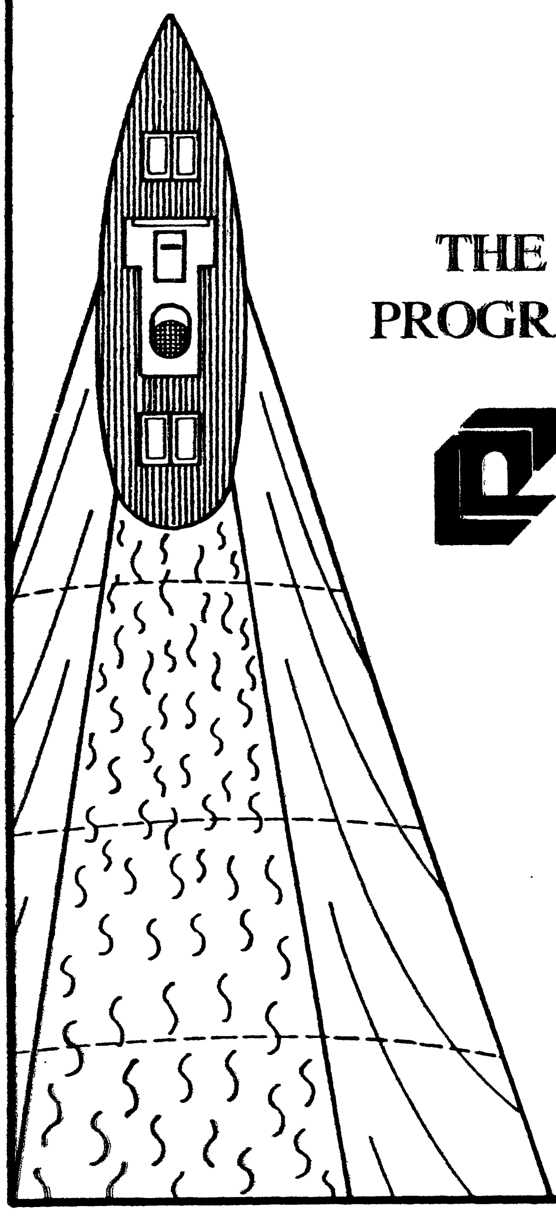
1991 End-of-Fiscal Year Report

Robert F. Beck, Project Director

Contract Number N000184-86-K-0684
October, 1991



THE UNIVERSITY OF MICHIGAN
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PROGRAM IN SHIP HYDRODYNAMICS
Executive Summary Report

by
Robert F. Beck, Project Director

The final year of the Program in Ship Hydrodynamics has seen further progress in the understanding of the interaction of vorticity and the free surface. Budget cuts and a delay in funding has caused reductions in the research program. However, 5 Ph.D. theses and one master thesis were completed this year. The experimental research continued to identify new phenomena using the instrumentation developed under this project. The numerical calculations have shown good agreement with the experiments and full scale results.

Appendix I lists the year-end reports written by the principal investigators for each of the research projects. These reports summarize the research goals and significant accomplishments of the past 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.

The instrumentation development is continuing. The laser doppler velocimeter (LDV) module of the hydrodynamic monitoring facility (HMF) was used in experiments in the towing tank for the first time. The LDV was mounted in a fixed position on the side wall of the tank for the large jet experiments. A subcarriage to carry the LDV behind a model is presently in the final design phase; construction should start within a month. Before the LDV was mounted in the tank the optical fibers had to be replaced. When the fibers were purchased TSI had warned us of their finite life but they did not have enough experience with them to give an accurate estimate of the total operating hours before replacement. The new fibers are of a non-degrading material and should last indefinitely.

The two other subsystems of the HMF are also under going modification. Software has been developed for determining surface velocities by tracking tagged fluid regions. The techniques are similar to that used in digital particle image velocimetry. Originally, the tagged fluid regions were to be warm spots created by a scanning infrared laser. The achievable number of tagged regions obtainable using this technique is insufficient to get the desired velocity and height resolution. Using particles to mark the free surface will allow a much higher density of velocity measurements. To obtain height measurements, a stereo-image pair technique is presently being adapted.

