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THE STRUCTURE OF TURBULENCE AND OTHER MOTIONS BENEATH AN AIR-WATER INTERFACE

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ABSTRACT

ONR Grant N00014-94-0190, "The structure of turbulence and other motions beneath an air-water interface" had a performance period from 11/01/93 to 05/31/97. Both physical experiments and numerical simulation experiments were used to study three-dimensional, unsteady, real-fluid flows beneath the air-water interface. The goals were to develop (1) an understanding of the flow physics and (2) a numerical simulation tool that allows *accurate prediction* of the motion from a specified set of initial conditions. This report summarizes our progress and cites the relevant references.

The focus of the numerical work was the kinematics of the interaction between surface waves and a turbulent current. The numerical method produces a time-accurate simulation of an unsteady turbulent free-surface flow in three space-dimensions.. The simulations are large-eddy simulations [LES], employing a dynamic two-parameter model, new treatment of the kinematic boundary condition in mapped space, and a moving boundary-fitted grid. A method of domain decomposition to enhance near surface resolution was also demonstrated.

The simulations show that the turbulence in the near-surface region is enhanced by the interactions between non-breaking waves and a turbulent shear current. Several conclusions were drawn: (1) simulation of three-dimensional, unsteady turbulent free-surface flows is practical using this numerical method; (2) a finite-amplitude surface wave can cause vertical stirring of the fluid where a surface wave propagates over a current with a strong shear; (3) turbulence in the near-free surface region is enhanced by interaction of the wave straining field acting on turbulent structures; and (4) rapid distortion of the turbulence by the wave straining field plays an important role in the wave/turbulence interactions.

A novel measurement technique, digital particle tracking velocimetry (DPTV), was developed and used to make near-surface measurements of the velocity field in wavy and non-wavy open channel flows. This approach is based on cross-correlation digital particle image velocimetry (DPIV), eliminates the need to interpolate the randomly located velocity vectors (typical of tracking techniques), and results in significantly improved resolution and accuracy. In particular, this approach allows for the direct measurement of mean squared fluctuating gradients, and thus several important components of the turbulent dissipation. The measurements made include the wave-induced mean flow, near-surface mean and oscillatory viscous boundary layers, and near-surface turbulence structure. The measurements of the wave-induced mean flows demonstrate that laboratory waves are rotational waves, inducing a depth decaying negative Eulerian-mean velocity that, near the free-surface, is exactly the negative of the Stokes' drift.

1. INTRODUCTION

ONR Grant N00014-94-0190, "The structure of turbulence and other motions beneath an air-water interface" had a performance period from 11/01/93 to 05/31/97. The research program coupled physical experiments and numerical simulation experiments to study three-dimensional, unsteady, real-fluid flows beneath the air-water interface. The overall goals were to develop (1) an understanding of the flow physics and (2) a numerical simulation tool that allows *accurate prediction* of the motion from a specified set of initial and conditions.

In the numerical simulation arena, our long-term objective was to be able to accurately simulate the interaction of wind, waves, vorticity, and turbulence at the ocean's free surface; including the effects of surface tension, surface contaminants, breaking waves, and submerged or surface-piercing bodies. Our grounding premise in the code development was that we must not inherently limit the potential for future expansion through choices made for the solution algorithm. Although we cannot simulate the entire physics of the ocean surface at this time, we have designed the code so that we can continue to build on it until we reach our long-term goals.

The main goals of the experimental work were to understand the mechanisms by which waves, sheared mean flows and turbulence interact, to document the effects of these interactions on the combined wavy flow, and to assemble a data base of wavy turbulent flows that can be used to assess the fidelity of free-surface codes like that which we are developing. Of particular interest to us were the effects of waves on turbulence properties like Reynolds stress and turbulence dissipation, on boundary layer structure (at the free surface and at a solid wall), and the extent to which gravity waves on sheared flows can be rotational.

Our working hypothesis was that the principal means of interaction between waves and turbulent flows is either by wave straining of turbulence or through the effects of wave vorticity, i.e., inherent rotationality of the waves, which are otherwise generally supposed to be irrotational. The Craik-Leibovich theory of Langmuir cells, which assumes irrotationality, describes an example of the former type of mechanism. It shows how the net effect of nearly periodic straining and advection of the turbulence by waves can yield rectified forces that act to produce large streamwise vortices, or at least intensified vertical and spanwise motions and enhanced streamwise correlation scales. It is also seems reasonable that the smallest, dissipative scales are in continuous equilibrium with the wave strains, leading to enhanced rates of turbulence dissipation. This is based on the fact that the wave flow fields must appear to be nearly steady to the smallest scales of turbulence which evolve on time scales short compared to typical wave periods.

Assessing the extent to which the dissipation scale motions are altered by the waves, the effects of wave strains on large-scale structure etc. requires the measurement of spatial flow structure. Accordingly, a key goal of our research program has been to develop a velocity measuring technique capable of recording wavy turbulent flows with sufficient resolution and accuracy to measure wave-induced vorticity and turbulence dissipation in the presence of large nearly irrotational strains.

During the grant period significant progress was made. This report summarizes this progress and cites the relevant references where details may be found.

