1990 End-of-Fiscal Year Report

Robert F. Beck, Project Director

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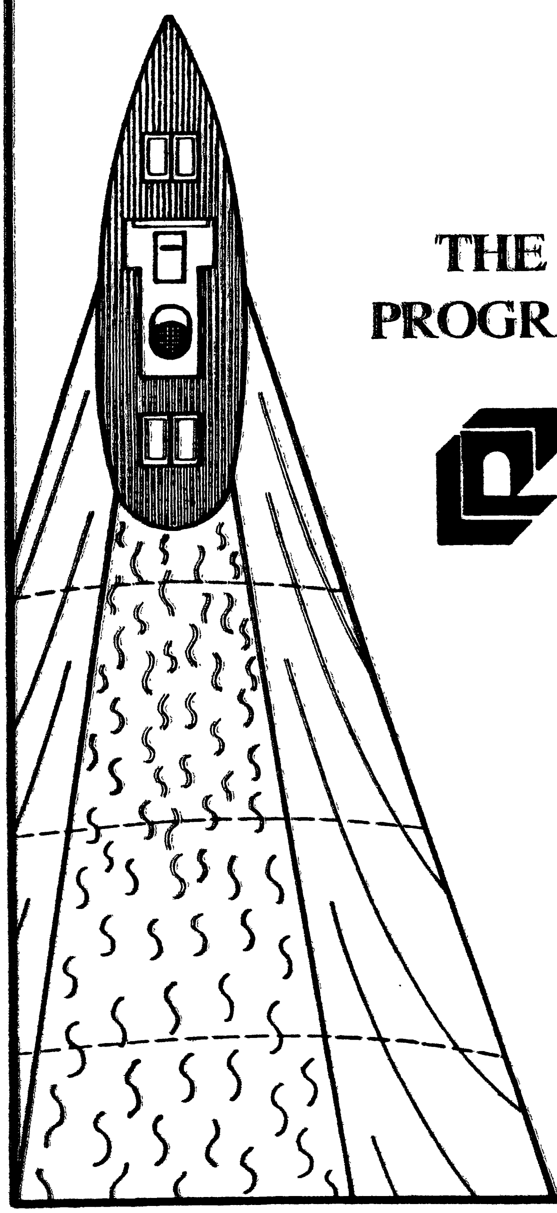

THE UNIVERSITY OF MICHIGAN PROGRAM IN SHIP HYDRODYNAMICS

COLLEGE OF ENGINEERING

NAVAL ARCHITECTURE & MARINE ENGINEERING

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SHIP HYDRODYNAMIC LABORATORY

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PROGRAM IN SHIP HYDRODYNAMICS
Executive Summary Report

by
Robert F. Beck, Project Director

The fourth year of the Program in Ship Hydrodynamics has seen a significant increase in research results. Much of the development work done in previous years is now complete. Both the HMF and LDA were used in experiments for which the results were published. Two new faculty members in the Department of Naval Architecture and Marine Engineering (Profs. Marc Perlin and Dave Walker) have been added to the program. Appendix I lists the year-end reports written by the principal investigators for each of the research projects. These reports summarize the research goals, significant accomplishments of the past year and proposed research for next year. Also presented is pertinent information such as publications and a list of participants in each project. In the second appendix are the abstracts from papers published or submitted for publication during the past year.

Substantial progress has been made in understanding the intricacies of the HMF. The slope scanning system is now capable of 80x80 points in a tenth of a second. The standard deviation of a measurement is still larger than desired due to the extreme sensitivity of the mepsicon camera picking up extraneous points. Various options are presently being examined to alleviate the problem. The performance of the warm spot tracking system has been improved by not using conventional videotape as the recording medium for the thermal images. Recording the output signals directly on an optical disk system has resulted in higher resolution and elimination of synchronization problems.

An inaugural set of hydrodynamic experiments utilizing the HMF in conjunction with ERIM's calibrated radar scatterometers were completed by Meadows and Lyzenga during the past year and published at the 18th ONR Symposium. The experiments investigated the role of buoyancy driven flows as a mechanism in maintaining the dark centerline wake observed in radar images of full scale ships. The results of this set of experiments indicate that the flow field generated by the buoyance flux associated with a rising bubble cloud is sufficient to produce significant wave/current interactions at the free surface. For these flows, blocking of wind generated Bragg waves is sufficient to produce suppression of the radar return comparable to that observed at full scale.

The 3-component, fiber optic, Laser Doppler Anemometer developed by Prof. Willmarth and Doug Anthony was put into operation this past year. The traversing system has also been designed and built. The LDA has been used in a small test tank but has not yet operated in the model basin. The initial set of experiments to use the LDA were designed to measure the hydrodynamic properties of a turbulent jet exiting just below the free surface. Both the three components of the mean flow and the nine components of the Reynold's stress were measured at various locations in the jet. The most startling observation was the formation of a thin surface layer of fluid flowing away from the jet centerline. This same phenomena has been observed in model scale and full scale measurements. The outward surface velocities in the wake of a ship are thought to be partly responsible for several characteristics of SAR images.

Several experimental and theoretical investigations this past year have examined the interaction of vorticity and the free surface. Large scale vortex ring experiments were conducted by Song, Bernal and Meadows in the towing tank using a generator capable of making rings up to 18 cm in diameter. As the ring approaches the free surface an instability develops that causes the ring to break up into individual vortex lines which reconnect with the free surface to form U-shaped vortices. Significant surface disturbances are associate with the interaction, break-up, and subsequent reattachment. The processes are well predicted by numerical calculations that have been done using techniques developed by the PSH.

The effects of surfactants on vortex free surface interaction have been investigated both experimentally and analytically. In a small tank, Bernal and Kachman have used Oleyl alcohol to produce controlled levels of surface contamination. For vortex rings approaching the free surface at incident angles of 20°, the upper half of the ring always reconnected even though a strong secondary vortex was generated because of the presence of the surfactant. However, with large contamination levels the secondary vorticity was strong enough to prevent the reconnection of the bottom half of the vortex ring. Analytic calculations have been done by Tryggvason and his students using the full viscous flow equations and finite difference techniques. The results show the generation of secondary vorticity for relatively small amounts of surfactant and are in qualitative agreement with the experiments.

The research into nonlinear waves is also continuing. Cao, Schultz and Beck have completed fully nonlinear calculations for a submerged spheroid started from rest. The results have been compared with linear calculations, Dawson method calculations, and other nonlinear calculations. For deep submergence all methods agree very well. As expected, the nonlinear calculations show significant differences for shallow submergences. Work is proceeding to identify solitons in the wake and to do computations for surface piercing bodies. Perlin has initiated experiments to study capillary-gravity wave interactions and wave stability. Messiter, Schultz and graduate students have analytically studied wave stability using the dissipative nonlinear Schroedinger equation. They are presently investigating effects due to spatial variations of surfactant concentrations.

Work on the capstone experiments for this URI have been initiated under the direction of Prof. Walker. A one-twelfth scale model of the Quapaw has been towed in the ship model basin with and without a propeller to measure various hydrodynamic properties of the wake. The evolution of the subsurface turbulent wake was studied using florescent dye injected into the boundary layer. The model was then towed through a stationary laser sheet oriented normal to the direction of travel. In this way a cross-section of the turbulent portion of the wake can be obtained and its evolution with distance aft of the model can be tracked. One of the features shown by the visualization was the rapid growth of a thin layer just under the free surface. This is consistent with the jet experiments, other model scale experiments and full scale measurements. It does not appear, as has been conjectured, that the lateral growth is due to any large scale vortical structure coming off the bilges.

Shadowgraph visualization of the free surface was done in the wake region of the Quapaw to investigate the surface disturbances. There is a very clear boundary between the turbulent region and the irrotational flow region of the Kelvin wake. In this boundary region, the unsteady random waves generated by the turbulence tend to organize into slightly irregular unsteady waves propagating outward with their crest aligned at a small angle relative to the ship track. This feature of the wake could be partially responsible for the bright vee wakes in a SAR image. The shadow-graph images are also populated by numerous small, circular dark spots indicative of the reattachment of vortices as they interact with the free surface. The surface disturbances tend to decrease as the distance downstream is increased.

The addition of a rotating propeller caused the flow in the stern region to be modified significantly; however, the effects on the behavior of the turbulent surface layer were small.

The width of the wake was unchanged. The propeller decreased the turbulent surface activity near the centerline but increased the activity near the edges, thus the unsteady waves at the edge were increased in amplitude.

More tests with the Quapaw are planned for the coming year. The HMF will be used to more accurately quantify the free surface disturbances. The LDA may or may not be used. Due to budget constraints it probably will not be mounted on the moving carriage.

The project on flow visualization under the direction of Prof. Beier will be discontinued next year due to budget constraints. The work on Han's Ph.D. thesis supported by this project was completed in October. The project developed a very powerful tool for flow visualization using color coded iso-surfaces. The iso-surface visualizes the magnitude of the velocity and the color gives the direction of the velocity vector. Using vector processing, a Stardent graphics software package, and a specially developed contouring algorithm, response times for the visualizations of the iso-surface is very good. Visualization techniques developed under this project have been used by many of the PSH researchers.

APPENDIX I

3.1.1 Hydrodynamic Monitoring Facility

Principal Investigator: G.A. Meadows

<u>Research Summary</u>

Description of Scientific Research Goals: To understand the hydrodynamic mechanisms which facilitate the remote sensing of ship generated disturbances, experimental measurements are required which correlate the hydrodynamic properties of the flow field with the electromagnetic properties of the sensing field.

To make these measurements, specialized facilities have been under development. This research effort has concentrated on the development of new, and accurate high-speed instrumentation which measures tangential velocities, displacements, and slopes of the water surface. The goal is to compare these observations through benchmark hydrodynamic studies with simultaneous radar scatterometer measurements. This data set will allow spatial and/or temporal correlations of the hydrodynamic surface, with the radar and infrared signatures.

