Breaking focused waves generated using the transient wave packet method and the breaking impact forces on a vertical cylinder

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Abstract

The presence of vital offshore infrastructure in deeper waters makes it essential to be able to evaluate the properties of steepness induced breaking waves. An extreme wave event in deep water can be modelled with a transient wave packet approach where shorter waves follow longer waves resulting in a steep, large extreme wave (focused wave) at a point of concentration. Wave breaking occurs when the steepness of the large wave crest front satisfies the breaking criteria. Generation of such extreme waves with phase-focussing waves through a spectrum such as the JONSWAP spectrum can be challenging. This paper shows the interaction of a focussed extreme wave generated using the transient wave packets method with a vertical cylinder under different impact scenarios.

Keywords: CFD, focussed waves, breaking waves, wave forces, REEF3D

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1 Introduction

The two major types of breaking waves in the marine environment are depth induced breaking waves and steepness induced breaking waves. Depth induced breaking waves are a feature of the coastal environment while the steepness induced breaking is a phenomenon observed in deeper waters away from the coast. The presence of offshore infrastructure in deeper waters makes it essential to be able to evaluate the properties of steepness induced breaking waves which vary from depth-induced breaking waves. The steepness induced wave breaking is a transient wave phenomenon where shorter waves followed by longer waves result in a focussed wave at a point of concentration. This steepness of this focussed wave induces wave breaking.

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Such a wave train is called a transient wave train are generated using a wave packet based approach.

Some of the notable numerical studies on focussed wave generation are Paulsen et al. (2014), Chen et al. (2014), Bihs et al. (2017*a*) among others. Here, irregular waves are generated based on an idealised wave spectrum such as the JONSWAP wave spectrum and the components are phase focussed such that the generated wave components focus at a predetermined point in the wave tank, to produce a focussed extreme wave event. Due to the inherent nature of the wave spectra, the individual wave components generated using this method to obtain a target focussed wave amplitude have large amplitudes themselves. This can result in wave breaking at a premature location and time than intended due to the super-positioning of certain large components. Thus, the desired focussed wave amplitude cannot be reached Bihs et al. (2017*b*).

The principle of transient waves was investigated by Davis and Zarnick (1966), where a wave train is generated with wave components of increasing wavelength. The longer, faster moving wave components then lead to the wave train converging at a certain location in the wave flume, producing a large focussed wave amplitude. The transient wave method was further improved by Kjeldsen (1982) for the generation of freak waves. A special Gauss-modulated amplitude spectrum to produce focussed extreme waves was presented by Clauss and Bergmann (1986) with wave groups of limited length being generated that converge at a predetermined location in the wave tank at a prescribed point in time. This technique has the advantage that a transient wave train can be generated, that needs a finite short duration of time for propagation and focussing at a predetermined location in the wave tank.

In this study the open source CFD model REEF3D Bihs et al. (2016) is used to generate a transient wave train using the wave packets approach and a breaking focussed plunging wave is simulated. The interaction of such a breaking wave with a slender vertical cylinder is studied under three different impact scenarios. The wave propagation in the numerical wave tank, the breaking wave characteristics and the total breaking wave forces on the vertical cylinder are calculated.

2 Numerical Model

The open-source CFD model REEF3D Bihs et al. (2016) used in this study solves the incompressible Navier-Stokes equations:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + g_i \tag{2}$$

where u is the time averaged velocity, ρ is the density of water, p is the pressure, ν is the kinematic viscosity, t is time and g is the acceleration due to gravity. Chorin's projection method Chorin (1968) is used for the pressure treatment. The high performance solver library HYPRE Center for Applied Scientific Computing (2006) is employed to solve the Poisson pressure equation using the PFMG-preconditioned BiCGStab algorithm Ashby and Flagout (1996).

The fifth-order conservative finite difference Weighted Essentially Non-Oscillatory (WENO) scheme proposed by Jiang et al. Jiang and Shu (1996) is used for the discretization of convective terms for the velocity u_i, the level set function ϕ, turbulent kinetic energy k and the specific turbulent dissipation rate ω. A TVD third-order Runge-Kutta explicit time scheme developed by Harten Harten (1983) is employed for time discretization in the model. It is a three-step scheme and involves the calculation of the spatial derivatives three times per time step. This scheme is used for the time advancement of the level set function and the reinitialisation equation.