2. NUMERICAL METHODS

Our basic premise was to focus on building a code with a strong future potential, an example being our retention of the ability of the code to handle arbitrary surface slopes. This has slowed our progress at times, but we believe that this has been the correct course. Our accomplishments include development of a numerical simulation code and development, improvement and application of a subgrid-scale model for large eddy simulations of turbulent flow.

2.1 Code for the simulation of three-dimensional free-surface flows with arbitrary surface slopes.

The culmination of this area of the work is the dissertation of Hodges [1997]{See also: Hodges, et al. [1996] and Hodges and Street [1996]}. The focus of this dissertation is the kinematics of the interaction between surface waves and a turbulent current. This basic research task was directed at increasing our understanding of the processes that occur where surface waves and turbulent undercurrents interact. The primary motivation was two-fold: (1) to investigate the physical processes of wave turbulence interaction in the near-surface region that affects both the "signature" of the turbulence at the free surface and the mixing beneath the surface, and (2) to develop a numerical simulation method that can be used for future investigations of free-surface phenomena where finite-amplitude waves, turbulence, and structures (such as ship hulls) interact with viscous and nonlinear effects.

In this work, we showed that the turbulence in the near-surface region is enhanced by the interactions between non-breaking waves and a turbulent shear current. The irrotational strains of the wave-induced velocity field serve to rotate and stretch the sheared turbulence in the current. As a wave crest passes over a turbulent current, it pulls the turbulent structure up toward the crest and into the region above the level of the trough. This can be considered an enhancement of the turbulent "stirring" of the fluid. As the trough approaches, the turbulence becomes trapped in and near the free-surface boundary layer. Successive crests and troughs appear to have a "pumping" effect on the turbulence trapped in this near-surface region. This intensification of the turbulent structures is due to the stretching and compression of vortex lines, which can be seen in data animations of the fluctuating enstrophy. These effects are demonstrated to occur with non-breaking finite-amplitude waves, and possibly contribute to the persistence of turbulent structures at a free-surface in the wake of a ship.

The numerical method used is an extension of Zang, et al. [1994] to a moving boundary-fitted grid. The simulations are large-eddy simulations [LES] and employ the dynamic two-parameter model described in the next section. The Hodges dissertation includes a detailed study of the numerical method developed for a time-accurate simulation of an unsteady turbulent free-surface flow in three space-dimensions with a progressive, finite-amplitude, free-surface wave. The simulation uses the time-dependent Navier-Stokes equations with the nonlinear kinematic and dynamic boundary conditions. A new treatment of the kinematic boundary condition in mapped space is presented and a new grid is generated at each time step with a Poisson equation method adapted from the 3DGRAPE/AL code [Sorenson and Alter, 1996]. The method is demonstrated to be accurate in the simulation of two-dimensional and three-dimensional flows of laminar standing waves. Comparisons with experimental studies [Cowen, 1996; see below] validate the method for turbulent free-surface flows, and provide insight into the flow behavior seen in laboratory flumes. Visualization of instantaneous and phase-averaged flow variables provide insight into the dynamics of the wave-turbulence interactions.

From this work several conclusions can be drawn: (1) simulation of three-dimensional, unsteady turbulent free-surface flows is practical using the numerical method developed in this research project; (2) a finite-amplitude surface wave can cause vertical stirring of the fluid where a surface wave propagates over a current with a strong shear; (3) turbulence in the near-free surface region is enhanced by interaction of the wave straining field acting on turbulent structures; and (4) rapid distortion of the turbulence by the wave straining field plays an important role in the wave/turbulence interactions.

2.2 Model for the subgrid-scale turbulence in large eddy simulations.

This work began with the presentation of the dynamic mixed model of Zang, et al. [1993]. Salvetti and Banerjee [1995] improved on that model. The final paper in this series [Salvetti, et al., 1997] describes large-eddy simulations of decaying turbulence in an open channel, using different dynamic subgrid-scale models, viz. the dynamic model of Germano, et al. (DSM), the dynamic mixed model (DMM), and the dynamic two-parameter model of Salvetti and Banerjee (DTM). These models are incorporated in a finite-volume solver of the Navier-Stokes equations [Zang, et al., 1994]. A direct numerical simulation of this flow conducted by Pan and Banerjee [1995] showed that near the free surface turbulence has a quasi-two-dimensional behavior. Moreover, the quasi-two-dimensional region increases in thickness with the decay time, although the structure remains three-dimensional in the central regions of the flow. The large-eddy simulations with both the DMM and the DTM reproduce the features of the decay process observed in the direct simulation and handles the anisotropic nature of the flow. Nevertheless, the addition of the second model coefficient in the DTM improves the agreement with the direct simulation. When the DSM is used, significant discrepancies are observed between the large-eddy and the direct simulations during the decay process at the free surface.

