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Decay of gravity-capillary waves in air/water sheared turbulence

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ABSTRACT

Direct Numerical Simulation (DNS) is used to analyze the wave-decay process in a countercurrent air/water turbulent flow. Three dimensionless numbers describe the problem: the Reynolds number Re_τ (which measures the importance of inertia compared to viscosity), the Weber number *We* (which measures the importance of inertia compared to surface tension) and the Froude number *Fr* (which measures the importance of inertia compared to gravity). We keep Re_τ constant and we vary *We* and *Fr*. Regardless of the values of the physical parameters, we observe an initial exponential decay followed by the achievement of a new statistically stationary condition. The parameters characterizing this exponential decay do depend on the specific values of *Re, Fr* and *We*. Wavenumber spectra computed at different time instants during the wave decay process reveal that the spectral properties of waves change in time: starting from a condition characterized by the predominance of low-wavenumber waves, we observe a "blue shift" of the energy spectra towards higher wavenumbers, indicating the emergence of a strong capillary behavior. At the new asymptotic steady state condition, wave energy spectra are in fair agreement with the predictions given by the Wave Turbulence Theory. We also characterize the statistical behavior of the interface deformation to highlight the interplay between gravity and surface tension in determining the interface structure.

1. Introduction

Understanding the physics of the deformable interface separating air and water in two phase turbulent flows is of great importance in many industrial and environmental flows, from the design of condensers/evaporators to the prediction of air-sea interaction for climate studies. Most of the previous theoretical (Zakharov et al., 1992), experimental (Falcon et al., 2007a) and numerical (Dyachenko et al., 2004) studies of wave dynamics in two-phase air/water flows considered statistically-stationary state conditions. Much less is known about nonstationary wave turbulence, which however occurs in any transient situation from a stationary state to another due to a change in the external forcing condition of waves. This is the case of wave decay, developing when the external forcing applied to maintain the wave dynamics is suddenly reduced or removed (sudden change of wind conditions).

Despite its importance, experimental studies on the wave decay process of surface waves are only a few. Deike et al. (2012) analyzed the free decay of capillary waves on a fluid surface and found that the average amplitude of the free surface deformation decays exponentially in time as the wave maker is stopped. During the decay process, the authors observed that the wave spectrum maintains a self-similar slope consistent with that characterizing the steady state regime. These findings support the idea that each instantaneous realization of freely decaying capillary turbulence is similar to the steady state capillary turbulence, though with a decreasing energy content in time. Recently, Bedard et al. (2013) studied the raising and decaying process of surface gravity waves in a large laboratory flume. Relevant to the present study is the observation that the entire decay process is made of a short initial power-law decay followed by an exponential decay (due to viscous friction). The above-mentioned experimental studies confirm previous theoretical predictions made in the framework of Wave Turbulence Theory (WTT) on the decay rate of gravity and capillary waves and on the self similarity of the wave spectrum (Falkovich et al., 1995; Kolmakov, 2006; Zakharov et al., 1992). However, experimental results (with only few exception, see Berhanu and Falcon, 2013) are usually limited to local measurements of the interface displacements. Obtaining a time-resolved description of the entire interface deformation in space (distribution of the interface displacement and of the interface curvature) is still an open issue.

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In this context, Direct Numerical Simulation (DNS) can help providing the time evolution of the interface deformation together with a detailed description of the flow above and below the interface. This is extremely important for non-stationary wave conditions, where it is essential to record the coupled fluid/interface interaction in time and space. Unfortunately, direct numerical simulations of the wave decay process have never been performed in a coupled air/water flow systems.

To fill this gap, we propose here a DNS-based study on the wave decay process. We consider a countercurrent flow configuration, where air and water are driven by an imposed pressure gradient and flow in opposite directions. We employ the numerical technique already used in Zonta et al. (2015) to study the wave generation process. We start from an initial wavy interface and we let the system evolve by reducing the interfacial shear. After a transient exponential decay, a new asymptotic steady state condition is observed. We try to characterize the statistical properties of waves both during the transient decay and at the new asymptotic condition. We finally highlight the role of gravity and surface tension in determining the interface deformation.

2. Governing equations and numerical modeling

With reference to the schematics of Fig. 1, we consider a turbulent air-water two-phase flow. The air and water phases are separated by a deformable interface and flow in opposite directions under the influence of an imposed pressure gradient. We use a cartesian coordinate system, with the streamwise, spanwise and interface-normal directions being denoted by $x-$, $y-$ and $z-$ respectively. Assuming newtonian and incompressible fluids, the dimensionless continuity and Navier–Stokes equations are:

$$\nabla \cdot \mathbf{u} = 0, \tag{1}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{Re_\tau} \nabla^2 \mathbf{u}, \tag{2}$$

where $\mathbf{u}$ is velocity, p is pressure and Re_τ is the shear Reynolds number (properly defined later). The reference quantities employed to obtain dimensionless variables in each subdomain (air and water) are the shear velocity $u_\tau = \sqrt{\tau_{int}/\rho}$ (τ_{int} being the shear stress at the interface and ρ the fluid density), the kinematic viscosity ν and the half depth of each subdomain h.