Project 3.1.1 has developed a set of three instruments to measure the free surface height, slope and surface velocities concurrently. The slope is determined on a user specified two-dimensional grid, using refracted laser light. The surface height and surface velocities are measured by tracking thermal images of "wave spots" - also on a user specified two-dimensional grid - which are created on the free surface by a CO_2 laser pulse. The warm spots are used to obtain velocity profiles, vorticity, and/or divergence on the free surface.

Significant Results in the Past Year: Substantial progress on the Hydrodynamic Monitoring Facility (HMF) has been made in two major areas. First the basic quality of the instrument system has been greatly improved. Improvements in both hardware and software have resulted in a quantification of the accuracy and resolution of the monitoring system. Second, the inaugural set of hydrodynamic experiments utilizing the HMF in conjunction with ERIM's calibrated radar scatterometers have been successfully completed and published. These experiments investigated the role of buoyancy driven flows as a mechanism in maintaining the dark centerline wake observed in radar images of full scale ships.

Primarily as a result of the dedicated work of our new faculty, substantial improvements have been made in the HMF hardware. Precise realignment and some redesign of the optical path in the visible laser system (two-dimensional slope scanner) have resulted in greater throughput efficiency. This accomplishment both stabilized and reduced the standard error of the slope measurement as well as increased the field of view for this system. Slope measurement errors are now on the order of 0.5 degrees with a scan area of 0.5 meter in diameter. Similarly, the IR system performance has been greatly improved by eliminating conventional videotape as the recording medium for the thermal imagers. Optical disk systems have provided two distinct advantages: higher resolution and elimination of synchronization problems. The result of these modifications is a thermal warm spot persistence of 0.75 seconds at a rate of approximately 30 spots/second.

The above improvements have allowed the successful completion of the inaugural experiment of the HMF. This combined hydrodynamic/electromagnetic experiment investigated the effect of buoyancy driven flows (produced by a rising bubble cloud) in maintaining large scale coherent structures in the wake of surface ships. Preliminary results of this experiment were presented at the ONR Bubbly Flows Meeting in Miami, and a detailed accounting of the experiment and instrumentation was presented at the Eighteenth Symposium on Naval Hydrodynamics. In addition, a second paper entitled "2-D Surface Reconstruction of Water Waves" by Wu and Meadows has been published by IEEE. This paper presents the analytical framework for surface reconstruction utilizing the HMF laser slope system.

Plans for Next Year's Research: Two major research topics are of critical importance to the URI and HMF Facility. As a result of the past years' efforts, we are now in a position to conduct our first series of experiments focusing on the wake of a towed ship model. The approach will be two-pronged, and is aimed at wake characterization and hydrodynamic/electromagnetic scaling. The flow visualization experiments of Prof. Walker will characterize the wake of Quapaw. The second set of experiments utilizing the Quapaw will involve a joint HMF-ERIM experiment to investigate the relevant hydrodynamic/electromagnetic scaling parameters between tow tank and full scale. Mechanics of Kelvin wave scaling are well understood; however, in the near centerline wake region both full scale and model ships generate "Bragg wave" components. The scaling of these unsteady waves, thought responsible for bright "V" wakes, remains a fundamental unanswered scientific question. The capabilities of the HMF and the ERIM Doppler radar facility provide a unique opportunity to address this issue. In addition, the combination of this scaling investigation with the flow visualization and wake characterization studies of Prof. Walker will provide a strong symbiotic experimental framework.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers in Refereed Proceedings/Journals

Meadows, G., D. Lyzenga, J. Lyden, and R. Beck, "Nonintrusive, Multiple-Point Measurements of Water Surface Slope, Elevation and Velocity", *Proceedings* of the Eighteenth Symposium on Naval Hydrodynamics, Ann Arbor, MI, August 20-24, 1990.

Wu, Z. and G. Meadows, "2-D Surface Reconstruction of Water Waves", *Proceedings* of Oceans '90, Oceanic Engineering Society of IEEE, Washington, D.C., September 24-26, 1990.

2. Technical Reports

Meadows, L., G. Meadows, A. Troesch, S. Cohen, K.-P. Beier, R. Beck, and A. Reed, "LaGrangian Velocity Profiles in the Wake of a High Speed Vessel", Program in Ship Hydrodynamics Technical Report No. 89-11, July 1989.

Meadows, L. and G. Meadows, "Detailed Analysis of Spaceborne Synthetic Aperture Radar Images of Ship Wakes", The University of Michigan, Ocean Engineering Lab Report No. OEL-9004-DTRC-0001, August 1990.

3. Presentations

Meadows, G., D. Lyzenga, R. Shuchman, G. Root, and L. Meadows, "Buoyancy Driven Bubbly Flows of the Surface Ship Wake", ONR Accelerated Research Initiative, Dynamics of Bubbly Flows, Inaugural Workshop, 1990.

LIST OF HONORS/AWARDS

none

LIST OF PARTICIPANTS

G.A. Meadows, Associate Professor
L. Meadows, Research Associate
M. Perlin, Assistant Professor
D. Walker, Assistant Professor
G. Root, M.S.E. Graduate
M. Song, Ph.D. Candidate
E. Wright, Research Engineer
Z. Wu, Ph.D. Candidate

D. Lyzenga, ERIM
J. Lyden, ERIM
R. Shuchman, ERIM
S. Gaboury, ERIM
J. Schipp, student

3.2.3 Large Scale Structure in Ship Wakes

Principal Investigator: W.W. Willmarth

<u>Research Summary</u>

Description of Scientific Goals: The problem addressed in this research is that of the experimental and theoretical investigation of the large scale structure of the three-dimensional turbulent flow in boundary layers and wakes produced by surface ships. The investigation is designed to provide basic information about the fundamental flow processes beneath and near the surface in the vicinity of the ship hull and propulsion system and in the resulting unsteady turbulent flow for downstream. It should then be possible to identify the flow processes responsible for the wake signatures of surface ships. Portions of the experimental facilities and equipment used for this research were developed and shared with Professor Bernal in his parallel investigations of the "Vortical Structure of Ship Wakes".

The investigation of these wake flows has led to the detailed study of the two-dimensional flow beneath the surface produced by a vortex pair and the three-dimensional flow produced by a turbulent jet which is very near the surface. These two problems include many of the fundamental flow processes which occur in the wake of a ship which sheds vorticity.

The primary goal of this research is to obtain as broad an understanding as possible of the dominant characteristics of the large scale structure of the flow field in the wake of a ship.

Significant Results in the Past Year:

<u>Facilities and flow measurement and visualization equipment</u>. During the time from October 1989 and July 1990 we completed or purchased and put into use the following equipment and instrumentation: a small towing tank 2.5 x 2.5 x 24 feet fitted with a wave development tank 2.5 x 8 x 10 feet in the center part of the towing tank, a 3 component laser Doppler anemometer (LDA), a 20 watt Copper Vapor Laser and a 5 watt Argon-Ion Laser for flow visualization and an image analysis system (NSF Grant and cost sharing with the University, no change to ONR).

<u>Delta wing and vortex pair wake flows</u>. We designed and constructed a computer controlled vortex pair generation system. Two flaps, which are initially vertical, are rotated towards each other until they touch, thus producing a pair of vortices which rise to the free surface. The system as it is presently configured generates laminar vortex pairs. With this system we have obtained trajectory and surface signature data for vortex pairs approximating the same circulation and Reynolds number vortex pairs found in the wake of an underwater delta wing at negative angle of attack. The flow field of the vortex pair generated by the system clearly shows and allows the study of all the major features observed in the wake of the delta wing. This includes the formation of a Kelvin oval of fluid which is transported to the surface with the vortex pair and the formation of striations and scars during and after the interaction of the vortex pair with the free surface.

Laser speckle-gram measurements of the two-dimensional vector velocity field in a cross-section plane normal to the axes of rotation of the vortex pair have been made. The specklegrams allow the direct measurement of the circulation around each vortex, the flow field near the surface, the flow field within the Kelvin oval (the fluid carried upward with the vortex pair) and the flow field outside the Kelvin oval.

In addition to the above investigations we have observed, investigated, documented and now understand the primary aspects of the interaction of vorticity with a free surface when surface active agents are present on the surface. We have shown that the trajectory of a pair of vortices near the surface is strongly dependent on the amount of surface active agent present on the surface. When the surface is clean, vortices which are not strong enough to make appreciable surface deformations (low Froude number) follow a path approximating the path of a vortex pair beneath a solid surface with a slip (zero viscosity) boundary condition. When surface active agents are present, the vortices follow a different path which approximates (but it not the same as) the path a vortex pair would take if the surface boundary were solid and allowed no slip. The difference in the trajectories of a vortex pair when the free surface is contaminated with surface active agents and when the free surface is cleaner has been measured. A joint paper on the subject has been written containing the above results and similar results found by Professor Bernal and his students for a vortex ring. The paper has been submitted and accepted for publication in the *Physics of Fluids A*.

It appears that in nature some surfactant will always be present so the above results are likely to be indicative of the actual results in any large body of water such as the ocean or the Great Lakes. To summarize, we observe that as surface active agents accumulate on the free surface, the surface wake flow includes the formation of a pair of Reynolds ridges on either side of the plane of symmetry of the surface wake produced by a vortex pair. If too much surfactant is present, the sub-surface flow field of the vortex pair cannot break the surface film and Reynolds ridges are not observed. In either case, at later times the surface wake flow field produced by the sub-surface vortex pair also shows surface striations and dimples mixed with random surface deformations. The primary result of our investigation is that the same large scale, surface wake phenomena and flow structures as first reported by Sarpkaya and Henderson in the wake of a delta wing towed beneath the surface are observed for a vortex pair when a given amount of surface active agent is present. It is important to note that Sarpkaya and Henderson observed the Reynolds ridge, but did not identify it as such. In fact, Sarpkaya and Henderson make no mention of the effects or possible effects of surface active agents. In our work we have established that all the large scale wake features observed using a delta wing towed in our tank or produced by a two-dimensional vortex pair are similar when the Reynolds number, Froude number and contamination of the surface active agents is the same.

