter linear spring ($k = 0.066$ N/mm), which provided the mooring's extension. The initial and maximum rated length of the spring was 0.63 m and 1.145 m respectively. In still water the spring was extended by 0.31 m. End stops, consisting of 4 Dyneema®

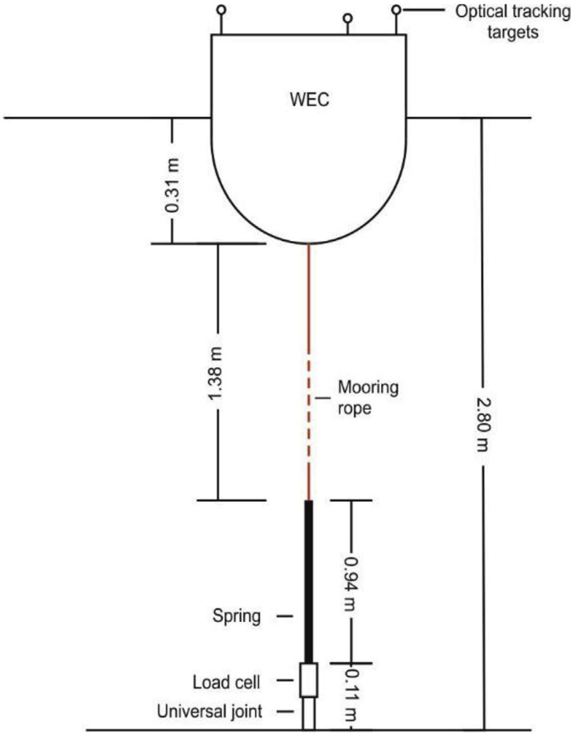

Fig. 1. Model set-up and instrumentation. The discrepancy of 0.06 m between 2.8 m water depth and the total length of the individual mooring components shown and submerged float is due to 3 × 0.02 m long shackles, located between the spring and load cell, the spring and mooring rope and the mooring rope and float.