The scanning laser system for multipoint, refractive free surface slope measurements is on hold. Due to signal-to-noise ratio problems, the mepsicron camera was converted from a photon counting mode of operation to a continuous mode. During testing of the new system, the sensor tube failed. Again, we had been warned that the tube had a finite life but the manufacturer could not predict how long. The replacement cost is $26,000 if a tube can be found because the manufacture, Electro-optics Division of ITT Corp., has suspended operations. If the stereo-image system works, the slope system will be redundant. It was therefore decided to cease further development until further information is available.

A holographic imaging technique is under development by Professor Bernal. The use of holography allows particles to be tracked in three dimensions and thus to resolve all three components of the velocity field within a measurement volume. The technique has been successfully used to measure the velocity field surrounding a vortex ring.

Research into the fundamental nature of the interaction of vorticity with a free surface by studying basic flows has continued. Experiments and numerical calculations with the vortex ring and submerged jet have been carried out; particular emphasis has been place on the role of surfactants and Reynolds number. Using particle image velocimetry (PIV), laser induced fluorescence (LIF), and shadowgraphs the interaction of a vortex ring with a contaminated free surface was examined. It was found that the interaction varies significantly depending on the contamination number. For moderately to heavily contaminated surfaces the circulation of the secondary vortices was approximately 26% of the primary vortex ring circulation. Surface contamination also strongly influenced the development of three-dimensionality in the vortex ring. Regardless of the contamination number, the fluid at the surface was never immobilized. Even for a clean free surface, the circulation of the primary vortex showed a marked reduction during the interaction process. This effect is believed to be associated with vorticity generated at the surface by surface curvature effects.

Numerical calculations for vortex ring interactions with the free surface have been carried out. Fully nonlinear free surface boundary conditions have been used for inviscid flow with a clean free surface. Non-deformable or linearized free surface boundary conditions were used for the contaminated surface and viscous fluid cases. Computations agree very well with the experiments. Both the primary and secondary reconnections have been simulated. Full simulations using a viscous fluid and a fully nonlinear free surface are presently underway.

Two sets of experiments have been completed in the towing tank. The first is the large scale jet experiments using an apparatus designed by Bill Willmarth. The 10 cm diameter jet is propeller driven and has screens and a honeycomb section for flow straightening and turbulence management. The jet has a 9:1 area-ratio exit contraction. Measurements showed no streamwise vorticity exists at the jet exit. The large jet experiments are intended to complement the small jet experiments performed last year by Anthony and Willmarth. Anthony's results were for a Reynolds number of 12,700 while the large jet has a maximum Reynolds number of 300,000. It has been determined that the lateral spreading of the surface current found by Anthony becomes independent of Reynolds number above $Re = 15{,}000$. Shadowgraph images of the free surface show considerable differences in the free-surface signatures over the range of Reynolds and Froude numbers examined. At high Reynolds number ($Re > 100{,}000$) considerably more small-scale activity appears in the free-surface visualizations. As compared to the $Re = 12{,}700$ jet, the high Reynolds number near-surface layer is more strongly influenced by the presence of the free surface.

The second set of experiments in the towing tank were continued tests with the Quapaw model. Both propelled and unpropelled cases have been conducted. As with the free surface jets, there is a thin surface layer of fluid with a strong outward (away from the wake centerline) velocity component. For the unpropelled model stern vortices interact with the wake to carry a significant portion of the wake fluid downward, away from the free surface. This interaction was modified by the swirl of the propeller. Fourier analysis of shadowgraph images of the wake behind the model has revealed a strong directional component in the spectrum associated with the short diverging Kelvin waves and a broad band spectrum associated with the waves at the edge of the turbulent wake. A complete analysis of all the Quapaw results is presently being prepared for publication.