Three component fiber optic laser Doppler anemometer (LDA). Since the last progress report Bill Willmarth and Douglas Anthony have completed the development of the LDA. It was first configured for measurements of the flow field of a turbulent jet. The initial configuration of the system includes the traversing system for the LDA in the small tow tank, the LDA interface, computer controlled LDA traversing system, software and hardware for on-line production and display of histograms for each component and software for final data storage and reduction.

Following the completion of the jet measurements in the small tow tank, the design and construction of the LDA traverse for the large NAME tow tank was completed. The LDA and new traverse system is now on main campus for use in the large tow tank.

Measurements with LDA in a jet flow near the free surface. Three jet nozzles (1/4, 1/2 and 1 inch diameter) and a settling chamber containing turbulence damping screens and honeycomb were designed and fabricated. A series of measurements were then made of all three mean velocity components and of all nine components of the Reynolds stress for one jet exit mass flow at many different distances downstream of the jet. These measurements show how the mean and fluctuating flow in the jet adapts to the presence of the free surface.

The effects of a clean and contaminated free surface on the development of a submerged round jet were also investigated. When the free surface is clean, vertical turbulent velocity fluctuations measured near the surface are significantly diminished while those parallel to the surface are enhanced. Fluid from the jet propagates laterally outward in a thin surface layer much wider than the jet flow beneath the surface. When the surface is contaminated with surface active agents this lateral spreading is suppressed. We have made flow visualization experiments to demonstrate this effect. The results suggest that the lateral spreading is a consequence of reduced vertical mixing which is suppressed by secondary vorticity of opposite sign generated just beneath the surface when surfactant is present.

The problem is therefore highly nonlinear since the turbulent structure changes near the surface in response to the image effect and as a result of the new vorticity (and the image of this new vorticity) generated when surfactant is present on the surface.

Plans for Next Year's Research: The work in the small towing tank in the Aerospace Laboratory is complete. Funds permitting, continuation of the work with the submerged jet is planed for the next year in the much larger NAME towing tank on a larger scale. Higher jet velocities and a larger jet will be used. The purpose is to determine how the surface current and surface wave interaction phenomena scale with Reynolds and Froude number.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. <u>Papers in Refereed Proceedings/Journals</u>

Bernal, L.P., A. Hirsa, J.T. Kwon, and W.W Willmarth, "On the Interaction of Vortex Rings and Pairs with a Free Surface for Various Amounts of Surface Active Agent," *Phys. Fluids A*, **1**, 12, 2001, Dec. 1989.

Hirsa, A., G. Tryggvason, J. Abdollahi-Alibeik, and W.Willmarth, "Measurement and Computations of Vortex Pair Interaction with a Clean or Contaminated Free Surface", *Proceedings* Eighteenth Symposium on Naval Hydrodynamics, August 1990.

Anthony, D.G., W.W. Willmarth, K. Madnia and L.P. Bernal. "Turbulence Measurements in a Submerged Jet Near a Free Surface," *Proceedings* Eighteenth Symposium on Naval Hydrodynamics, Ann Arbor, August 1990.

Anthony, D.G., A. Hirsa, and W.W. Willmarth, "On the Interaction of Jet Turbulence with a Clean and Contaminated Free Surface", submitted as a letter to *Physics of Fluids A*, September 1990.

Hirsa, A. and W.W. Willmarth, "Experiments on Vortex Pair Interaction with a Clean or Contaminated Free Surface", to be submitted to *Physics of Fluids A*.

Anthony, D. and W.W. Willmarth, "Experiments on Vortex Pair Interaction with a Clean or Contaminated Free Surface", to be submitted to *Physics of Fluids A*.

Anthony, D. and W.W. Willmarth, "Turbulence Measurements in a Submerged Jet Near a Free Surface", to be submitted to *Physics of Fluids A*.

2. Technical Reports

Anthony, D., "The Influence of a Free Surface on the Development of Turbulence in a Submerged Jet", Ph.D. Thesis, PSH Technical Report #90-2, October 1990.

3. Presentations

Anthony, D.G., "On the Interaction of Jet Turbulence with a Clean and Contaminated Free Surface", David Taylor Ship Research and Development Center, New Directions in Naval Hydrodynamics Research, June 27, 1990.

Willmarth, W.W., D. Anthony, and A. Hirsa, "Flow Field of a Submerged Turbulent Jet Interacting with a Clean Free Surface", 43rd Annual Meeting of the Division of Fluid Dynamics of the American Physical Society, November 18-20, 1990.

Anthony, D.G. and W.W. Willmarth, "Turbulence Measurements Using a 3-Component LDA in the Flow Field of a Submerged Turbulent Jet Interacting with a Clean Free Surface", 43rd Annual Meeting of the Division of Fluid Dynamics of the American Physical Society, November 18-20, 1990.

LIST OF HONORS/AWARDS

Douglas G. Anthony won an award at David Taylor Model Basin for three years of research support on subject of choice.

LIST OF PARTICIPANTS

W.W. Willmarth, Professor
L.P. Bernal, Assistant Professor
G. Tryggvason, Assistant Professor
A. Hirsa, Graduate Student and Research Assistant - now Professor Aerospace and Mechanical Engineering at Rensellaer Polytechnic Institute
D. Anthony, Graduate student on leave from David Taylor Model Basin. Now Ph.D. and has returned to the Model Basin.
J. Abdollahi-Alibeik, Graduate student and Research Assistant

3.2.5 Flow Visualization of Turbulent Burst

Principal Investigator: K.-P. Beier

Research Summary

Description of Scientific Research Goals: The major goal of this project was to gain a better understanding of the details of turbulent burst by using advanced computer graphics methods to analyze existing data. This goal involves the development of a new visualization concept for the graphical representation of a turbulent channel flow. The flow is described by its properties (like velocity vectors) given on a spatial grid as a function of time. The loci of constant property magnitude are complex three-dimensional surfaces. These so-called iso-surfaces are changing their shape in time. The iso-surfaces can be calculated from the given data set and can be used to build an 'onion' model of several surface layers each representing a different constant property magnitude. The layers can be displayed as translucent surfaces and can be animated in time. The visualization principle can be applied to various flow properties like velocity, pressure, vorticity, etc.

Significant Results in the Past Year: During the past year, the Stellar Graphics Supercomputer GS1000 has been upgraded to a faster model, a Stardent GS2000, with two fully equipped color monitors. In addition, the main memory capacity of the system has been increased from 32 MegaBytes to 64 MegaBytes. The improvement of the system, which was the major research tool for the flow visualization project, had a significant impact on the progress of this project. The transition to the new model Stardent GS2000 and to a new version of the graphics software package PHIGS+ required several modifications of the iso-surface program. Once these modifications were in place, a filter program was developed allowing for a more effective link to the Application Visualization Software (AVS) from Stardent. AVS was then used for the interactive rendering and shading of the iso-surfaces. It also allows an onion model consisting of several layers of iso-surfaces to be viewed using a translucent display technique.

Iso-surfaces are only capable of inspecting the distribution of scalar properties in a given volume. When inspecting vector properties like velocities, only one vector component or only the magnitude (absolute value) of the vectors can be visualized. A new technique was developed which allows color-coding of an iso-surface by converting the direction of a vector in a color derived from a double hexacone HLS color model. Iso-surfaces for a velocity field can now be visualized by creating an iso-surface for the velocity magnitude and by color-coding the surface according to the direction of the velocity vectors. The resulting displays are very unusual but capable of revealing flow structure characteristics which otherwise remain undetected. Several well-known flow structures (e.g., doublet in a uniform flow, horseshoe vortex, rotation near the ground) were visualized using the iso-surface program and the color-coding method in order to gain a better understanding of the resulting displays.

A new two-dimensional contouring algorithm based on an indexed search method was developed in order to improve the response time for the generation of wire-frame representations of iso-surfaces. This technique is useful for quick inspection of a property distribution within a given volume. A systematic study of the algorithm was performed with the goal to optimize the use of vector and parallel processing.

The last months of the past year were used to implement final improvements in the iso-surface software and to document all results of the project "Flow Visualization of Turbulent Burst". The documentation is part of the doctoral dissertation of Graduate Student Research

Assistant S.H. Han. A copy of the dissertation as well as an abstract will be published as a PSH report.

Plans for Next Year's Research: Due to budgeting constraints, the project is being discontinued. Support for this project from the Program in Ship Hydrodynamics ended in August 1990. The work was finalized in October 1990 with the completion of Dr. Han's dissertation.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

Beier, K.-P. and S.-H. Han, "Iso-Surface Construction", PSH Technical Report #90-3, June 1990.

Han, S.-H., "Computer-Aided Visualization of Simulated Turbulent Channel Flow", Ph.D. Thesis, The University of Michigan, October 1990.

LIST OF HONORS / AWARDS

none

LIST OF PARTICIPANTS

K.-P. Beier, Associate Professor
S.H. Han, Graduate Student Research Assistant
C. Churchill, System Research Programmer II

3.2.6 Vortical Structure of Ship Wakes

Principal Investigator: L.P. Bernal

Research Summary

Description of Scientific Objectives: The main objective of this project is to obtain a better understanding of the turbulent viscous wake of surface ships and underwater vehicles by means of an experimental investigation of the underlying large scale vortical structure and its dynamics.

During the past year the research has focussed on the effect of surface active agents on the dynamics of vortical flows near the free surface. Large scale ship wake tests have shown the presence of strong surfactant bands in the wake of ships. Our own laboratory tests have demonstrated the important dynamic role played by surfactants on the evolution of vortex rings and pairs near a free surface. The experiments conducted during this year have the common objective of addressing issues of scaling and surface contamination on the interaction of vortical flows with the free surface.

Two different cases have been considered: a) Interaction of a large vortex ring with the free surface. The main objective of this investigation was to determine the surface signature and fundamental flow processes during the interaction of a large-scale high-Reynolds-number vortex ring with a clean free surface. b) Interaction of a vortex ring with a contaminated free surface. The main goal of these experiments was to determine the effect of known amounts of contaminants on the interaction of vortex rings with the surface at inclined and normal incidence.