2.3 Application of domain decomposition methods to wavy topography

Calhoun and Street [1997] reported on the LES of a laboratory-scale channel flow. Both a wavy and a three-dimensional "topography" were studied; these studies have relevance to near surface flows in the ocean and the atmosphere. In this simulation we used the solver and SGS model discussed above, together with two non-aligned, overlapping component grids. This domain decomposition allows fine-scale resolution near the wavy surface and coarse grid scales in the interior of the flow. A comparison was made with available experimental data and the agreement was excellent. The ability to give detailed estimates of the friction and pressure drag on the wavy surfaces was clearly demonstrated.

3. EXPERIMENTS

The culmination of this area of work is found in the dissertation of Cowen [1996]. A novel measurement technique, digital particle tracking velocimetry (DPTV), was developed and used to make near-surface measurements of the velocity field in wavy and non-wavy open channel flows. These measurements include the wave-induced mean flow, near-surface mean and oscillatory viscous boundary layers, and near-surface turbulence structure. The measurements of the wave-induced mean flows demonstrate that laboratory waves are rotational waves, inducing a depth decaying negative Eulerian-mean velocity that, near the free-surface, is exactly the negative of the Stokes' drift. Laser Doppler anemometry measurements indicate that this velocity deficit is transported at the waves' group velocity and is not a consequence of retrograde currents induced by the zero-net mass transport requirement. Lagrangian surface drift measurements indicate that the wave-induced surface drift is zero for clean free-surfaces, contradicting Stokes' theory, which predicts that waves induce the Stokes' drift. The measured mean properties of laboratory-generated waves are better described as Gerstner waves [a rotational wave exactly satisfying the free-surface boundary condition and the zero mass flux boundary condition on the wave maker] than Stokes waves.

The near-surface measurements reveal the existence of a dual viscous boundary layer. The inner layer is oscillatory, extremely thin and satisfies the free-surface stress condition. The outer layer is spatially growing and is driven by the wave amplitude decay and resultant excess wave momentum (radiation stress). Turbulence measurements indicate that this mean stress is balanced by the Reynolds stress. Turbulence measurements near a quiescent free-surface show the expected decay in the vertical velocity fluctuations as the free-surface is approached and the coincident increase in the horizontal fluctuations to conserve turbulent kinetic energy. The presence of capillary waves in the wavy flow measurements contaminate the very-near-surface measurements of turbulence intensity; however, away from the free-surface indications are that the turbulence intensities are reduced relative to the quiescent case.

The new approach [Cowen and Monismith, 1997a&b] to digital particle tracking velocimetry (DPTV) based on cross-correlation digital particle image velocimetry (DPIV) is particularly significant because it eliminates the need to interpolate the randomly located velocity vectors (typical of tracking techniques) and results in significantly improved resolution and accuracy. In particular, this approach allows for the direct measurement of mean squared fluctuating gradients, and thus several important components of the turbulent dissipation. The effect of various parameters (seeding density, particle diameter, dynamic range, out-of-plane motion, and gradient strength) on accuracy for both DPTV and DPIV were investigated using a Monte Carlo simulation and optimal values were reported. Validation results were presented from the comparison of measurements by the DPTV technique in a turbulent flat plate boundary layer to laser Doppler anemometer measurements in the same flow as well as direct numerical simulation data. The DPIV analysis of the images used for the DPTV validation is included for comparison.

4. SUMMARY

ONR Grant N00014-94-0190, "The structure of turbulence and other motions beneath an air-water interface" had a performance period from 11/01/93 to 05/31/97. The research program coupled physical experiments and numerical simulation experiments to study three-dimensional, unsteady, real-fluid flows beneath the air-water interface. The overall goals were to develop (1) an understanding of the flow physics and (2) a numerical simulation tool that allows *accurate prediction* of the motion from a specified set of initial and conditions.

The focus of the numerical work was the kinematics of the interaction between surface waves and a turbulent current. The numerical method produces a time-accurate simulation of an unsteady turbulent free-surface flow in three space-dimensions using a moving boundary-fitted grid. The simulations are large-eddy simulations [LES] and employ the dynamic two-parameter model based on work by Salvetti and Zang. A new treatment of the kinematic boundary condition in mapped space is presented. A method of domain decomposition to enhance near surface resolution was also demonstrated.

Several conclusions were drawn from the simulations: (1) three-dimensional, unsteady turbulent free-surface flow simulations are practical using the numerical method developed in this research project; (2) a finite-amplitude surface wave can cause vertical stirring of the fluid where a surface wave propagates over a current with a strong shear; (3) turbulence in the near-free surface region is enhanced by interaction of the wave straining field acting on turbulent structures; and (4) rapid distortion of the turbulence by the wave straining field plays an important role in the wave/turbulence interactions.

A novel measurement technique, digital particle tracking velocimetry (DPTV), was developed and used to make near-surface measurements of the velocity field in wavy and non-wavy open channel flows. The new results in significantly improved resolution and accuracy. In particular, it allows for the direct measurement of mean squared fluctuating gradients, and thus several important components of the turbulent dissipation. The measurements made include the wave-induced mean flow, near-surface mean and oscillatory viscous boundary layers, and near-surface turbulence structure. The measurements of the wave-induced mean flows demonstrate that laboratory waves are rotational waves, inducing a depth decaying negative Eulerian-mean velocity that, near the free-surface, is exactly the negative of the Stokes' drift.

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