Annual Report
Experimental and Theoretical Studies of Wakes in Stratified Flows
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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 a 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 β, 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 β-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 $u_1/u_0 = 2\pi(KC)(Sf)$, where u_1 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 $u_1/u_0 > 0.1$.

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 ω/N against a/D planes for fixed

ND^2/ν are developed from the laboratory observations; here ω is the cylinder oscillation frequency, N is the buoyancy frequency, a is the oscillation amplitude and ν 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 Fi and the Reynolds number Re, but at high Re, Fi becomes the only governing parameter. Measurements show that stratified turbulent wakes can be classified into three flow regimes, based on Fi. When $Fi \lesssim 2$, the wakes do not grow downstream, and remain at approximately constant height. For $2 \lesssim Fi \lesssim 3$, the wakes grow to a maximum height at $Nt \approx 5$ and then collapse physically; for $Nt \gtrsim 3$, the maximum height is achieved at $Nt \approx 2.5$, 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 Fi 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 discribed above.

94-P Davies, P. A., Boyer, D.L., Fernando, H.J.S. and Zhang, X. 1994 On the periodic motion of a circular cylinder through a linearly stratified fluid. Phil. Trans. Roy. Soc., Lond. A, **345**, 353-386.

94-P Lin, Q., Boyer, D.L. and Fernando, H.J.S. 1994 The vortex shedding of a streamwise-oscillating sphere translating through a linearly stratified fluid. Phys. Fluids A, **6(1)**, 239-252.

94-P Flor, J. Fernando, H.J.S. and van Heijst, G.J.F. 1994 The evolution of an isolated turbulent region in a two-layer fluid. Phys. Fluids A, **6(1)**, 287-296.

94-P Lin, Q., Boyer, D.L. and Fernando, H.J.S. 1994 Flows generated by the periodic horizontal oscillation of a sphere in a linearly stratified fluid. J. Fluid Mech., **263**, 245-270.

94-PS Xu, J., Fernando, H.J.S. and Boyer, D.L. 1994 Turbulent wakes of stratified flow past a circular cylinder. Physics of Fluids, under review.

94-PS Xu, J. , Boyer, D.L., Fernando, H.J.S. and Zhang, X. 1994 Motion fields generated by the oscillatory motion of a circular cylinder in a linearly srtatified fluid. Journal of Fluid Mechanics, under review.

92-PS Fernando, H.J.S., van Heijst, G.J.F. and Fonseka, S.V. 1993 The evolution of an isolated turbulent region in a stratified fluid. J. Fluid Mech., under revision.

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a. Number of papers submitted to refereed journals but not yet published: 3

b. Number of papers published in refereed journals: 4

c. Number of books or chapters submitted but not yet published: 0

d. Number of books or chapters published: 0

e. Number of printed technical reports and non-refereed papers:0

f. Number of patents filed: 0

g. Number of patents granted: 0

i. Number of presentations at workshops or professional society meetings: 0

j. Honors/awards/prizes for contract/grant employees: 0

k. Total number of graduate students and post-docs supported at least 25% this year on this contract/grant:

Grad Students: 2 and Post -Docs 0 ,including
Grad Students Female: 1 and Post-Docs Female: 0
Grad Students Minority: 0 and Post-Docs Minority: 0