Significant Results in the Past Year:

a) Large Vortex Ring Experiment

A vortex ring generator capable of generating vortex rings up to 18 cm diameter was used in the Tow Tank at the Ship Hydrodynamics laboratory. The interaction with a clean free surface was investigated for Reynolds numbers in the range $\Gamma/\nu \sim 15{,}000$ to 65,000. This investigation was conducted in collaboration with Profs. G. Tryggvason and G. Meadows. The main conclusions of the investigation are:

(i) As the vortex ring approaches the free surface a core instability develops which results in transition to a fully three-dimensional state. The transition process is characterized by breaking and reconnection of the vortex lines with the free surface and the formation of U-shaped vortices.

(ii) The flow characteristics are different before and after the instability. Before the instability the flow field is essentially axisymmetric. The surface signature consists of a surface depression slightly outwards of the vortex core. At high Froude number waves are generated ahead of the depression. Most of these features are well captured by an axisymmetric vortex filament model. In particular, the distance from the core to the surface and the outward speed of the core at the later stages of this regime are shown to be very sensitive to the core size.

(iii) After the three-dimensional instability, the surface signature is characterized by the onset of short waves and the appearance of dark spots produced by the vortex reconnection processes. The later replace the dark band associated with the surface depression above the vortex core. The speed of the outward motion in this fully three-dimensional regime is significantly reduced compared to the axisymmetric case. This aspect of the problem was not address theoretically.

b) Vortex Ring Interaction with a Contaminated Free Surface

Two different experimental configurations are being considered: 1) Interaction at inclined incidence; 2) Interaction at normal incidence

(1) Inclined Incidence. Systematic experiments were conducted to determine the effect of surface contamination on vortex reconnection at a free surface. The interaction of a vortex ring ($\Gamma/\nu = 5{,}000$) was investigated for an incidence angle of 20° and various levels of contamination. Oleyl alcohol was used to produce controlled levels of surface contamination. Contamination is characterized by the contamination number, C, defined as $\Pi a/\mu\Gamma$, where Π is the surface pressure, a is the vortex ring diameter, μ is the viscosity and Γ is the ring circulation. Values of this contamination number used in the present study were C = 0, 3, 9, 80 and 178. The main conclusions of this study are as follows:

(i) Vortex reconnection of the top part of the vortex core is always observed, at all levels of contamination, up to C = 178.
(ii) Vortex generation and secondary vortex formation was observed during the interaction of the top vortex core with the free surface. The rolled up secondary vortex did not prevent the reconnection process. It appears that secondary vorticity generation and associated viscous effects are not sufficient to prevent vortex reconnection.
(iii) Vortex reconnection of the bottom core was strongly influenced by the surfactant. For C = 3 reconnection of the bottom core was observed. At higher values of the contamination number, the much stronger secondary vorticity generation caused a stronger secondary vortex which deflected the primary core trajectory away from the surface.
(iv) Contaminant front (i.e., Reynolds ridge) were observed in all cases when surfactant was added to the free surface.

(2) Normal Incidence. A new facility was designed and assembled to study the interaction of vortex rings with a contaminated surface at normal incidence. The main design features are the provision for direct surface tension measurement on the facility and a new piston type vortex generator. These type of generator is capable of producing larger diameter vortex rings to facilitate PIV (Particle Image Velocimetry) measurements during the interaction with the free surface. A velocity bias technique for PIV measurements has also been developed using a rotating mirror.

Plans for Next Year Research: Vortex Ring Interaction with a Contaminated Free Surface. Fundamental studies of the interaction of vortex rings with a contaminated free surface will be completed. Measurement will be conducted using PIV to determine the velocity and vorticity field during the interaction. In addition, extensive flow visualization and surface slope measurements will be used to characterize the interaction.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers in Refereed Proceedings/Journals

Bernal, L.P., A. Hirsa, J.T. Kwon, and W.W Willmarth, "On the Interaction of Vortex Rings and Pairs with a Free Surface for Various Amounts of Surface Active Agent," *Phys. Fluids A*, 1, 12, 2001, Dec. 1989.

Anthony, D.G., W.W. Willmarth, K. Madnia and L.P. Bernal. "Turbulence Measurements in a Submerged Jet Near a Free Surface," *Proceedings* Eighteenth Symposium on Naval Hydrodynamics, Ann Arbor, August 1990.

Song, M., N. Kachman, J.T. Kwon, L. P. Bernal and G. Tryggvason, "Vortex Ring Interaction with a Free Surface," *Proceedings* Eighteenth Symposium on Naval Hydrodynamics, Ann Arbor, August 1990.

Song, M., L.P. Bernal, and G. Tryggvason, "Head-on Collision of a Large Vortex Ring with a Free Surface", in preparation to be submitted to *Physics of Fluids A*.

Kachman,N., E. Koshimoto, and L.P. Bernal, "Interaction of a Vortex Ring with a Contaminated Surface at Inclined Incidence," submitted to the ASME Symposium on Dynamics of Bubbles and Vortices Near a Free Surface, June 16-19, 1991.

2. Technical Reports

Kachman, N., E. Koshimoto, and L.P. Bernal, "Interaction of a Vortex Ring with a Contaminated Surface at Inclined Incidence", in preparation Program in Ship Hydrodynamics Technical Report, The University of Michigan.

3. Presentations

Bernal, L.P., "Three-Dimensional Vortical Interactions at a Free Surface," Fluid Dynamics Seminar, Graduate Aeronautical Laboratory, California Institute of Technology, November 16, 1989.

Bernal, L.P., "Three-Dimensional Vortical Interactions at a Free Surface," Fluid Dynamics Seminar, Department of AMES, University of California at San Diego, November 14, 1989.

Kachman, N. and L.P. Bernal, "Interaction of Vortex Rings with a Contaminated Free Surface," Abstract submitted to 43rd Annual Meeting of the Division of Fluid Dynamics, American Physical Society, Cornell University, Ithaca N.Y., November 18-20, 1990.

LIST OF HONORS/AWARDS

none

LIST OF PARTICIPANTS

L. P. Bernal, Assistant Professor
W.W. Willmarth, Professor
N. Kachman, PhD Student
E. Koshimoto, Graduate Student

3.3.1 Nonlinear Ship Waves

Principal Investigator: W.W. Schultz

Research Summary

Description of Scientific Research Goals: We intend to study the fully nonlinear ship wave problem using a boundary integral method with panels on the ship and on the actual free surface. Ultimately, we wish to be able to incorporate vorticity, subgrid models of capillary waves (based on the analytical subtasks of this project), and empiricism from tow tank data into the program to get a more accurate representation of the wake SAR signature.

Toward that goal, we are now concentrating on developing boundary integral techniques to study nonlinear waves caused by moving bodies beneath the free surface and pressure disturbances on the surface.

Significant Results in the Past Year: The algorithm developed in Cao, *et al* (1990) has been shown to be much more efficient and accurate than Newman's and Hess' and Smith's methods for wave problems. We have also shown that the indirect method (solving for singularity strength rather than the velocity potential) is more effective when desingularization is used, especially at the truncated boundaries. We are continuing to improve "radiation-type" boundary conditions. This is especially important in how the upstream boundary conditions are determined for two-dimensional shallow water problems with a moving computational window. We have been able to duplicate some runaway soliton results of Wu. A PSH technical report on this will be published shortly in preparation for an examination of 3D solitons in the wake of a ship. We are also preparing a manuscript entitled, "Nonlinear Computations for Wave Resistance of a Submerged Spheroid", with Volker Bertram from the Institut für Schiffbau, Universit at Hamburg comparing our time-marching results to their steady-state calculations.

We have performed a formal multiple scale procedure to capillary-gravity waves with small viscosity in a manner similar to Djordjevic and Redekopp (1977) to form a dissipative nonlinear Schroedinger equation. A subsequent stability analysis shows that viscosity may inhibit the Benjamin-Feir type resonance. A formal boundary layer procedure has been used to solve for damping coefficients of slightly viscous linear waves. The PSH report "Evolution of Weakly Nonlinear Water Waves in the Presence of Viscosity and Surfactant", by S.W. Joo, A.F. Messiter and W.W. Schultz is being modified to allow for a more general surfactant model before being resubmitted to *J. Fluid Mech.*

We are also finding the effect of spatial variations of surfactant caused by a ship's passage on wave motion in two limits--a sudden change as in that caused by a Reynold's ridge and a gradual change (where the surface tension varies only slightly within one wavelength). The first study uses the method that Lewy used for the dock problem and finds reflection coefficients. The second limit uses formal ray theory to find the deflection and attenuation of waves. Both studies are nearing report form.

A PSH report "Potential energy in steep and breaking waves", coauthored by W.W. Schultz, O.M. Griffin and S.E. Ramberg, is under review by the *Proceedings* of the Royal Society.

Plans for Next Year's Research: The thrust of the desingularized three-dimensional potential method is to now examine the wave pattern caused by a surface pressure disturbance that approximates the displacement of a ship. We will search for solitary waves that fall inside the Kelvin wave pattern.

The formal multiple scale procedure for capillary-gravity waves with small viscosity has been modified for values of the surface tension parameter that causes resonance (Wilton's ripples). The resonance work is continuing with the computations of J. Huh.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers in Refereed Proceedings/Journals

Joo, S.W., W.W. Schultz, and A.F. Messiter, "An Analysis of the Initial Wavemaker Problem", *Journal of Fluid Mechanics* 214:161-183, 1990.

Schultz, W.W and S.-W. Hong, "A Complex Boundary Integral Method for Two Dimensional Potential Problems", *Journal of Comp. Physics* 84:414-440, 1989.

Cao, Y., W.W. Schultz, and R. Beck, "Three Dimensional Desingularized Boundary Integral Method for Potential Problems", to appear *Int. Journal Num. Meth. Fluids*.

Cao, Y., W.W. Schultz and R.F. Beck, "Three-Dimensional Nonlinear Wave Computation by Desingularized Boundary Integral Method", 5th International Workshop on Water Waves and Floating Bodies, Manchester UK, March 1990.