Analytic and numerical methods have been used to investigate nonlinear waves in the ship wake. Fully nonlinear wave calculations utilizing the desingularized method have been employed to investigate the solitary inner-angle wave packets observed in ship wakes. Comparisons to linear calculations using a time-domain Green function have revealed that it is the unsteadiness of the flow field that causes the wave packets and not nonlinear interactions. Fully nonlinear calculations have also been done for submerged bodies. Work is proceeding on developing techniques for surface piercing vessels.

Analytic methods have also been used to investigate the modification of surface waves by surfactant slicks. Surfactant slicks cause surface tension gradients which in turn modify the propagation of capillary-gravity waves. Results have been obtained for the variation in wave amplitude for the two limiting cases of abrupt and slow spatial change in surfactant concentration. The methods developed are general so that additional effects can be incorporated as necessary in order to study realistic conditions found in the ocean.

APPENDIX I

3.1.1. Ship Wake Signatures

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. Efforts during this most recent period have concentrated upon more theoretical aspects utilizing experimentation conducted during previous portions of this URI. These efforts have been directed toward understanding the hydrodynamic and electromagnetic scaling properties within the surface ship wake.

The fundamental goal of this research is to investigate the limits to which both experimental and analytical descriptions of surface ship wake phenomena can be utilized to determine the hydrodynamic sources of the surface signature. Theoretical aspects of this research have concentrated on the solution of geophysical inverse problems.

Significant Results in the Past Year: As a result of previous experimental investigations, scaling between full scale and model scale mean wake components have been well established (Meadows *et al.*, 1991). It has been shown that both the longitudinal and transverse mean velocity components have approximately a 1/x decay with distance downstream based upon the full set of nearly 30,000 LaGrangian velocity observations in the near wake with correlation coefficients of 0.98 and 0.94, respectively. Froude scaling was used in the model tests. Preliminary comparison with full scale measurements indicates good agreement with the model tests for both magnitude and rate of decay of the mean wake components.

Similarly, the Ph.D. dissertation of Z. Wu has investigated scaling as used in association with the Kelvin wake portion of the ship wake signature. Wu (1991) has demonstrated a successful, constrained, nonlinear inversion technique to determine basic ship and operating characteristics from the observed Kelvin wake signature. His efforts, again, have utilized both laboratory as well as full scale data.

The extraction of ship information is based on the relations of the ship's wave spectra, wave amplitude function and hull geometry. In this research, an analytic representation of wave elevation is introduced with the use of the Hilbert transform, and the derivation is given for the calculation of the wave amplitude function from the Fourier spectrum of one and two dimensional complex-valued wave elevations. Methods and formulas are given for estimating a ship's speed and direction from the spectrum of a two-dimensional wave patch, a single wave cut or two wave cuts. A theoretical model of the wave amplitude function is developed, and three methods are designed for the estimation of a ship's length from the wave amplitude function. Under the assumption of thin-ship theory, an inversion technique to predict the geometry of a ship's hull from the wave amplitude function or its magnitude is developed through the application of a spectral method and the constrained maximum likelihood method. Examples comparing theoretically calculated data and tow tank experimental data are given to demonstrate the methods developed and estimated performance.

The final remaining component of the ship wake of interest is the centerline wake. Our previous investigations have indicated that mean flow components decay rapidly with distance behind the vessel. Hence, the persistence of the late wake as viewed in many SAR images may be the result of large scale turbulent vortical structures which persist for long periods of time and periodically interact with the free surface. To investigate this hypothesis, the classic work of Lamb (1945) on the Cauchy-Poisson disturbance of the free surface was expanded to three dimensions and applied theoretically to the surface ship wake problem. Preliminary results are encouraging and provide a plausible explanation for the generation of small scale surface waves in the late wake. Results to date of this work were presented at the Ship Wake Consortium workshop.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

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

Wu, Z. and G. Meadows, "A remote sensing technique for the estimation of a moving ship's velocity and length from its wave spectra," *Proceedings* IEEE Oceans '91, Honolulu, Oct. 1991.

