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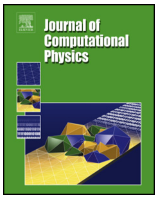

Modeling of ocean–atmosphere interaction phenomena during the breaking of modulated wave trains

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ABSTRACT

Air water interaction phenomena taking place during the breaking of ocean waves are investigated here. The study is carried out by exploiting the combination between a potential flow method, which is used to describe the evolution of the wave system up to the onset of the modulational instability, and a two-fluids Navier–Stokes solver which describes the strongly non-linear air–water interaction taking place during breaking events. The potential flow method is based on a fully non-linear mixed Eulerian–Lagrangian approach, whereas the two-fluid model uses a level-set method for the interface capturing. The method is applied to study the evolution of a modulated wave train composed by a fundamental wave component with two side band disturbances. It is shown that breaking occurs when the initial steepness exceed a threshold value. Once the breaking starts, it is not just a single event but it is recurrent with a period associated to the group velocity. Results are presented in terms of free surface shapes, velocity and vorticity fields, energy and viscous dissipation. The analysis reveals the formation of large vortex structures in the air domain which are originated by the separation of the air flow at the crest of the breaking wave. The form drag associated to the flow separation process significantly contributes to the dissipation of the energy content of the wave system. The energy fraction dissipated by each breaking event is distinguished.

1. Introduction

Breaking of surface waves, as an oceanic phenomenon, has many important implications. Scientifically, these are the problems of wave dynamics, atmospheric boundary layer, air–sea-interactions, upper ocean turbulence mixing, with respective connections to the large-scale processes including ocean circulation, weather and climate. In engineering, these are naval architecture, structural design of offshore developments and pipelines, coastal and bottom erosion, marine transportation, navigation, among many others [1].

The wave breaking process has received a considerable interest over the last decades, and some of the main features such as characteristics of the breaking onset and probability of breaking, have been described, quantified and parameterized (see e.g. [2] for a review). Much less has been done with respect to the breaking severity and to the air–water interaction phenomena taking place during the breaking event, which are the topics addressed in the present paper.

If the breaking strength is defined as energy loss in a single breaking event, then the breaking severity coefficient can be identified in a number of ways, that is through the measurements of the individual breaking wave, of the group where

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the breaking occurred, of spectra of the respective group before and after the breaking. Magnitude of such coefficient varies greatly, virtually from 0% to 100%.

Such wide range of variation cannot be disregarded or substituted with some mean value in applications which involve the breaking severity. This is for example the case of the wave-energy dissipation function employed in wave forecast models. It can in principle be directly determined as a product of the breaking probability and breaking severity, but without reliable parameterizations of the latter, a set of inventive indirect, usually speculative, methods have been elaborated to estimate the dissipation function [3].

The waves break when they reach some critical steepness at which the water surface becomes unstable and inevitably collapses [4,5]. A significant number of processes in the ocean can make this happen, e.g. hurricane wind-forcing, surface currents with horizontal velocity gradients, bottom proximity, modulation of long waves by short waves, among others. In typical background deep-water oceanic conditions for dominant waves, however, these processes are two: linear superposition and modulational instability [6].

Most of the research studies of the wave breaking process in controlled laboratory conditions was done for the linear-superposition scenario. Classical work of [7] concludes for such wave-breaking strength: “The loss of excess momentum flux and energy flux was measured and found to range from 10% for single spilling events to as much as 25% for plunging breakers”. That is, in such case the breaking severity is some limited fraction of the pre-breaking wave energy. In [8] similar conclusions were derived by using the two-fluids Navier–Stokes solver.

Remarkably different is wave-breaking severity in case of breaking caused by the modulational instability. In [9] it was demonstrated that it can be anything, from virtually 0%, i.e. a mere toppling the wave crest, to 100%, i.e. the breaking wave disappears. In fact, it can be shown that due to the modulational instability, the wave steepness can be significantly amplified up to three times the initial value, depending on the spectrum [10]. With such amplification effect, even apparently gentle wave system may break.

Despite such interest, only few laboratory studies have investigated the breaking originated by modulational instability, e.g. [11]. Numerically, the attention was focused to the identification of the conditions for the onset of the breaking by using weakly or fully non-linear potential flow methods, e.g. [12,13], but, to the authors knowledge, nothing is available for the breaking phase.

The description of the breaking process requires a model which can account for possible topological changes of the interface as well as for the air–water interaction processes. This is possible by using a two-fluid model which has been already used in the past to investigate the breaking obtained by linear-superposition [8,14].

The use of such highly expensive computational tools has to be limited in space and time. Even with large supercomputers available, simulations cannot span over all the scales ranging from the hundreds of kilometers, needed to describe the wave generation under the action of the wind in open ocean, up to the finest whitecaps detail with tiny drops and bubbles. But even focusing the attention to a basic problem like the instability of a modulated wave train, large computational domains (several fundamental wavelengths) are required for an accurate description of the wave dynamics and, moreover, very long time intervals, up to hundreds of wave periods, are needed for the development of the instability and for the onset of the breaking. The use of two-fluids numerical methods for such long intervals is too expensive from the computational viewpoint and, moreover, unless a highly refined discretization is adopted, there is the possibility that little amount of artificial dissipation of the numerical scheme, accumulated over long integration times, may prevent the development of the instability [15].

The common practice in wave forecasting is to use spectral approaches with ideal fluid assumption, in which a dissipation term is introduced to account for the breaking occurrence. A rather recent example is [16]. However, there is evidence that such dissipation term deserves a deeper investigation, e.g. [3,9,17]. This gave the motivation to undertake a study in which a potential flow model is used to describe the wave dynamics up to the onset of the breaking and then the solution is passed to a two-fluid solver to describe the breaking phase. The final aim is to derive an improved parameterization of the breaking dissipation which can relate the pre-breaking spectrum to the energy dissipation and to the post-breaking spectrum. In the present work, a fully non-linear potential flow model is adopted in a first stage during which the modulational instability develops. At the onset of the breaking, the potential flow solution is used to compute the velocity field in the air and water and to start the two-fluids simulation. It is worth remarking that both computational models use a two-dimensional assumption. Note that the initialization procedure adopted here can be used without any relevant change, in combination with spectral approaches. The fully non-linear method was preferred as it better identifies the breaking occurrence.

The combined method is applied to the study of the modulational instability of a fundamental wave with two side bands components. The analysis follows the development of the instability for different values of the initial steepness of the fundamental component, and two-fluids numerical simulations are used from a time just before the onset of the breaking. Results are presented in terms of free surface shape, velocity and vorticity fields and energy dissipation. It is worth noticing that some results have been already presented in [18]. Therein, the energy amount transferred in air as a consequence of the dipolar formation is analyzed and it is shown that, in the simulation period, the integrated energy dissipation in air is about twice that in water. The result is found to be almost independent of the wave steepness. Here a more detailed discussion of the computational approach and several additional physical aspects are provided.

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