Krasny, R., "Vortex Sheet Roll-Up Due to the Motion of a Flat Plate", *Proceedings* International Symposium on Nonsteady Fluid Dynamics. ASME Fluids Engineering Division, Vol. 92, J. A. Miller, D. P. Telionis, Eds. Book no. H00597, p. 449-453, 1990.

Cao, Y., W.W. Schultz, and R.F. Beck, "Three-Dimensional, Unsteady Computations of Nonlinear Waves Caused by Underwater Disturbances", Eighteenth ONR Symposium on Naval Hydrodynamics, Ann Arbor, August 1990.

Krasny, R., "Vortex Sheet Computations: Roll-Up, Wakes, Separation", AMS-SIAM Summer Seminar in Applied Mathematics, Vortex Dynamics and Vortex Methods. C. Anderson, C. Greengard, Eds., Lectures in Applied Mathematics, to appear Springer-Verlag, 1990.

Krasny, R., "Computing Vortex Sheet Motion", *Proceedings* International Congress of Mathematicians, Kyoto, to appear Springer-Verlag, 1990.

Reed, A.M., R.F. Beck, O.M. Griffin, and R.D. Peltzer, "Hydrodynamics of Remotely Sensed Surface Ship Wakes", *Transactions* Society of Naval Architects and Marine Engineers, November 1990.

2. Technical Reports

none

3. Presentations

Schultz, W.W. and J. Huh, "Spectral Boundary Integral Methods for Potential Flow", U. of Wisconsin, April 1990.

LIST OF PARTICIPANTS

W. W. Schultz, Assistant Professor
R. F. Beck, Professor
R. Krasny, Assistant Professor
A. F. Messiter, Professor
J. Huh, Ph.D. Student
Y. Cao, Ph.D. Student
S. Gou, Ph.D. Student

3.3.2 Interaction of Vorticity and Free Surface Flows

Principal Investigator: G. Tryggvason

Research Summary

Description of Scientific Research Goals: To contribute toward the understanding of the interaction of vortical flows and the free surface. Particular emphasis is on the surface signature of unsteady flows, and how surface waves are generated and modified. This understanding is sought by considering idealized model problems where the various mechanisms may be isolated. Generally the model equations, even for fairly "clean" problems, are inherently nonlinear and numerical techniques are the only feasible solution method. Our studies employ a generalized vortex method and boundary integral techniques for problems where viscosity may be neglected, and finite difference methods for problems where it is essential to account for viscous effects.

Significant Results in the Past Year: A thorough computational study of the collision of a vortex pair with a flat, but contaminated free surface, has been completed and the results written up as a PSH report which will be submitted for publication. The full viscous fluid equations are solved with a finite difference technique. At the free surface the evolution of the contaminant concentration is followed, and the shear induced by uneven distribution used as boundary conditions for the fluid motion. The results show that a relatively small amount of surface contaminant can cause secondary vortices to form and the primary vortices to rebound. This is in agreement with Willmarth's experiments. Computations for various Reynolds numbers and equations of state for the contaminants have been done. In addition to complementing the experimental investigations of Willmarth, this study suggests that in the limit of high Reynolds number, the evolution depends only on a nondimensional number describing the effect of the contamination, and for large values of this number the evolution becomes identical to the case where the free surface is replaced by a rigid wall.

Another study that is currently being prepared for publication is an experimental and computational investigation of the head-on collision of a large vortex ring with a free surface. This study has been conducted in collaboration with Bernal and Meadows. The results suggest that the problem can be broken down into at least two more manageable sub-problems; namely the initial collision of the ring with the surface, and the subsequent breaking-up of the ring and the reconnection of its parts with the surface. The numerical modeling has focused on the first problem. The vorticity is taken as a single ring, and the full nonlinear free surface conditions are used. It has been shown that the initial collision is well described by an axisymmetric, inviscid model and quantitative comparisons of the numerical and experimental results are in good agreement. The experimental work has identified the nature of the three-dimensional surface signatures that appear rather early after the ring collides with the surface. Each break-up appears to be rather independent, and may therefore be studied in isolation from the rest of the ring.

Studies of the reconnection of a vortex filament with a free surface, in a slightly different configuration than in the experiment, are also well underway. An inviscid vorton model of a vortex ring colliding with a linearized free surface shows that the "opening-up" takes place on a time-scale that is much shorter than the time scale for the rest of the motion and generates significant surface disturbances. In some cases the ring reconnects again, forming two U-vortices in agreement with experimental observations. These results are also being written up.

A short review of the computations of vortex interactions with a free surface and density interfaces was presented at the AMS/SIAM summer seminar in Seattle on June 18-29. A manuscript accompanying the talk has been submitted to Lectures in Applied Mechanics.

Plans for Next Year's Research: During the next year we expect to focus on the viscous vortex ring problem. We have recently started to work on the three-dimensional counterpart of the problem described in the paper with Willmarth. Viscous vortex rings, colliding with a flat, but contaminated surface are simulated using a conventional finite difference method. Preliminary results have been obtained. We are also investigating the interaction of vortex rings with deformable interfaces. Currently, most of the three-dimensional calculations have been with weak density interfaces, but we plan to use an extension of the code (already running) to simulate large stratification and a free surface. The intention is to combine both efforts to simulate deformable, contaminated free surfaces, but this may not be accomplished next year.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers in Refereed Proceedings/Journals

Tryggvason, G., "Deformation of a Free Surface as a Result of Vortical Flows", *Phys. Fluids*, Vol. 31, pp. 955-957, 1988.

Willmarth, W.W., G. Tryggvason, A. Hirsa, and D. Yu, "Vortex Pair Generation and Interaction with a Free Surface", *Phys. Fluids*, Vol. A 1, pp. 170-172, Vol. A 2, pp. 656-659, 1989.

Yu, D. and G. Tryggvason, "The Free Surface Signature of Unsteady, Two-Dimensional Vortex Flows", *J. Fluid Mech.*, Vol. 218, pp. 547-572, 1990.

Tryggvason, G., S.O. Unverdi, M. Song, and J. Abdollahi-Alibeik, "Interaction of Vortices with a Free Surface and Density Interfaces", submitted to *Lectures in Applied Mathematics*, 1990.

Tryggvason, G., J. Abdollahi-Alibeik, W. Willmarth, and A. Hirsa, "Collision of a Vortex Pair with a Contaminated Free Surface", Program in Ship Hydrodynamics Technical Report No. 90-1, to be submitted to *Phys. Fluids*.

Hirsa, A., G. Tryggvason, J. Abdollahi-Alibeik, and W. Willmarth, "Measurement and Computations of Vortex Pair Interaction with a Clean or Contaminated Free Surface", *Proceedings* of Eighteenth Symposium on Naval Hydrodynamics, National Academy Press, Washington, D.C., 1990.

Song, M., N. Nachman, J.T. Kwon, L.P. Bernal, and G. Tryggvason, "Vortex Ring Interaction with a Free Surface", *Proceedings* of Eighteenth Symposium on Naval Hydrodynamics, National Academy Press, Washington, D.C., 1990.

Tryggvason, G., "Vortex Dynamics of Stratified Flows", Mathematical Aspect of Vortex Dynamics, ed. R. Caflish, SIAM, Philadelphia, pp. 160-170, 1988.

Yu, D., "Numerical Simulations of Vortex Interactions with a Free Surface", Ph.D. Thesis, The University of Michigan, 1990.

3. <u>Presentations</u>

Tryggvason, G., M. Song, and L. Bernal, "Vortex Interaction with a Free Surface", 42nd Meeting of the American Physical Society, Division of Fluid Dynamics, NASA, Ames, CA, Nov. 19-21, 1989, Abstract in *Bull. Amer. Phys. Soc.* 34:2295.

Tryggvason, G., J. Abdollahi-Alibeik, M. Song, and S.O. Unverdi, "Interaction of Vortices with a Free Surface and a Density Interface", invited presentation at the AMS-SIAM Summer Seminar on Vortex Dynamics and Vortex Methods, Seattle, WA, June 18-29, 1990.

LIST OF HONORS/AWARDS

none

LIST OF PARTICIPANTS

G. Tryggvason, Assistant Professor
D. Yu, Ph.D. Student (no longer with project, graduated Spring 1990)
M. Song, Ph.D. Student
J. Abdollahi-Alibeik, Ph.D. Student (part-time)
Y.-J. Jan, Ph.D. Student (part-time)
S.O. Unverdi, Ph.D. Student, (part-time, graduating Dec. 1990)

3.3.3 Turbulence-Free Surface Interaction in Model Ship Wakes

Principal Investigator: D.T. Walker

Research Summary

Description of Scientific Research Goals: The objective of this project is to determine the relationship between the free-surface features and the hydrodynamics (both free-surface and subsurface) of model ship wakes. This study will make use of the various experimental techniques and instrumentation developed as part of the PSH to examine the structure and free-surface features of the turbulent wake created by a model ship.

Significant Results in the Past Year: During the past year, a one-twelfth scale model of the fleet tug USS Quapaw has been obtained from the David Taylor Naval Ship Research and Development Center (DTRC Model 3531). The Quapaw was used in the Georgia Straits full-scale experiments with airborne synthetic aperture radar (SAR); hence, it is one of the more well documented non-combatants in the Navy's fleet. A set of flow-visualization experiments was conducted in the SHL towing tank in the spring and summer of 1990. For these tests the model was configured two different ways. It was first used as a drag body with no propeller attached; subsequent experiments were done with a propeller and rudder attached. These experiments included fluorescent dye visualization of the turbulent, subsurface wake and shadowgraph visualization of the free surface at various locations in the wake.

