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RANS investigation of the kinematics of an alternative extreme wave

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ABSTRACT

The traditional "new-wave" which is the highest wave that is most likely to be seen in a given sea-state has been of great interest in recent times but could there be other kinds of waves with similar likelihood of occurrence which can exert comparable or even more severe loads in the same sea-state? This work investigates and compares the kinematics of an alternative extreme wave and the traditional extreme ("new-wave"). It was observed that although the alternative wave is not as high as the traditional extreme wave it can produce more severe kinematics and by extension, higher loads on a bottom-fixed marine structure. In the specific case investigated, the alternative wave broke while the traditional extreme wave did not break through-out the simulation. This suggests that height alone is not sufficient to characterize an extreme wave and an alternative extreme can occur which though not being the highest is more severe.

1. Introduction

The majority of work on extreme waves has tended to define "extreme" in terms of height. With the new-wave theory of Tromans et al. (1991) it is possible to define the highest wave that is most likely to be seen in a given sea-state by essentially scaling the auto-correlation function of the underlying spectrum with typically, the one in 3 hour amplitude. But how does the kinematics of this wave and by extension induced loads, compare with those of the steepest wave that is most likely to occur in the same sea-state? Indeed, it was found in the investigation of wave forces and overturning moments on a slender stiff cylinder by Kjeldsen et al. (1986) that responses induced by a moderate but breaking deep-water wave was much higher than those induced by a much larger wave similar to the traditional design wave. Earlier, Kjeldsen and Myrhaug (1979) had concluded in their investigation of extreme (typically asymmetric) waves, that front-steepness is a more relevant parameter than the traditional definition of wave-steepness which depended on height since the magnitude of shock pressures recorded in their experiment depended on the wave-form which they did not find to have a unique relationship with the traditional definition of wave-steepness based on height. An alternative extreme wave can be defined in terms of maximized front-steepness to give the steepest wave that is most likely to occur in a sea-state by applying the new-wave theory to the spectrum of surface slope instead of the spectrum of surface amplitude as in the traditional extreme wave (most probable highest wave) characterized by height. This definition was developed and used by Xu and Barltop (2005), Xu and Barltrop (2008 (1)) to conduct experimental investigation of steep wave impact on FPSO bows. Calculations based on the linear theory have been presented by Xu and Barltrop (2008 (2)) and Xu et al. (2007), for impact pressures and underlying kinematics. However, extreme waves are highly non-linear and in the present study, it is sought to understand the loads induced by the alternative extreme wave in terms of the underlying kinematics and how it differs from those of the traditional new-wave (most probable highest wave). Swan et al. (2001) had earlier modelled a simple version of this alternative extreme wave where component wave-slopes rather than crests are focused and it was concluded that such a wave resulted in the more extreme particle accelerations. However their input spectrum was narrow banded relative to standard spectra like JONSWAP, PM and Bretschneider. Also, the same spectral amplitudes were used in generating the steepest as well as the highest waves and therefore, crest-height statistics was not taken into account in order to ensure that the probability of occurrence remained equivalent. As a result, their steepest and highest wave case are not comparable in the context of a realistic random sea-state since their steepest wave input spectrum implies (in the context of random waves) that maximum wave-slope and height

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Nomenclature

T_z	zero-crossing period,
H_s	significant wave-height,
G	gravity acceleration,
$L_z = gT_z^2/2\pi$	zero-crossing wave-length,
MWL	mean water level,
FPSO	floating production, storage and offloading vessel.

occur together so that the amplitudes of the frequency components of the steepest wave are equal to those of the highest wave. The new-wave theory shows that this is not so in a realistic random wave spectrum rather the maximization of slope (front-steepness) negatively compensates for height and vice versa. The implication is that relative to the most probable highest wave, the most probable steepest wave will be lower and much lower than the case where statistics are not considered as in Swan et al. (2001). Therefore in a situation where the most probable steepest wave is being compared with the most probable highest wave, the question arises as to which of the two extremes result in higher particle kinematics in a standard ocean wave spectrum. The present work is an attempt to answer this question.

