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Three-dimensional Large Eddy Simulation of air entrainment under plunging breaking waves

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Abstract

The scope of this work is to present and discuss the results obtained from simulating three-dimensional plunging breaking waves by solving the Navier-Stokes equations, in air and water, coupled with a dynamic subgrid scale turbulence model (Large Eddy Simulation, LES). An original numerical tool is used for the complete description of the plunging breaking processes including overturning, splash-up and the occurrence of air entrainment. The first part of the paper is devoted to the presentation and the validation of the numerical models and methods. Initial 3D conditions corresponding to unstable periodic sinusoidal waves of large amplitudes in periodic domains are then used to study further the ability of the numerical model to describe accurately the air entrainment occurring when waves break. The numerical results highlight the major role of this phenomenon in the energy dissipation process through a high level of turbulence generation. The numerical model represents a substantial improvement in the numerical modelling of breaking waves since it includes the air entrainment process neglected in most previous existing models.
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1. Introduction

Wave breaking is a very complex phenomenon, which is crucial to study as it plays an important role in sediment transport processes and in the transfer of mass and momentum in coastal zones. During the last two decades, a number of important reviews have described and discussed in detail the general mechanisms involved in the breaking process (Peregrine, 1983) and the surf zone dynamics (Battjes, 1988; Svendsen and Putrevu, 1996), while Christensen et al. (2002) detailed the recent advances that have been made in the numerical modelling and the measurement techniques for the study of the surf zone. In this current study, plunging breakers are considered.

The jet-splash cycles, occurring several times in a single plunging breaker, are responsible for the generation of a sequence of large-scale coherent vortices. Some authors have highlighted the generation and the importance of the air entrainment during the wave breaking process. A review of this aspect of the research area has been presented by Battjes (1988). Among the most important works to consider, Miller (1976) investigated experimentally the internal velocity field, indicating the importance of what he called breaker vortices, the size and strength of which are a function of breaker shape. Some pictures from Miller (1976) indicate the formation of a large quantity of air bubbles during the jet-splash cycles and illustrate that the vortices in plunging breakers significantly affect the bottom flow. Nadaoka and Kondoh (1982) showed experimentally that the velocity field is characterized by the existence of very active turbulence associated with air entrainment, which is responsible for wave energy damping in the surf zone. In their measurements, it appears that the entrained air bubbles are contained mostly in the large structures and diffused towards the bottom due to the eddies. Lin and Hwung (1992) found from experimental measurements that the main mechanism driving the motion in the bubble region was the vortex system that was

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generated during the jet-splash cycles. Experiments showed that the eddies contained a large quantity of air bubbles which enhanced the upwelling of sediment. Chanson and Lee (1997) observed that the rate of energy dissipation was increased with the bubble penetration depth and with the characteristic length of the plunging jet shear flow. Chanson et al. (2002) studied experimentally the mechanisms of air bubble entrainment by plunging breakers. The results highlighted strong vertical motions induced by the rising air bubbles.

