Goals

The long range goal of this research is to obtain, by laboratory experimentation and associated theoretical/numerical analysis an increased understanding of the dynamics of stratified flow past three-dimensional obstacles. Emphasis is given to such phenomena as blocking, flow separation, vortex shedding, lee-wave generation, unsteady characteristics of the free stream, and lift and drag on the obstacles in question.

Objectives

The near term objective of the research is to study the dynamics of simple body shapes (e.g., spheres) free to move in the vicinity of bounding surfaces under the action of oscillatory background motions. This objective was motivated by the recently expressed Navy interest in the motion of cobbles within and beyond the surf zone.

Approach

The experiments will employ a computer-controlled tow tank and a new standing wave facility 4 m long, 1 m wide and 1 m deep to be constructed in the near future. The flows will be observed by utilizing a variety of flow visualization techniques, including dye tracers, electrolytic precipitation, neutrally buoyant particle tracers and laser-induced fluorescence. A two-component laser-Doppler velocimetry system and hot film anemometer system are available for obtaining quantitative measures of the motion fields. An image processing system for obtaining motion fields from neutrally buoyant particle tracers is also now available. Concurrent with the laboratory experimental phase of the program, theoretical and numerical analyses of the motion of model cobbles will be considered.

Tasks Completed

Experiments on the horizontal oscillation of a sphere in a linearly stratified fluid were completed, the data were analyzed and a paper has appeared in the Journal of Fluid Mechanics (Lin et al. 1994). In a similar fashion, work was completed on the vortex shedding of a streamwise oscillating sphere translating through a stratified fluid; the work has appeared in the Physics of Fluids (Lin et al. 1994). Experiments have been completed and accompanying numerical models developed for a long circular cylinder undergoing
either pure vertical or pure horizontal oscillations in a linearly stratified fluid. These results have been submitted and are presently under review by the Journal of Fluid Mechanics (Xu et al. 1994). Experiments were also completed on analyzing the turbulent wake of stratified flow past a long horizontal cylinder. These results have been submitted for publication to the Physics of Fluids (Xu et al. 1994).

Results

Horizontal Oscillation of a Sphere

The flow field induced by a sphere oscillating horizontally in a linearly stratified fluid was studied using a series of laboratory experiments. The resulting flows are shown to depend on the Stokes number $\beta$, the Keulegan-Carpenter number $KC$ and the internal Froude number $Fi$. For $Fi < 0.2$, it is shown that the nature of the resulting flows is approximately independent of $Fi$ and, based on this observation, a flow regime diagram in the $\beta$-$KC$ plane was developed. The flow regimes include: (i) fully-attached flow; (ii) attached vortices; (iii) local vortex shedding; and (iv) standing eddy pair. An internal wave flow regime is also identified, but, for such flows, the motion field is a function of $Fi$ as well. Some quantitative measures are given to allow for future comparisons of the results with analytical and/or the experiments of Tatsuno and Bearman (1990) on right circular cylinders oscillating in homogeneous fluids.

Vortex Shedding of a Horizontally-Translating, Streamwise-Oscillating Sphere

The flow past a horizontally translating, streamwise oscillating sphere through a linearly stratified fluid was investigated in a series of laboratory experiments. The pertinent governing parameters are shown to be the internal Froude number $Fi$, the Reynolds number $Re$, the Keulegan-Carpenter number $KC$ and the normalized frequency $Sf$. A $KC$ against $Sf$ regime diagram for flows at $Fi = 0.07$ and $Re = 190$ was developed; for these parameters, the flow is approximately two dimensional in the horizontal zone $-1/2 < z/D < 1/2$, where $z$ is the vertical coordinate and $D$ is the sphere diameter. Numerous flow regimes are delineated, and it is shown that the regime boundaries approximate the lines of constant $u_l/u_0 = 2\pi(KC)(Sf)$, where $u_l$ is the amplitude of the sphere oscillation and $u_0$ is the magnitude of the mean background flow. Vortex shedding occurs for the entire range of experiments at these $Fi$, $Re$ values. Lock-on of the shedding frequency to the sphere oscillation frequency occurs for $u_l/u_0 > 0.1$.