To examine the evolution of the turbulent subsurface wake, a fluorescent dye was injected into the boundary layer of the model and the model was towed through a stationary laser sheet oriented normal to the direction of travel. In this way a cross-section of the turbulent portion of the wake can be obtained and its evolution with distance aft of the model can be tracked. This visualization showed that the turbulent wake grows laterally near the free surface at a higher rate than elsewhere. The high rate of lateral growth near the free surface is consistent with both full-scale and model-scale experimental results for various hulls which show a significant velocity component directed outward from the ship track. This behavior has been linked with the existence of large-scale vortical structure in the ship wake. The only observable large-scale vortical structure is a pair of counter-rotating circulation cells which form in the cavities on either side of the rudder (stern vortices). These regions appear to be highly turbulent with small mean circulation. The sense of rotation for these cells (inboard rotation) is such that they interact to carry a significant amount of the turbulent wake fluid downward, away from the free surface. Hence, this vortical structure cannot be the direct cause of the observed surface current.

Shadowgraph visualization of the free surface was done in various locations between the stern of the model and a distance two ship lengths aft. In this region there is an easily discerned boundary between the turbulent portion of the wake and the irrotational free stream. Inside this boundary there are random, unsteady surface disturbances with some evidence of large-scale organized structure, but no preferred propagation direction. Well outside of this region the steady Kelvin wave pattern is seen. Between these two regions, there are unsteady features which are a result of surface disturbances generated in the turbulent portion of the wake propagating into the irrotational portion of the flow. Taken together, these disturbances appear as slightly irregular, unsteady waves propagating outward with their crests aligned (approximately) at a small angle relative to the ship track. The shadow-graph images of this region are also populated by numerous small, circular dark spots. These spots are characteristic of signatures generated by vortices with their axes of rotation oriented normal to the free surface. All the above described features are most distinct near the model and become more difficult to discern with increasing distance aft. This is due to the growth of the length scales in the turbulent portion of the wake and the subsequent reduction in velocity fluctuations resulting in smaller magnitude surface disturbances. These smaller disturbances are more difficult to detect using the shadowgraph technique.

The addition of the rotating propeller caused the flow in the region of the stern vortices to be modified significantly, however the effects on the behavior of the turbulent surface layer were small. The propeller decreased the turbulent surface activity near the center of the wake but increased the activity near the edges. The width of the wake was unchanged and the unsteady waves at the edge of the wake remained, but increase in amplitude. The propeller effects are currently being examined in detail.

Plans for Next Year's Research: The plans for the next year include further analysis of the visualization data already obtained. This will be carried out as part of Vincent Johnston's MSE thesis research and will focus on quantifying the observed free-surface features and relating the growth and extent of the subsurface turbulent wake with the observed free-surface features. Along with the identification of qualitative features in the wake, quantitative analysis of the shadowgraph and flow visualization results will yield length scales and directional information for free surface features, and growth rates for the subsurface turbulent wake. These results will also be used as a guide for quantitative measurements using the Hydrodynamic Monitoring Facility.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

Johnston, V.G. and Walker, D.T., "1990 Observations of Turbulence Near the Free Surface in the Wake of a Model Ship", submitted for ASME Symposium on Dynamics of Bubbles and Vortices Near a Free Surface, Columbus, Ohio, June 16 - 19, 1991.

LIST OF HONORS/AWARDS

none

LIST OF PARTICIPANTS

D.T. Walker, Assistant Professor
V.G. Johnston, Graduate Research Assistant

3.3.4 Experiments on Gravity-Capillary Water Waves

Principal Investigator: M. Perlin

Research Summary

Description of Scientific Research Goals: During the period 17-June-1990 through 15-July-1990, several sets of exploratory experiments were conducted at the University of Florida's ripple tank. The objective of these experiments was to foster future experiments. The series of experiments were fourfold and included: 1) a study of gravity-capillary wave frequencies in the stable band (as regards the nonlinear Schroedinger equation, i.e., 6.4 Hz through 9.8 Hz) in a wide channel, 2) an effort to generate quasi-steady Ma solitons in a wide channel using a specially machined, hyperbolic-secant-shaped paddle, 3) an attempt to study Wilton's ripples (second-harmonic resonance) in a narrow channel, and 4) an effort to generate steep waves by programming the wavemaker to follow the surface of a Crapper-like wave.

Significant Results of the Past Year: The first series of experiments yielded some interesting results. It was the aim of these experiments to show that nowhere within the 6.4-Hz through 9.8-Hz frequency band was there a stable wave. (These instabilities, however, are believed to be the result of internal near-resonances, namely second-, third-, fourth-, etc. harmonic, near-resonances rather than the directional instabilities found by Perlin and Hammack.) A second objective was to determine which resonance was occurring for a given frequency. Since the band of third-harmonic near-resonance had already been quantified by McGoldrick (and reaffirmed by the 8 Hz experiments of Perlin and Hammack), experiments concentrating on the frequency band between third- (8.4 Hz) and second- (9.8 Hz) harmonic resonance were conducted. Spatial and temporal results were inconclusive. For example, frequency spectra at two spatial locations for 8.8-Hz waves both displayed a disordered third harmonic (larger than second harmonic) which indicated that third-harmonic resonance may have occurred; however, it may be coincidental that at these two locations, the second harmonic, which for second-harmonic resonance trades energy with the primary wave, happened to be at its minimum amplitude condition. Thus the data are inconclusive. The overhead, high-speed video wavenumber spectra showed no disordering, but did have significant amplitude at the second harmonic. In the case of non-collinear triads, the closure (or lack of closure) of the wave-vectors resolves whether the wave energy was free (or forced) and thus whether resonances had occurred. For collinear triads, one resorts to the frequency spectra, at various locations, and if it is clear that energy is being traded amongst the triad members, it is concluded that triad resonance had occurred. For situations in which multiple internal resonances can occur, it is now clear that frequency (wavenumber) spectra must be measured at (over) several locations to be conclusive.

The generation of quasi-steady, Ma solitons using a prescribed signal and a specially machined wave paddle showed promise. The temporal modulations in stroke, input at the wavemaker, propagate downstream; however, the distribution of the wave amplitude across the wide channel, which represents the unique feature of this spatial soliton, was not correct. One explanation is that the choice of the free parameters in the analytical solution (for which there is no guidance) was such that the Ma soliton did not occur. It is believed that with a sufficient number of experiments, these solitons could be generated, essentially by trial and error of the choices in the free parameters.

It was anticipated that second-harmonic resonance (Wilton's ripples) would be studied experimentally and used for comparison to Professor W.W. Schultz's numerical experiments. The reality was that the contact-line damping was so severe in the narrow channel (one-half inch wide channel constructed of glass sidewalls), that the resonance phenomenon was inhibited. It is possible that this problem could be overcome with a more powerful electrodynamic shaker capable of longer stroke and greater acceleration.

The attempt to generate a Crapper-like, steep wave did not work due to, among other things, the failure of the electrodynamic shaker to follow the prescribed signal. A program was written to oscillate a wavemaker in a narrow channel such that its displacement followed the surface displacement of a Crapper wave. The inability of the shaker to produce sufficient acceleration to duplicate the signal precluded the possibility of generating the proper waveform. Also, it is clear that the generation of steep waves in a narrow channel is not trivial.

Plans for Next Year's Research: In the coming year, the construction of a University of Michigan ripple tank will be completed. (It is presently under construction.) A more powerful electrodynamic shaker capable of larger stroke and greater acceleration than the University of Florida shaker will be purchased. Experiments will focus on wave damping. Clean versus contaminated surfaces and wave scouring of surface surfactants and the resulting effects on the wave field will be investigated.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

none

LIST OF HONORS / AWARDS

none

LIST OF PARTICIPANTS

M. Perlin, Assistant Professor

APPENDIX II

Proceedings of the Eighteenth Symposium on Naval Hydrodynamics

Nonintrusive, Multiple-Point Measurements of Water Surface Slope, Elevation and Velocity

by
G. Meadows, D. Lyzenga, J. Lyden, R. Beck

This paper describes the Hydrodynamic Monitoring Facility (HMF), an instrument designed to measure slope, elevation, and velocity simultaneously at an array of spatial locations over an area of the water surface. The instrument was designed to provide quantitative measurements used in the study of ship wake phenomena. The HMF is comprised of three separate systems: an optical wave slope measurement system which uses a Helium-Neon (HeNe) laser source and a wave height/surface velocity measurement system which uses a CO_2 laser. These systems and the results of an initial experiment will be discussed in detail.

The experiment utilized a subsurface air bubble source and a surface wind wave source, in conjunction with the HMF, to investigate the effects of short wave propagation on a spatially variable current. A multi-frequency Doppler radar system was employed to concurrently investigate the interaction of active microwave energy with the surface buoyant driven flow.

Proceedings of Oceans '90

2-D Surface Reconstruction of Water Waves

by
Z. Wu and G.A. Meadows

A method to reconstruct the 2-D surfaces of water waves from sequential positions of a refracted beam penetrating the air/water interface is presented in this paper. In this method, the laser beam is emitted from below the water surface to scan the wave surface in two dimensions with sufficiently high speed (about 10^4 realizations/second) to "freeze" the small scale wave motion. Simultaneously, the position of the refracted laser beam is imaged on a screen above the water surface and its instantaneous position is measured by a position detector on a point by point basis. With the position data and the angle information of the incident laser beam, the water surface slopes are calculated in two dimensions. The wave surface is then reconstructed from these slopes. Simulation results show that the accuracy of the resultant wave slopes and the reconstructed wave surface is high for perfect input data. A statistical error analysis and simulation with noise in the input data are also given in this paper.

Ph.D. Thesis, 1990
PSH Technical Report #90-2

The Influence of a Free Surface on the Development of Turbulence in a Submerged Jet

by
D.G. Anthony

Radar images of the ocean surface made when surface ships are moving within the imaged area reveal distinctive surface signatures attributed to the interaction of the turbulent wake of the ship with the free surface. In order to study the behavior of turbulence near a free surface, the flow in a round, turbulent jet issuing beneath and parallel to a clean surface was investigated experimentally. A three-component Laser Doppler Velocimeter (LDV) was used to make detailed measurements of the mean flow velocity and Reynolds stress tensor throughout the flowfield. Surface shadowgraphs and Laser Induced Fluorescence (LIF) were used to visualize features of the free surface deformations and the subsurface flowfield.