Meadows, L., G. Meadows, A. Troesch, S. Cohen, K.P. Beier, G. Root, O.M. Griffin and T.F. Swean, Jr., "LaGrangian Velocity Profiles in the Wake of a High Speed Vessel," submitted to *Ocean Engineering*, 1991.

2. <u>Technical Reports, Non-Refereed Papers</u>

Wu, Z., "On the estimation of a moving ship's velocity and hull geometry information from its wave spectra," Ph.D. Thesis, University of Michigan, PSH Technical Report #91-1, Sept. 1991.

3. <u>Presentations</u>

Meadows, G., "Comparison of laboratory and full scale wake measurements," ONR Code 12 Ship Wake Consortium, 1991 Spring Workshop, Ann Arbor, MI, May 1991.

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
J. Acuna, MSE Candidate
M. Song, Ph.D. in May 1991
E. Wright, Research Engineer
Z. Wu, Ph.D. in August 1991

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

3.2.6. Vortical Structure of Ship Wakes

Principal Investigator: L.P. Bernal

<u>Research Summary</u>

Description of Scientific Objectives: The main goal 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.

The scientific objective of the investigation conducted this past year was to obtain a better quantitative understanding of the role of surface contamination on the dynamics of vortical flows at a free surface. The suitability of a contamination number based on the initial surface pressure, rather than surface elasticity, to scale the surface contamination effects was investigated.

A second objective of the research was to develop Holographic Particle Image Velocimetry (HPIV) for three-dimensional flow field measurements in turbulent free-surface flows. The main issue addressed in this research was the resolution characteristics of the holographic imaging system.

Significant Results in the Past Year: The interaction of a vortex ring with a contaminated free surface was investigated to determine the effect of surface contamination on the dynamics of vortical flows at a free surface. Laminar vortex rings were generated with a piston type vortex ring generator propagating normal and toward the surface. The effect of surface contamination was investigated by depositing on the surface various amounts of Oleyl alcohol. The contamination level was characterized by direct measurements of surface tension. Flow visualization of the subsurface flow using LIF and of the surface deformation using shadowgraph was conducted. The subsurface flow and the free surface flow were measured using PIV. The Reynolds number range investigated was $\frac{\Gamma}{\nu}$ = 5,000 - 10,000. The contamination number range investigated was $W = \frac{\Pi \, a}{\mu \, \Gamma} = 0 - 310$, where Π = surface pressure; a = diameter of the ring; μ = coefficient of viscosity; Γ = vortex circulation strength.

The main conclusions of this investigation can be summarized as follows: 1) The contamination number W as defined above properly scales surface contamination effects. For $W < 5$ the flow evolution is very similar to the evolution with a clean free surface. For $W > 10$ the outward motion of the vortex ring is arrested by a secondary vortex. 2) The Reynolds ridge is observed over a limited range of contamination numbers $5 < W < 20$. For comparatively clean surfaces, contaminants did not accumulate in sufficient quantities to form a Reynolds ridge. For high contamination number, the fluid motion at the surface is not enough to clean the surface and form the Reynolds ridge. 3) The circulation of the secondary vortices formed for $W > 10$ was measured using PIV and found to be approximately 26% of the initial vortex ring circulation. 4) The circulation of the primary vortex using PIV showed a marked reduction during the interaction with the surface even for a clean surface. This effect is believed to be associated with vorticity generated at the surface by surface curvature effects. 5) Surface contamination strongly influenced the development of three-dimensionality in the vortex ring. Vortex core reconnection to the surface was observed at low contamination numbers. At higher contamination numbers the formation of the secondary vortex and rebounding of the primary vortex strongly influenced the evolution of three-dimensional instabilities. 6) The fluid at the surface was never immobilized. PIV measurements of the surface flow showed fluid motion even at the highest contamination investigated as well as the appearance of vortical motions at the surface.