Flows at large $Fi$ are shown to exhibit three-dimensional motions in the near wake and, owing to stratification, exhibit vertical collapse at a certain distance downstream. The far wake develops into a horizontal vortex street pattern for all flows when stratification is present. At large $Fi$, $Re$ combinations, turbulent patches are found in the wake. The inverse normalized streamwise distance between shed vortices (an effective Strouhal number) is shown to scale as $Sf$, independent of $KC$. Measurements of the horizontal separation angles and times for the collapse of the vertical structure were also made.

Vertical or Horizontal Oscillation of a Long Right Circular Cylinder

The flow field induced by either the vertical or horizontal oscillation of a long right circular cylinder (axis horizontal) in a linearly stratified fluid was investigated in the laboratory and by a numerical model. Flow regime diagrams in the $\omega/N$ against $a/D$ planes for fixed
$ND^2/\nu$ are developed from the laboratory observations; here $\omega$ is the cylinder oscillation frequency, $N$ is the buoyancy frequency, $a$ is the oscillation amplitude and $\nu$ is the kinematic viscosity of the fluid. Internal waves are not observed in the far field for experiments for $\omega/N > 1$. On the other hand, for $\omega/N < 1$, the far field is dominated by internal waves. During the early stages of the cylinder oscillation, this wave field is in close accord with linear theory. As time passes, wave reflections from the free surface and the tank boundaries lead to a highly complex flow field. Numerical experiments, under the assumption of incompressible flow and employing the Boussinesq approximation, are carried out for the initial phases of the motion for one case at $\omega/N > 1$ and one at $\omega/N < 1$. The instantaneous streamline, vorticity and density fields obtained from the numerical experiments at various phases in the oscillatory cycle are in good agreement with the laboratory observations.

Turbulent Wakes of Stratified Flow Past a Cylinder

Laboratory measurements were carried out to investigate the evolution of a turbulent wake behind a right circular cylinder moving in a linearly stratified fluid. The flow field is determined by the internal Froude number $F_i$ and the Reynolds number $Re$, but at high $Re$, $F_i$ becomes the only governing parameter. Measurements show that stratified turbulent wakes can be classified into three flow regimes, based on $F_i$. When $F_i \leq 2$, the wakes do not grow downstream, and remain at approximately constant height. For $2 \leq F_i \leq 3$, the wakes grow to a maximum height at $Nt \approx 5$ and then collapse physically; for $Nt \geq 3$, the maximum height is achieved at $Nt = 2.5$, before the collapse begins. The evolution of such other length scales as the Ozmidov, Kolmogorov, overturning and Thorpe scales and the maximum Thorpe displacements were measured, and their behavior in the above $F_i$ ranges delineated. Length scale diagrams for the evolution of stratified turbulence in cylinder wakes were constructed, and compared with previous theoretical predictions. The present results provide new insights into the evolution, collapse and two-dimensionalization of stratified turbulent flows.

Accomplishments

The laboratory experiments, associated data analysis and numerical models have demonstrated the nature of a wide range of flow phenomena resulting from the interaction of obstacles with steady and unsteady free stream flows in the presence of background stratification. The horizontally oscillating sphere case, for example, has shown how periodically shed vortices can feed large scale vortical motions in the vicinity of the obstacle. The ability to have available both physical models, as well as numerical ones, as in the cases of the vertically and horizontally oscillating cylinders, greatly facilitates the understanding of the physics of such complex phenomena. A better understanding of the nature of turbulence in stratified flows is in need of more quantitative measurements of the type done for the uniform steady flow past a cylinder described above.


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b. Number of papers published in refereed journals: 4
c. Number of books or chapters submitted but not yet published: 0
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Grad Students Minority: 0 and Post-Docs Minority: 0