The numerical methodologies available to capture the interface dynamics belong to two different categories. The interface can be described using an approximate approach (where the interface is considered a thin transition layer) or using an exact sharp approach (where the interface is a zero-thickness layer). Examples of approximate numerical approaches include Level Set (LS), Phase Field (PF), Volume of Fluid (VOF) and Front Tracking (FT) methods. We will briefly discuss only VOF, due to their widespread use in the description of surface waves. VOF methods are based on a concentration field C defined at the center of each computational cell. The concentration C assumes uniform values $C = 1$ and $C = 0$ in the bulk fluids, whereas $0 < C < 1$ in the cells crossed by the interface. Suitable reconstruction algorithms are required to obtain the correct shape of the interface from the value of C. The accuracy/efficiency of these algorithms is crucial to avoid a wrong estimate of the local normal vector n and of the local curvature (which are indeed important in the computation of capillary forces).

In the exact sharp approach, the fluid properties change sharply from one fluid to the other when crossing the zero-thickness interface. Differently from the approximate methods mentioned above, in this case boundary conditions must be prescribed at the moving interface. The only numerical method that can be used to obtain a sharp description of the interface is a fully resolved boundary fitted method (as the one employed in the present work). Boundary fitted methods are based on the advection of interfacial points subject to an external velocity (and stress) field. Once the position of the interfacial points is updated, the domain is deformed. A domain mapping technique must be used to transform the deformed domain into a cartesian one when a Fourier/Chebyshev pseudo-spectral solver is adopted to solve the governing equations of the flow (as in the present case). Note that this combined approach maintains a spectral accuracy with negligible numerical dissipation/dispersion. A detailed presentation of the numerical method is provided in the following.

In the present case, the distorted physical domain (x, y, z, t) is mapped into a rectangular parallelepiped in the computational domain $(\psi_1, \psi_2, \psi_3, \tau)$ using an algebraic mapping (De Angelis et al., 1997)

$$\psi_1 = x, \quad \psi_2 = y, \quad \psi_3 = \frac{z}{h + \eta(x, y, t)}, \quad \tau = t, \tag{3}$$

where η is the function describing the deformed interface boundary (see Fig. 2). Governing equations can be transformed from the physical space $X = (x, y, z, t)$ to the computational space

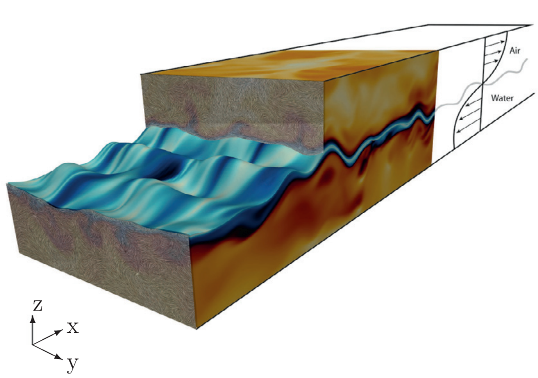

Fig. 1. Sketch of the physical domain: water (resp. air) flows below (resp. above) the interface. Water and air are driven by a fixed pressure gradient and flow in opposite directions. Note that the interface deformation has been magnified (× 100).

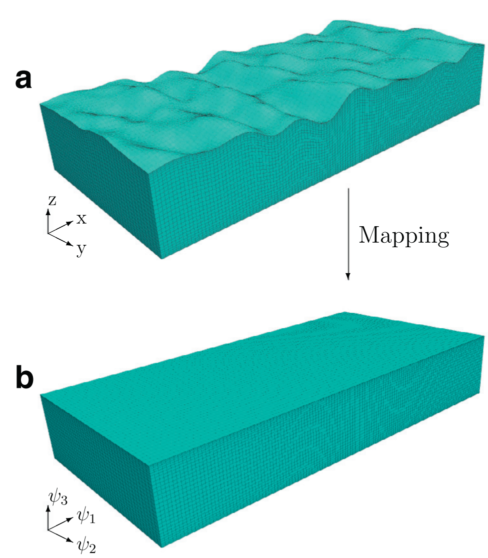

Fig. 2. Physical and computational domain: the deformed physical domain (x, y, z) is transformed into a cartesian computational domain (ψ_1, ψ_2, ψ_3) using a proper coordinate transformation (mapping).

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