A Cartesian grid is used in the numerical model for spatial discretisation. The Immersed Boundary Method (IBM) Peskin (1972) is used to incorporate the boundary conditions for complex geometries. The free surface is obtained using the level set method where the zero level set of a signed distance function, $\phi(\vec{x}, t)$ is used to represent the interface between air and water. Moving away from the interface, the level set function gives the closest distance of the point from the interface. The sign of the function represents the two fluids across the interface.The level set function is reinitialised after every iteration using a partial differential equation (PDE) based reinitialisation procedure presented by Sussman et al.Sussman et al. (1994) to retain its signed distance property after convection.

Wave generation and absorption is carried out using the Active Wave Absorption (AWA) method Schäffer and Klopman (2000). At the wave absorption boundary, the velocities opposite to the reflected wave are imposed so that the reflected wave is cancelled out. In this study, since a focussed wave train is used, the effect of reflection on the solution is negligible as the reflection occurs only after some duration after the focussed wave interaction with the structure in the tank. The focussed waves are generated using a Fourier amplitude spectrum as follows Henning (2005):

$$|F| = \frac{27\left(\omega - \omega_{beg}\right)\left(\omega - \omega_{end}\right)^2}{4\left(\omega_{end} - \omega_{beg}\right)^3} \tag{3}$$

where ω is the angular frequency, the ω_{beg} and ω_{end} define the extent of the Fourier spectrum on the frequency axis. The free surface, $\eta^{(1)}$ at the wave generation is then calculated as:

$$\eta^{(1)} = \sum_{i=1}^{N} A_i cos\theta_i \tag{4}$$

where A_i is the amplitude of the each wave component and θ_i is the phase of the each wave component generated. defined as:

$$\theta_i = k_i x - \omega_i t - \epsilon_i \tag{5}$$

where k_i is the wave number of each component. The parameter ϵ_i is the phase angle, which is chosen in such a way that each wave component focuses at a specified time t_f and location x_f.

3 Results and Discussion

The numerical simulations are carried out in a 25 m long, 5 m wide and 8 m high wave tank with a water depth of 4 m and a cylinder of diameter 0.7 m is placed using a grid size of $dx = 0.05$ m. The wave generation, focussing and breaking point are first confirmed using a 2D study in a numerical wave tank of the same dimensions. A grid resolution study is also carried out to verify the representation of the breaking wave. The focussed wave amplitude is set to 2.13 m with a focus distance of 15 m from the inlet boundary at 15 s with 500 wave components used in the wave generation. The wave breaking point is determined to be $x_b = 14.30$ m.

The 3D studies are carried out for three different impact scenarios:

- scenario 1: focussed wave breaking point at cylinder front surface
- scenario 2: focussed wave breaking point $1D$ in front of cylinder
- scenario 3: focussed wave breaking point $2D$ in front of cylinder

The resulting total breaking wave forces on the cylinder in the three different impact scenarios are presented in Fig.(1). It is seen that the maximum peak breaking wave force is seen in the scenario where the overturning focussed wave crest impacts the cylinder around crest level. This is slightly different from the numerical investigation with regular breaking waves on a slope Kamath et al. (2016) due to the varying nature of the breaking wave kinematics. The free surface features associated with the focussed breaking wave impact in scenario 1 are presented in Fig. (2). The vertical wave crest front impacting the cylinder, the separation of the wave front around the cylinder and the subsequent overturning of the wave crest are clearly seen.

