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ENTRAINMENT OF AIR BUBBLES DURING STRONG VORTICITY–FREE-SURFACE INTERACTION

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Summary The air entraiment induced by vorticity–free-surface interaction is here numerically investigated using a two-fluid model which describes the flow in air and water as that of a single incompressible fluid whose density and viscosity vary smoothly across the interface. The numerical approach is used for the simulation of a viscous vortex pair vertically rising toward the free surface. Several flow conditions are studied aimed at understanding the role played by vortex intensity, surface tension and gravity forces on the amount of entrained air and the mechanisms for its entrainment.

INTRODUCTION

The problem of air entrainment generated by free surface dynamics has several important implications in nature and in the technical context as well. In the naval field interest in air bubble entrainment is connected to the design of stealth ships: the long bubbly wake developing past fast ships, makes them visible through Sintetic Aperture Radar (SAR) images of the ocean surface. In addition to visibility problems, the dynamics of air bubbles entrained in the bow region is responsible for noise generation which alters the response of the Sonar.

On the basis of the above consideration, a research activity has been undertaken aimed at studying some of the mechanisms leading to air entraiment and understanding the dynamics of the entrapped bubbles. A two-fluids numerical approach has been initially developed to study the complex flow generated by the breaking of free surface waves [3]. At large scales wave breaking is characterized by the formation of a plunging jet which leads to the encompassment and to the successive entrainment of a significant amount of air. At shorter scales, owing to the increased role played by the surface tension, the breaking event takes place in a more gentle way with the plunging jet being replaced by a bulge which slides down along the forward face of the wave thus leading to the formation of a strong shear layer beneath the free surface which originates at the toe of the bulge and propagates downstream [4]. In this condition the total amount of entrained air is significantly reduced and the vorticity–free-surface interaction becomes the leading mechanism for the entrainment of air.

In order to study this mechanism for air entrainment, the simpler problem of a vortex dipole rising below a free surface is here considered. This problem has been studied in the past by several authors either experimentally or numerically. In [7] the three dimensional effects are experimentally investigated showing that free surface striations are caused by short wavelength instability of the vortex pair. The free surface deformation caused by a rising vortex pair has been studied in [8] in the framework of an inviscid assumption. Ohring & Lugt did a careful numerical study of both the vertical [6] and oblique [5] ascent of a viscous vortex pair toward the free surface. In their study, which assumes a two-dimensional flow, different intensities of the vortex pair have been analysed and different values of the surface tension and of the gravity force have been used to vary the free surface “stiffness”. The role of the free surface stiffness on the generation of secondary vorticity and on the path of the primary vortex are investigated. Since Navier-Stokes equations were solved on a boundary-fitted grid, their study couldn’t get too close to the incipient condition for air entrainment when a too strong grid deformation takes place.

In the present paper the same study is carried out with the help of a two-fluid approach which allows to go closer and also further than the incipient conditions for air entraiment. The two-dimensional assumption is still retained for the sake of the computational effort. Ratio among physical quantities, like density and viscosity, are assumed to be the same as for air and water. Some of the conditions used in [6] are analysed for the purpose of the code validation. For a mild vorticity–free-surface interaction a rather good agreement is obtained. For a stronger interaction, in contrast with results presented in [6], air entrainment is found. A deeper verification of the results is currently running aimed at better understanding the reason for the differences in the results.

NUMERICAL MODEL

The flow in air and water is numerically computed with the help of a Navier-Stokes solver for a single incompressible fluid whose density and viscosity values vary smoothly across the interface. The system of Navier-Stokes equation is written in curvilinear coordinates and discretized on a non staggered grid layout by using a numerical approach based on that originally proposed in [9] suitably modified to deal with the two-fluid system in [2]. The method makes use of a fractional step approach: the momentum equation is first advanced in time by neglecting the pressure contribution (predictor step) which is successively reintroduced by enforcing the continuity of the velocity field (corrector step). The diagonal part of the dominating diffusive terms are computed with a Crank-Nicolson scheme whereas all other contributions are treated explicitly with a three-step Runge-Kutta method.