Recent progress in applied mathematics and computer architecture offer the possibility of developing numerical models for studying the breaking processes. The most direct method to investigate numerically the complexity of the flow in the surf zone is to solve the Navier-Stokes equations, coupled with a mathematical treatment for the free surface. The first and simplest way of solving the Navier-Stokes model is the Direct Numerical Simulation, with the assumption that the mesh grid size used to discretized the numerical domain is sufficiently refined to take into account all the length-scales of the flow, which is never the case in practice. The majority of the studies followed that method (Abadie et al., 1998; Chen et al., 1999; Iafrati et al., 2001; Abadie, 2001; Guignard et al., 2001; Watanabe and Saeki, 2002; Lubin et al., 2003; Iafrati and Campana, 2003; Biausser et al., 2004; Song and Sirviente, 2004) and gave very promising results for the overall flow description, including the shoaling and the breaking of the waves. But the turbulence is not described or analyzed. A majority of these studies consider theoretical fluids, more viscous and lighter than water. Some recent research implemented the Reynolds Averaged Navier-Stokes (RANS) modelling of the surf zone (Lemos, 1992; Takikawa et al., 1997; Lin and Liu, 1998a,b; Bradford, 2000). These studies considerably improved in the understanding of the processes taking place in the surf zone but the turbulence levels at breaking were found to be overestimated. It should be noted that the work of Lin and Liu (1998a,b) and Bradford (2000) did not take the air entrainment into account. Except in the recent promising simulations shown by Lubin et al. (2003) and Biausser et al. (2004), all the previously cited work was two-dimensional simulations. Another very recent way of simulating turbulence in breaking waves is the Large Eddy Simulation (LES) method. Turbulence is taken into account in the Navier-Stokes equations thanks to a turbulence model for the subgrid scales of the flow. Zhao and Tanimoto (1998) first applied the LES method to breaking waves and showed very promising results compared with experimental measurements, considering a two-dimensional configuration. Mutsuda and Yasuda (2000) presented the first numerical results of three-dimensional Large Eddy Simulations of a plunging breaking wave, describing the air entrainment phenomenon. Christensen and Deigaard (2001) used a fully three-dimensional numerical tool based on the Navier-Stokes equations and studied spilling, weak and strong plunging breakers. Some very interesting visualizations and encouraging results describing the internal velocity field perturbed by three-dimensional vortices were shown. Similar results were obtained by Watanabe and Saeki (1999) with three-dimensional numerical simulations of plunging breakers. Very recently, Hieu et al. (2004) studied two-dimensional breaking waves and Zhao et al. (2004) implemented a new multi-scale method where the two-dimensional flow structures were fully resolved with a *k*–*l* RANS approach, while the three-dimensional turbulence interactions are modelled with a three-dimensional subgrid-scale eddy viscosity model. A good general agreement with experimental data was obtained, significantly improving the RANS results. Nevertheless, as the authors themselves stated, the air entrainment was not taken into account.

Few conclusions can be highlighted from this presentation of the previous studies. The experimental studies show that it is important to accurately describe the air entrainment process as it is responsible for a large amount of gas being entrapped and entrained in the water, which, in turn, plays a considerable role in the dissipation of the wave energy. Moreover, plunging breakers have the ability to entrain a large quantity of air at great depths, leading to long bubble residence time in the water column, which induces a large dissipation of energy (Chanson and Lee, 1997; Chanson et al., 2002). A considerable improvement in the numerical methods dedicated to the Navier-Stokes equations has been demonstrated, enabling the free surface and the general behavior of turbulent flow structures to be described with a very promising accuracy. Nevertheless, all the authors agree that solving the Navier-Stokes equations in an air–water configuration is a real challenge, due to the strong interface deformations and air entrainment phenomenon. Thus, the effect of air has not been studied yet in detail in most of the cited two- and three-dimensional simulations. The numerical methods are then a field of research requiring efforts and improvements in order to gain in accuracy and speed. The objective of our work is first to present new numerical methods for solving the two-phase flow Navier-Stokes equations in air–water configurations, including an up-to-date subgrid-scale model implemented in the numerical tool to take turbulence into account. Finally, we aim to describe the air entrainment and the internal velocity field under broken waves in three-dimensional configurations in order to contribute to the understanding of the energy dissipation processes involved in the wave breaking. We have chosen to study plunging breaking waves as their potential for air entrainment is much greater than the other breaker types (Cokelet, 1977; Chanson and Lee, 1997). Indeed, Miller (1976) experimentally measured the average bubble concentration in plunging and spilling breakers and indicated a larger bubble density presence in plunging breakers (about 31% in the late stage compared to 19% for spilling breakers).

The paper is organized in three sections. In what follows, Section 2 details the numerical tool and the interface tracking technique. In this section, we also discuss the originality of the methods. Two test cases are described to illustrate the ability of the numerical methods to handle accurately with two-phase flows. The scope of Section 3 is to present detailed three-dimensional descriptions of the overturning motion and the general flow motion observed during the breaking of a wave. The resulting splash-up phenomenon is accurately analyzed. A considerable care is taken to describe the generation of large scale vortices, the air entrainment process, and its implications for the turbulence generation and the dissipation energy occurring during the three-dimensional plunging breaking process.

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