The jet Reynolds number,, and Froude number, were comparable to those of the jet flow investigation of Bernal and Madnia, 1988. Large-scale turbulent structures within the jet generated surface waves that were observed to propagate nearly perpendicular to the jet axis. Measurements of the wavelength and wave speed from shadowgraph images showed these waves to be gravity-capillary waves.

The LDV measurements revealed that near the jet centerline, the RMS velocity fluctuations become anisotropic as the free surface is approached: The fluctuations normal to the surface are diminished, while those parallel to the surface are enhanced. Measurements made near the surface on either side of the jet revealed the existence of a shallow surface current much wider that the primary jet flow. Within this current, the magnitudes of the cross-stream and vertical RMS velocity fluctuations are approximately the same, but are greater than that of the streamwise fluctuations. This is attributed to motions arising from surface waves propagating perpendicular to the jet axis and superposed on the surface current.

LIF images of the surface current show it to consist largely of fluid emitted from the jet. Beneath a clean free surface, these emissions propagate to considerable distance under the influence of their images above the surface. When a surfactant is placed on to the water surface, vortical fluid ejected from the jet interacts with secondary vorticity generated beneath the surfactant covered surface, and the surface current is suppressed.

Ph.D. Thesis, 1990

Computer-Aided Visualization of Simulated Turbulent Channel Flow

by
S.-H. Han

Iso-surfaces are used as a visualization method to study turbulent phenomena, especially the turbulent burst process. A database of numerical simulations of turbulent channel flow has been investigated. Organized motions observed in the turbulent flow visualization experiments can be recognized from numerical simulation results.

An iso-surface construction algorithm has been developed which can handle all cases of iso-surface geometry. The algorithm is robust and gives correct results by treating the ambiguous cases properly. The algorithm has been devised after a thorough study of possible iso-surface construction methods. Since iso-surfaces can be applied only to scaler fields, a color-coding scheme for the iso-surface representation has been developed which allows the visualization of a vector field. The iso-surface is created for the magnitude of the given vector information and is subsequently color-coded according to the directional information derived from the vector field.

For the wireframe representation of an iso-surface, a fast algorithm for 2-D contour construction has been developed. Significant performance improvement was gained based on an indexed search method instead of a sequential search as used in existing algorithms. The goal of real-time response in the iso-surface generation and the view manipulation process has been achieved.

The developed algorithms have been used to visualize well-known flow structures and to study near-wall turbulent structures. The design of effective data structures and the proper integration of the algorithms with an efficient user interface allows a thorough study of large scalar and vector fields in a reduced amount of time. The new algorithms and tools are helpful in gaining a better understanding of the complex phenomena found in turbulent flows.

Submitted to the 43rd American Physical Society Meeting, Div. of Fluid Dynamics

Interaction of a Vortex Ring with a Contaminated Free Surface

by
N.J. Kachman and L. Bernal

An experimental investigation was conducted to determine the effect of different concentrations of a surfactant (oleyl alcohol) on the breaking and reconnection process of vortex lines at a free surface. A laminar vortex ring with a Reynolds number of 5000 was fired at the free surface with an angle of incidence of 20°. At these flow conditions the interaction with a clean free surface consists of two successive vortex line breaking and reconnection processes leading to the formation of two half vortex rings propagating away from each other. Flow visualization experiments show that the interaction of the upper vortex core with the contaminated surface results in vorticity generation and roll up. This does not prevent the vortex lines from breaking and reconnecting with the free surface. The interaction of the lower core with the contaminated surface also results in vorticity generation and roll up at the free surface. In this case however, the rolled up secondary vorticity causes the vortex core to rebound preventing vortex line breaking at the surface. In addition a Reynolds ridge forms in front of this second interaction.

Phys. Fluids A, 1, 12, 2001

On the Interaction of Vortex Rings and Pairs with a Free Surface for Varying Amounts of Surface Active Agent

by
L.P. Bernal, A.Hirsa, J.T. Kwon and W.W. Willmarth

Observations are reported of the interaction with a free surface of vortex rings and vortex pairs moving normal to the surface when different amounts of surface active agents are present on the surface. At a vortex ring Reynolds number $\Gamma/\nu \approx 3800$, the interaction with a contaminated free surface results in the generation of secondary and tertiary vortex rings that limited the outward motion of the vortex ring core. When the experiment was repeated with a cleaner surface the formation of the secondary vortex ring was delayed so that the outward motion and stretching of the vortex ring core was much more than for the contaminated surface. At a Reynolds number $\Gamma/\nu \approx 18000$, the vortex pair was observed to rebound from the free surface contrary to what one would expect for an inviscid flat boundary. When the surface was cleaned by draining away a portion of the contaminated surface water the amount of rebound was reduced. These changes in interaction are believed to be caused by the reduction in concentration of the surface active agent which, in turn, results in a reduced generation of secondary vorticity ahead of the vortex ring or pair before and during the interaction with the surface.

Submitted for presentation at the ASME Symposium on Dynamics of Bubbles and Vortices Near a Free Surface and in preparation for PSH Technical Report

Vortex Ring Interaction with a Contaminated Surface at Inclined Incidence

by
N.J. Kachman, E. Koshimoto and L. P. Bernal

An experimental investigation was conducted to determine the effect of a surfactant on the breaking and reconnection process of a vortex ring interacting with a free surface. A laminar vortex ring with a Reynolds number of 5000 was fired at the free surface with the angle of incidence of 80 degrees with respect to the free surface. For a clean surface, as was shown in a previous work (Kwon, 1989), the top of the vortex ring will break upon contact with the free surface and reconnect to form a half vortex ring that then propagates along the free surface. The bottom of this half vortex ring will continue toward the free surface and strike it resulting in this part of the ring breaking again and reconnecting with the free surface, thereby causing two half-vortex rings to form and propagate along the surface.

Oleyl alcohol was used as a surfactant and it was found that for small pressure changes (0.5 dyne/cm), the vortex reconnection process remained the same, but as the surface pressure increased (1.4 dyne/cm or greater), secondary vorticity was formed in the interaction that prevented the reconnection process. In particular, after the first breaking and reconnection occurred, as the bottom of the half-vortex ring approached the surface, secondary vorticity would form in front of it. The induced velocity field due to this secondary vorticity would drive the bottom half of the vortex ring away from the free surface and thereby prevent the second breaking and reconnection.

The production of secondary vorticity due to the interaction of the vortex ring with the free surface was also seen in the first interaction of the top of the vortex ring with the free surface. This secondary vorticity did not affect the first breaking and reconnection because this vorticity rolled up behind pressures (above 13 dyne/cm). When the top core struck the surface it left part of its vorticity behind which paired up with the secondary vorticity. This pair was then swept forward by the induced velocity field of the vortex ring.

A Reynolds ridge was also observed in front of the interaction. This was seen in the top view as a sharp white/black band that formed a semicircle in front of the vortex interaction.

Fluid Dynamics Seminar, 1990
California Institute of Technology and University of California, San Diego

Three-Dimensional Vortical Interactions at a Free Surface

by
L. P. Bernal

The results of several experiments on the interaction of vortex rings with a free surface will be presented. The experiments were conducted with laminar vortex rings at small Froude number. Several types of interaction are observed depending on the incidence angle of the vortex ring. When the vortex ring propagates normal to the surface the interaction is very sensitive to the presence of surface active agents on the surface. The surface active agents on the free surface cause generation of vorticity at the surface which rolls up into secondary and tertiary vortices thus strongly influencing the flow development. When the vortex ring approaches the surface at inclined incidence a fundamentally different interaction is observed. Underwater vortex lines in the ring brake during the interaction and terminate on the surface. At certain flow conditions the vortex ring undergoes two of these interactions resulting in two semicircular vortical regions. These half vortex rings propagate along diverging paths after the interaction. Measurements show that this reconnection process occurs in an inviscid time scale. Detailed measurements of the surface velocity field using Laser Speckle techniques indicate that the reconnection process is driven by the strain rate field during the interaction which causes a rapid decay of the vorticity component parallel to the surface and a rapid increase of the vorticity component normal to the surface.

To appear Int. Journal Num. Meth. Fluids

Three-Dimensional Desingularized Boundary Integral Method for Potential Problems

by
Y. Cao, W.W. Schultz, and R.F. Beck

The concept of desingularization in the three-dimensional boundary integral computations is reexamined. The boundary integral equation is desingularized by moving the singular points away from the boundary and outside the problem domain. This allows the surface integrals, which become nonsingular, to be evaluated by simpler techniques. The effects of the distance of desingularization on the solution and the condition of the resulting system of algebraic equations are studied for both the direct and indirect versions of the boundary integral method. Computations show a broad range for the desingularization distance in which accurate solutions can be obtained with significant saving in the computation time.

Transactions Society of Naval Architects and Marine Engineers, Nov. 1990

Hydrodynamics of Remotely Sensed Surface Ship Wakes

by
A.M. Reed, R.F. Beck, O.M. Griffin, and R.D. Peltzer

Recently, there has been much interest in the remote sensing of surface ship wakes using synthetic aperture radar (SAR). Ship wake signatures obtained using SAR have several distinct features such as a dark trailing centerline region, bright-line images aligned at some angle to the ship's path, and sometimes the Kelvin wave pattern. The reasons for these features are not well understood. Many different theories are available to explain one or more of the features. These theories are often in conflict and no definitive answers are yet available. Much analytical and numerical research, and both laboratory and full-scale experiments are presently underway in order to develop proper explanations. This paper surveys the present research and the state-of-the-art in the hydrodynamics of remotely sensed ship wakes.

The paper first describes in some detail the distinctive features of SAR images. Actual examples from early SEASAT SAR images, and the more recent JOWIP/Georgia Straight and SIR-B remote sensing experiments will be given. The observed radar image morphology includes dark centerline wake features, narrow-V bright line features, and Kelvin wake manifestations.