In a different investigation, holographic imaging of small particles was used to measure three-dimensional velocity fields in a volume. An in-line holographic recording system was used. Systematic tests were conducted to determine the resolution and other imaging characteristics of holographic systems. These experiments were conducted in water and air with particles of various sizes. A two axis holographic system was also used to improve the axial resolution of the measurements. The main conclusions of this investigation are: 1) The particle size resolution of a holographic system is determined by the Fraunhofer number of the holographic recording system given by $F = \frac{d^2}{\lambda\ z}$, where z is the distance from the particle to the holographic plate, λ is the laser wavelength, and d is the diameter of particle. It was found that the imaged particles must satisfy $F > F_c$. For holographic recording in air without optical windows $F_c > 0.003$ was demonstrated. In these experiments 15 μm particles were consistently imaged in a volume 10x10x10 cm. The axial position resolution of a particle is limited by the depth of field of the particle image. The depth of field was measured on particle images and found to be $\pm 2d^2/\lambda$. To improve the axial resolution, a two axis system was developed and used to measured the velocity field in a vortex ring.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

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

Kachman, N.J. and L.P. Bernal, "Vortex ring dynamics at a contaminated surface," submitted to National Fluid Dynamics Congress, Los Angeles, CA, June 22-25, 1992.

Song, M., L.P. Bernal, and G. Tryggvason, "Head on collision of a large vortex ring with a free surface," submitted to *Physics of Fluids A*.

Scherer, J. and L.P. Bernal, "Resolution characteristics of Holographic Particle Image Velocimetry," AIAA paper no. 92-0009, submitted to Aerospace Sciences Meeting, AIAA, January 1992.

Kachman, N.J., "The interaction of a vortex ring with a contaminated free surface," PhD Thesis, University of Michigan, 1991.

Kachman, N.J., E. Koshimoto, and L.P. Bernal, "Vortex ring interaction with a contaminated surface at inclined incidence," *Proceedings* Symposium on Dynamics of Bubbles and Vortices Near a Free Surface, 1991 ASME Applied Mechanics Meeting, Columbus, OH, June 16-19, 1991.

Bernal, L.P. and J. Scherer, "Holographic particle image velocimetry," *Bull. Am. Phys. Soc*, 35:10:2238, 1990. (Abstract only)

Kachman, N.J. and L.P. Bernal, "Interaction of a vortex ring with a contaminated surface," *Bull. Am. Phys. Soc*, 35:10:2267, 1990. (Abstract only)

2. Technical Reports

none

3. Presentations

Bernal, L.P. and J. Scherer "3-D velocity field measurement by holographic particle image velocimetry," Advanced Workshop on Particle Image, Speckle and Holographic Velocimetry, Heriot-Watt University, Edinburgh U.K., Sept. 23-25, 1991.

Kachman, N.J. and L.P. Bernal, "Interaction of a vortex ring with a contaminated surface at normal incidence," ONR Code 12 Ship Wake Consortium, 1991 Spring Workshop, Ann Arbor, MI, May 1991.

Scherer, J. and L.P. Bernal, "Recent experiments on holographic particle image velocimetry," ONR Code 12 Ship Wake Consortium, 1991 Spring Workshop, Ann Arbor, MI, May 1991.

Bernal, L.P., "Experimental investigations of vortex reconnection at a free surface," ONR 1991 Free Surface Vorticity Workshop, UCSD, La Jolla, CA, Feb. 25-26, 1991.

Bernal, L.P., "Interaction of vortex rings with clean and contaminated free surfaces," Invited Seminar Department of Aerospace and Mechanical Engineering, University of Arizona, Tucson, AZ, Feb. 27, 1991.

Bernal, L.P., "A status report on holographic particle image velocimetry," Thermal-Fluids Seminar, Department of Mechanical Engineering and Applied Mechanics, University of Michigan, Dec. 5, 1990.