For the purpose of this study, the traditional ''new-wave'' is simply referred to as the *''highest wave''* while the alternative extreme wave which represents the steepest wave that is most likely to occur is also simply referred to as the *''steepest wave''*. Based on the alternative definition of ''extreme'' in terms of wave-slope, an alternative understanding of wave-steepness which defines steepness as the slope of a wave-front is assumed through-out this work rather than the traditional definition of wave-height to wave-length ratio which, does not properly account for the asymmetry inherent in extreme waves. This alternative extreme has not been given much consideration probably because it implies a relatively lower crest-height in a random wave spectrum. It is useful to note that earlier, Drake (1997, 2000, 2001) used a similar most probable extreme value statistics to obtain the shape of the wave which produced the most probable extreme green water and linear hull-girder wave-loads respectively by scaling the auto-correlation function of the linear hull-girder response spectrum with maximum mid-ship moment and bow-motion.

2. Extreme wave modelling

It has been traditional to study kinematics of extreme waves using experiments but several conflicting experimental measurements have been presented. This discrepancy in the conclusions of different authors about maximum particle kinematics at higher wave-steepness's, underscores the difficulty inherent in obtaining reliable experimental results at the top of extreme wave crests where incidentally, maximum velocities are expected. Theoretical methods are therefore desirable for obtaining more precise kinematics in the crest of extreme waves and several methods have been proposed.

2.1. *Viscous-flow modelling*

Yan and Ma (2008) have noted that with the exception of viscous-flow and fully non-linear potential flow methods, most proposed methods are unable to cope with very extreme surface deformations inherent in extreme waves. It is not intended to compare potential and viscous-flow in this study, rather a viscous-flow method is adopted because the present study is part of a larger study that seeks to establish the scale-effects of surface-tension and viscosity on the breaking of model-scale new-waves. Results of extreme wave modelling using viscous-flow-based methods have been presented by several authors (see e.g. Westphalen et al., 2008; Clauss et al., 2006, 2007, 2008; Kristiansen et al., 2005; Zhaowei et al., 2005; Kleefsman, 2005; Nielsen and Mayer, 2004). These studies were not concerned with the extreme wave defined in terms of steepness (slope of wave-front) as defined herein.

Viscous-flow solution of the Navier–Stokes equation is achieved using 3 main approaches—direct numerical simulation (DNS), large eddy simulation (LES) and Reynolds averaged Navier–Stokes (RANS). The LES and RANS techniques are implemented in commercial codes like FLUENT, CFX, STAR CCM and Flow3d. In the present work, the RANS technique implemented in Fluent is used.

2.2. *Wave generation in numerical wave tank*

Since wave-maker motions were not recorded in the physical experiment, the suggestion of prescribing velocities at the in-let according to a suitable wave theory (Kleefsman, 2005) was adopted. The new-wave theory is used to simulate the ''most probable extreme wave'' and by coupling the resulting velocities with the predicted height of water at the in-let, realistic waves were generated.

2.2.1. *The new-wave theory*

The ''new-wave'' theory presented by Tromans et al. (1991) accounts for the random nature of the sea, and gives the most probable extreme in a random field: notably, maximum wave crest elevation. It describes the surface elevation and by extension of the kinematics, of a focused wave group.

2.2.2. *Extended new-wave theory*

In Xu and Barltrop (2005) the new-wave theory is modified to generate waves of varying front-steepness's with equivalent likelihood of occurring as the unmodified (highest) wave. Essentially, this modification involves the transformation of a standard energy spectrum into a so-called slope spectrum and applying the new-wave theory to the modified spectrum to obtain the most probable wave having the specified steepness (slope of wave-front) which in the present case is the most probable maximum.

3. The present numerical wave tank

The mesh is a two dimensional structured grid, 360 m high and 468 m long and consists of a very fine region around the mean water level and very coarse regions far away from the mean water level (see Fig. 1). Cells in the very fine region are 0.66% (19.75 cm) of the extreme wave-height and is slightly finer than the 0.91% recommended for grid-independence (Westphalen et al., 2007, 2008).Water depth is kept at 300 m to generally represent deep-water (dominant wave-length = 187 m) and the length of the numerical tank is such that reflected waves do not reach the target position until well after the extreme event has occurred (target time). General sketch of the physical and numerical tanks are shown in Figs. 2 and 3.

The wave is simulated using a pressure based segregated unsteady solver with times steps of 0.01 s. Laminar flow and a