The discussion of the research into surface ship wake hydrodynamics presently being conducted at the David Taylor Research Center, the Naval Research Laboratory, and The University of Michigan is divided into two parts: flow phenomena at and near the free surface, and submerged wake phenomena. SAR images are formed by only the phenomena right on the free surface since electromagnetic waves do not penetrate the water surface. However, these surface flows are a manifestation of the sub-surface flows and the two regimes must be investigated concurrently. In each part of the paper, physical experiments, numerical simulations, and related analytical work are described.

Research into phenomena at and near the free surface has included investigations into surface films and surface-active materials, interaction of turbulence with the free surface, and vortical flows including vortex ring and line vortex interactions with the free surface. Wave-wave and wave-turbulence interactions, and surface thermal layers are also topics of active research. Experimental, analytical and numerical studies have been conducted and some comparisons between the three approaches are now possible.

While an extensive base of submerged wake flow data is available in the literature, relatively little data has been collected with a free surface also present. This paper describes recent research into wake flows at and beneath a free surface, in particular as it relates to surface ship wake hydrodynamics. The overall hydrodynamic field which results from the ship's passage is discussed in terms of its relation to the distinctive surface signature which can be remotely sensed by synthetic aperture radar as one principal example.

To appear Springer-Verlag, 1990

Vortex Sheet Computations: Roll-Up, Wakes, Separation

by
R. Krasny

Chorin's vortex blob method has been proposed as a way to extend vortex sheet motion past the singularity formation time, into the physically important roll-up regime. Two basic questions are: 1. Does the vortex blob method converge to an infinite spiral as the smoothing parameter tends to zero? 2. Do vortex blob computations approximate real fluid motion? This paper will present and discuss three computations which are relevant to these issues: a) periodic roll-up, b) wake pattern in a thin soap film, c) separation at a sharp edge.

Proceedings of the International Symposium on Nonsteady Fluid Dynamics

Vortex Sheet Roll-Up Due To the Motion of a Flat Plate

by
R. Krasny

The vortex-blob method is extended to compute vortex sheet separation at a sharp edge. A smoothing parameter controls the amount of detail occuring in the rolled-up spiral. Calculations are presented for the case of vortex sheet roll-up due to an impulsively started flat plate.

Proceedings of the International Congress of Mathematicians
To appear Springer-Verlag, 1990

Computing Vortex Sheet Motion

by
R. Krasny

Coherent vortex structures occur in many types of fluid flow including mixing layers, jets and wakes. A vortex sheet is a mathematical model for such structures, in which the shear layer is approximated by a surface across which the tangential fluid velocity has a jump discontinuity. Vortex sheet motion belongs to the field of vortex dynamics, one of the main approaches to understanding fluid turbulence. Careful numerical experiments have helped advance the mathematical study of vortex sheets. Difficulties arise in computing vortex sheet motion due to short wavelength instability,singularity formation, and spiral roll-up. This paper reviews the problem of computing vortex sheet motion and presents several applications.

Journal of Fluid Mechanics, Vol. 218, pp. 547-572

The Free-Surface Signature of Unsteady, Two-Dimensional Vortex Flows

by
D. Yu and G. Tryggvason

The inviscid interaction of two-dimensional vortex flows with a free surface is studied numerically using a combined vortex/boundary integral technique. The vorticity is modelled as point vortices, vortex sheets and finite area vortex regions. Two problems are studied in considerable detail, the head-on collision of a vortex pair with a free surface and the large-amplitude Kelvin-Helmholtz instability of a submerged shear layer. The interaction is controlled by a Froude number and by the geometric parameters describing the initial vortex configuration. In the large Froude-number limit, the surface motion follows the vortical flow, but depends only weakly on the actual value of the Froude number. For low Froude numbers, the free surface remains almost flat, and the disturbances caused by the vortical flow decrease rapidly with Froude number.

Submitted to Lectures in Applied Mathematics

Interaction of Vortices with a Free Surface and Density Interfaces

by
G. Tryggvason, S.O. Unverdi, M. Song, J. Abdollahi-Alibeik

Recent investigations of vortex interactions with a sharp density interface and a free surface are reviewed. Particular emphasis is on numerical simulations, but experimental investigations are discussed also. The collision of a vortex pair and a vortex ring with an interface or a free surface has been studied in considerable detail. In most cases the major control parameter is the Froude number, representing the relative strength of the vortices and the action of gravity. For high Froude numbers the vortices penetrate through the interface, and their motion is only minimally modified for a time that is long relative to the time scale of the vortex motion. For low Froude numbers, on the other hand, the free surface acts like a rigid surface and inhibits the motion of the vortices in a direction normal to the surface. Rebounding is observed under a variety of circumstances, and is found to have numerous causes.

PSH Technical Report #90-1
To be submitted to Phys. Fluids

Collision of a Vortex Pair with a Contaminated Free Surface

by
G. Tryggvason, J. Abdollahi-Alibeik, W. Willmarth, A. Hirsa

Collision of a viscous vortex pair with a free, contaminated surface is studied numerically. The Froude number is assumed to be small so the surface remains flat. The full Navier-Stokes equations and a conservation equation for the surface contaminant are solved numerically by a finite difference method. The shear stress at the free surface is proportional to the contamination gradient, and simulations for several values of the proportionality constant (W), as well as Reynolds numbers, have been performed. The evolution is also compared with full-slip and no-slip boundaries. As the vortices approach the surface, the upwelling between them pushes the contaminant outward, reducing the amount directly above the vortices, and leading to a clean region for low W, as well as for full-slip boundaries. As W is increased the clean region becomes smaller, and eventually no clean region is formed. Except for very low W, the contaminant layer leads to the creation of secondary vortices, causing the original vortices to rebound in a similar way as compared with experimental measurements with satisfactory results. Computations of a vortex pair colliding obliquely with a contaminated surface and head-on collision of axisymmetric vortex rings are also presented.

Phys. Fluids, Vol. 31, pp. 955-957, 1988

Deformation of a Free Surface as a Result of Vortical Flows

by
G. Tryggvason

The deformation of a free surface caused by the roll up of a vortex sheet below the surface is studied. The large amplitude motion depends on both the strength and depth of the vortex sheet. A distinction is made between three different scenarios of the free-surface motion: a breaking wave, entrainment of air, and the generation of relatively short surface waves.

Ph.D. Thesis, 1990

Numerical Simulations of Vortex Interactions with a Free Surface

by
D. Yu

The inviscid interaction of two-dimensional vortex flows with a free surface is studied numerically using a combined vortex/boundary integral technique. The vorticity is modeled as point vortices, vortex sheets and finite area vortex regions.

For generation of surface deformation by vortical flows two problems are studied in considerable detail, the head-on collision of a vortex pair with a free surface and the large amplitude Kelvin-Helmholtz instability of a submerged shear-layer. The interaction is controlled by a Froude number and by the geometric parameters describing the initial vortex configuration. In the large Froude number limit, the surface motion follows the vortical flow, but depends only weakly on the actual value of the Froude number. For low Froude numbers, the free surface remains almost flat, and the disturbances caused by the vortical flow decrease rapidly with Froude number.

The modification of surface waves by vortical flows was studied by considering a wavetrain propagating over a single, submerged vortex. For strong and shallow vortex the vortex generated current stops the waves, but weak and deep vortex has minimum effect. To facilitate the use of many computational elements, in this last problem, a Multipole Expansion Technique was used to speed up the calculations.

Mathematical Aspect of Vortex Dynamics, 1988

Vortex Dynamics of Stratified Flows

by
G. Tryggvason

After a brief review of vortex methods for stratified flows, recent work on the evolution of vortical flows in the vicinity of density interfaces and free surfaces is discussed. Two specified examples are considered: free surface deformation due to the roll up of a submerged vortex sheet, and the mixing across a weak density interface due to the head-on collision of vortex pairs and vortex rings. The conclusion discusses boundary integral methods for three-dimensional flows, as well as alternative vorticity formulations for general stratified flows.

Proceedings of Eighteenth Symposium on Naval Hydrodynamics, 1990

Measurement and Computations of Vortex Pair Interaction with a Clean or Contaminated Free Surface

by
A. Hirsa, G. Tryggvason, J. Abdollahi-Alibeik, W.W. Willmarth

Observations of surface deformations produced by the interaction of trailing vortices with a free surface, behind a submerged delta wing at negative angle of attach, were described by Sarpkaya and Henderson (1985). The flow field during the laminar interaction with the free surface is studied experimentally using a pair of vertically oriented, computer controlled, counter rotating flaps to generate laminar vortex pairs with the same Reynolds number and Froude number as the trailing vortices. Numerical computations in two-dimensions, flow visualization (laser induced fluorescence and shadowgraph) and particle image velocimetry (PIV) with known surfactants on the surface show that surface contamination has a significant influence on the flow field and surface motion during the interaction. New vorticity produced on either side of the vortex pair when the surface is contaminated initially forms a Reynolds ridge, (the surface signature at the leading edge of a subsurface boundary layer), and then the new vorticity beneath the contaminated surface rolls up to form secondary vortices outboard of the original vortices and with opposite sign. The secondary vortices cause the original vortex pair to rebound from the free surface.

Proceedings of Eighteenth Symposium on Naval Hydrodynamics, 1990

Vortex Ring Interaction with a Free Surface

by
M. Song, N. Kachman, J.T. Kwon, L.P. Bernal, G. Tryggvason

The results of numerical and experimental studies on the interaction of vortex rings with a free surface are presented. New results are reported on the interaction of a large vortex ring with a clean surface at normal incidence. The early stages of the interaction are well described by a simple axisymmetric vortex filament model. Transition to a fully three-dimensional state is observed at later stages of the interaction. Surface waves are generated at high Froude numbers by these three-dimensional motions. Results are also presented on the interaction of vortex rings with clean and contaminated free surfaces at inclined incidence. The phenomenon of vortex lines breaking and attachment to the free surface is documented. It is shown that small amounts of surface active agents greatly alter the interaction at inclined incidence. The effects differ depending on the local topology of the vortex lines. A Reynolds ridge and secondary vorticity generation are observed during the interaction with a contaminated surface.