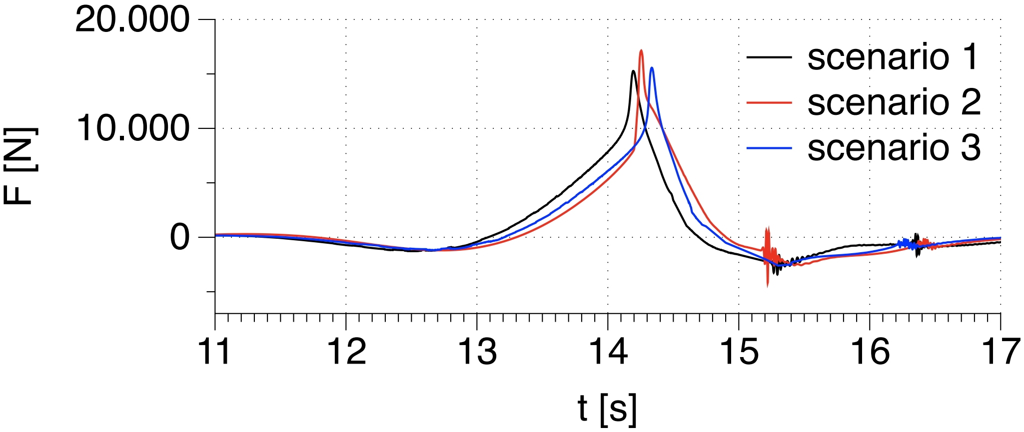
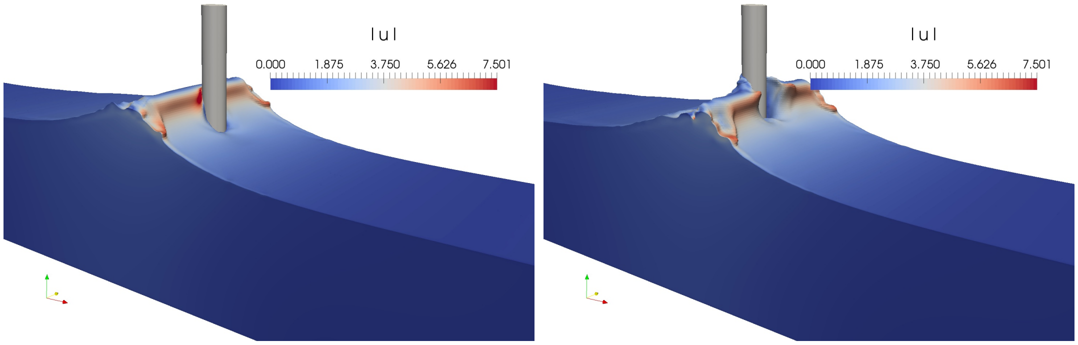


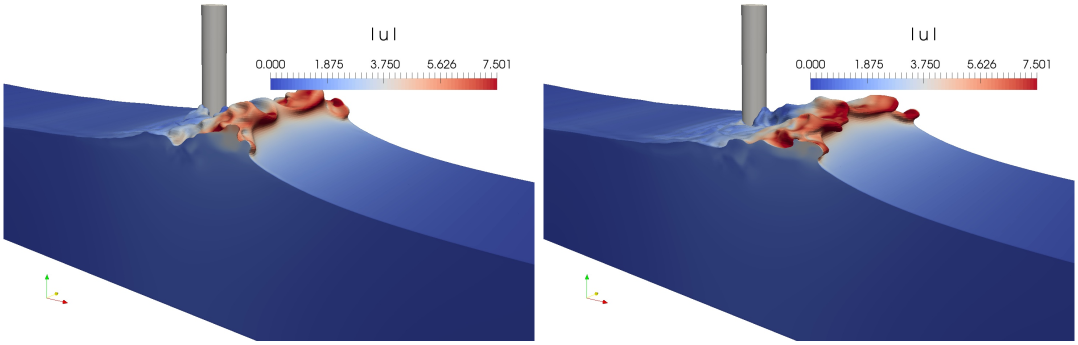
Figure 1: Breaking wave forces on a vertical cylinder due to focussed breaking wave impact at different cylinder locations

4 Conclusion

The open-source CFD model REEF3D is used to generate focussed breaking waves using the method of transient wave packets. The method produces extreme breaking waves without premature breaking of the individual wave components and different impact scenarios with a vertical cylinder are simulated. The results show that the maximum peak breaking wave forces are calculated for the scenario where the overturning focussed breaking wave impacts the cylinder just below the wave crest level. Free surface features involved in the different



(a) $t = 14.20$ s (b) $t = 14.40$ s



(c) $t = 14.75$ s (d) $t = 14.90$ s

Figure 2: Free surface features around the cylinder under the impact of a focussed breaking wave

impact scenarios are presented and discussed. Further studies regarding the distances of the cylinder from the breaking location of focussed waves produced using wave packets is to be carried out.

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