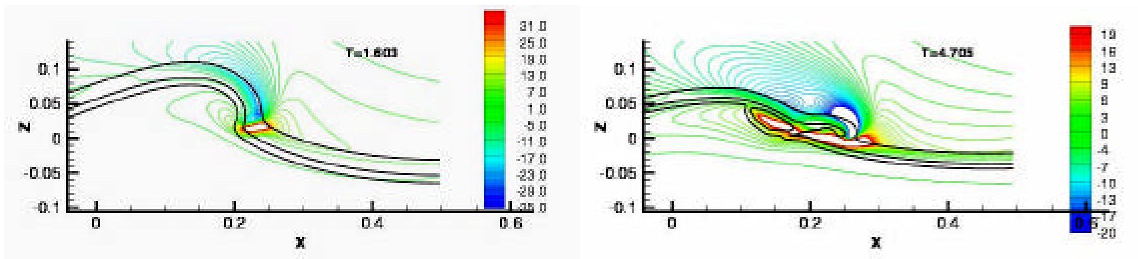
Navier-Stokes Simulation of Steep Breaking Water Waves with a Coupled Air-Water Interface



Instantaneous transverse vorticity contours for a spilling breaking wave (left) and a plunging breaking wave (right). Black lines represent the air-water interface.

Wave breaking on the ocean surface significantly facilitates the transfer of mass, momentum, heat and energy across the air-sea interface. In the context of the near field flow about a surface ship, the breaking bow wave is a key element to the bubbly signature and an appreciable portion of the wave drag of the ship. Yet, despite its direct effect on many aspects of ocean engineering, this phenomenon is not well understood even at a basic level. Most of the knowledge has been contributed by experiments in the laboratory and the field although results are often limited due to the difficulty in taking measurements of local quantities during the breaking event. Numerical solution of the breaking wave problem has generally been limited to the pre-breaking phase as it avoids complex mechanisms such as surface re-entry, spray formation, air entrainment and strong turbulence. Additionally, relatively few experimental or numerical studies exist which dynamically couple the air-water interface.

The objective of this thesis is to contribute to the knowledge of steep breaking waves in the context of the coupled air-water interface. Of central importance are basic kinematics and dynamics, the rate of energy dissipation and energy flux at the interface during the breaking event. To this end, a systematic study of a range of breaking waves is performed by direct numerical simulation (DNS) of the Navier-Stokes equations using an Eulerian interface capturing method. The advantage of the DNS approach is that all physical scales are resolved and no turbulence closure models are necessary. However, because of this, DNS is limited to the study to moderate Reynolds numbers with a relatively high computational cost for each simulation. For this reason, this study is limited to two-dimensional flows at Reynolds number $O(10^3)$. The interface capturing method used is a modified form of the level set method which is better suited for simulating coupled air-water flows. The level set method provides a natural numerical treatment of the coupled air-water interface through complex surface topology changes. Thus, no *ad-hoc* treatment of the air-water interface during the breaking event is necessary.

The key findings of this thesis represent new contributions to the study of breaking waves in three distinct areas. The first is the kinematics and dynamics of deep water breaking waves for both spilling and plunging types. For the waves in this study, there was no indication of flow reversal or separation in the water while the air flow showed separation on the front face of the wave and over the crest. Localized shear regions are found in spilling breaking waves and curvature effects are identified as the dominant mechanism of vorticity generation in both types of breaking waves.

The second area is the energy dissipated by breaking waves. The volumetric dissipation rates as well as its spatial variation for both air and water are presented for the range of waves in this study. While the water volume experienced an increase in dissipation rate during the breaking event, the increase is more pronounced in the air volume to the point that it becomes the same order of magnitude as that in the water for some waves. The amount of energy in the wave lost due to breaking is quantified as a function of the energy in the wave prior to breaking. A threshold below which waves do not break is identified and qualitative comparisons to experiment are made when applicable.

The third area is the transfer of energy at the air-water interface during breaking which is an aspect of the breaking process that has not received much attention in the literature. In this thesis, the formulation of a term in the energy equation which accounts for the energy flux rate at the air-water interface is presented. The waves in this numerical study give evidence that this quantity is appreciable. Although the calculation of this term is sensitive to errors associated with the conservation of energy, values as high as 25% of the energy lost to breaking are found. At the Reynolds numbers in this study, the dominant mechanism for each type of wave is identified as inviscid for spilling breaking waves and viscous for plunging breaking waves.

This numerical effort has contributed to the basic knowledge of wave breaking at moderate Reynolds numbers. Through the inclusion of the coupled air-water interface, unique insights to the kinematics, dynamics, dissipation and energy fluxes of breaking waves was obtained. The information gained in this study provides an initial step towards physics-based turbulence models for the study of wave breaking at larger scales.

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