The location of the air-water interface is captured as the zero level of a function $d(\boldsymbol{x}, t)$ which is initialized as the signed normal distance from the interface with $d > 0$ in water and $d < 0$ in air. During the motion the function d is transported with the flow and the new interface location is reconstructed as the level $d = 0$. Hence, the function d is reinitialized as the signed normal distance from the new interface configuration.

As proposed in [1], surface tension effects are included in the momentum equation as a continuum force acting on a neighborhood about the interface whose thickness is $2\delta_T$. To avoid troubles when evaluating derivatives numerically, the jump in density and viscosity is also smeared on a small region about the interface whose width is $2\delta_P$. Numerical tests, aimed at understanding how the two parameters δ_T and δ_P affects the solution, have shown that both of them should be at least three grid cells to guarantee stability of the calculation but should not be too large for the sake of the accuracy.

PRELIMINARY RESULTS

The numerical model discussed above is used for the simulation of the vertical rising of a vortex pair toward the free surface. The study is carried out for different values of the Reynolds (Re), Froude (Fr) and Weber (We) numbers. Initial and boundary conditions are assumed equal to that used in [6]. In order to validate the numerical procedure, a mild interaction is analysed by first. Flow parameters are assumed as $Re = 100, Fr = 0.2, We = 0$ and results, shown in Fig. 1, are in rather good agreement with those reported in [6].

By reducing the gravity, that is for $Fr = 0.4$, the free surface stiffness is reduced and a stronger interaction takes place. For this condition, the results obtained by the present model, reported in Fig. 2, seem to differ from those reported in [6]. In particular, the present model predict some entrainment of air which was not shown in [6]. A deeper verification of the results is currently running aimed at clarifing this point.

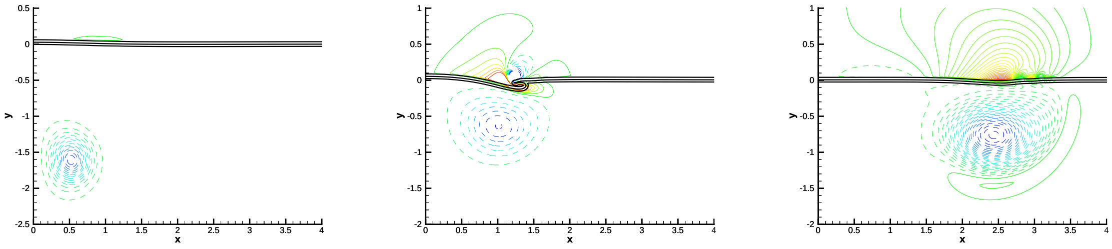

Figure 1. For a mild vorticity–free-surface interaction no air is entrained. Three density levels are plotted with black lines ($\varrho/\varrho_w = 0.03, 0.50, 0.95$). Vorticity contours are also shown with dashed lines used for negative levels.

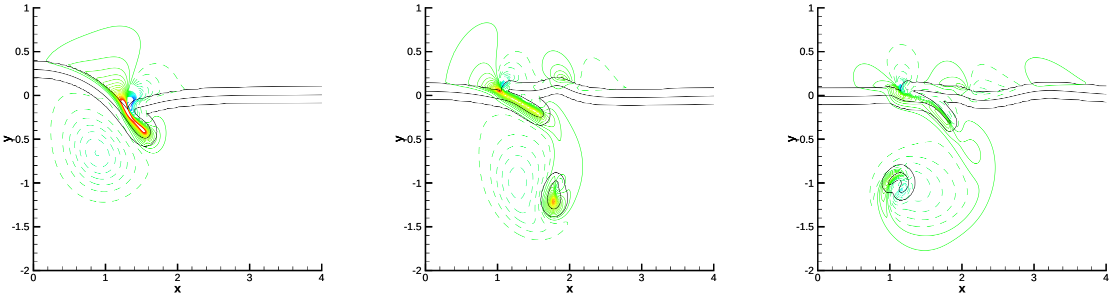

Figure 2. Three different stages of a stronger vorticity–free-surface interaction leading to air bubble entrainment.

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