LIST OF HONORS/AWARDS

none

LIST OF PARTICIPANTS

L.P. Bernal, Associate Professor
N. Kachman, Ph.D. in December 1991
J. Scherer, Ph.D. Candidate

3.3.1. Nonlinear Ship Waves

Principal Investigator: W.W. Schultz

Research Summary

Description of Scientific Research Goals: To develop numerical techniques that will allow fully nonlinear wave computations. Particular emphasis is being placed on Kelvin ship wave patterns in the far wake. Ultimately, the model should incorporate vorticity, breaking waves, and subgrid models of capillary waves (based on the analytical subtasks of this project).

Significant Results in the Past Year: The desingularized boundary integral method has been used to study several nonlinear wave problems effectively. The first problem was the generation of upstream runaway solitons by a moving disturbance in shallow water. We were able to duplicate the results of Wu for the weakly nonlinear cases. We also studied strong nonlinear cases and the waves due to submerged bodies which cannot be considered in Wu's fKdV model. Our results were presented at the Sixth International Water Waves and Floating Bodies Workshop. The second problem was the computations of nonlinear waves due to submerged bodies. In Bertram *et al.* (1991) the forces and moments on a submerged spheroid were computed using the desingularized method. Very good agreement was found when compared to both linear and nonlinear calculation methods. The inner-angle "solitary" wavepackets inside the wake of a ship were investigated using the desingularized method, the linear time-domain Green function technique and the stationary phase analysis. It has been shown that nonlinear effects are not essential for the generation of the inner-angle wavepackets while the unsteadiness of the wake can result in the inner-angle wavepackets. The abstract of a tentative paper entitled "Inner-Angle Wavepackets in an Unsteady Wake" has been accepted for presentation at the 19th Symposium on Naval Hydrodynamics. A manuscript on this topic is also being prepared for submission to *Journal of Fluid Mechanics*.

It has been observed that surfactant slicks cause appreciable changes in capillary-gravity waves. With this in mind, a study has been carried out by S. Gou, A.F. Messiter, and W.W. Schultz to predict the effect of surface tension gradients on the propagation of capillary-gravity waves. Analytical results for changes in wave amplitude have been obtained in two limiting cases, for abrupt and slow spatial changes in surfactant concentration and therefore in surface tension. For the former case, solved using a complex integration, a manuscript for publication has just been completed. For the latter case, studied using matched asymptotic expansions and multiple scales, a manuscript is in preparation. While certain simplifying assumptions have been used up to this point, the methods developed are now available for incorporating additional effects and for application under realistic conditions.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers in Refereed Proceedings/Journals

Bertram, V., W.W. Schultz, Y. Cao and R.F. Beck, "Nonlinear computations for wave drag, lift and moment of a submerged spheroid," *Ship Technology Research* **38**:3-5, 1991.

Cao, Y., "Computations of nonlinear gravity waves by a desingularized boundary integral method," Ph.D. Thesis, University of Michigan, Ann Arbor, 1991.

Joo, S.W., A.F. Messiter and W.W. Schultz, "Evolution of weakly nonlinear water waves in the presence of viscosity and surfactant," *Journal of Fluid Mechanics*, **229**:135-158, 1991.

Cao, Y., W.W. Schultz and R.F. Beck, "Three-dimensional desingularized boundary integral methods for potential problems," *Int. J. Num. Meth. Eng.* **11**, 1991.

Schultz, W.W. and J.-M. Vanden-Broeck, "Steep free-surface standing waves," *Bull. Am. Phys. Soc,* **35**:10:2290, 1990. (Abstract only)

Reed, A.M., R.F. Beck, O.M. Griffin and R.D. Peltzer, "Hydrodynamics of remotely sensed surface ship wakes," SNAME *Transactions* **98**:319-363, 1990.

2. Technical Reports

none

3. Presentations

Cao, Y., W.W. Schultz, and R.F. Beck, "Two-dimensional solitary waves generated by a moving disturbance," Sixth International Workshop on Water Waves and Floating Bodies, Woodshole, MA, 1991.

Messiter, A.F., "Some surfactant effects on deep-water waves," seminars presented at University of East Anglia, Norwich, and at Imperial College, University of London (both in England), April 1991.

Cao, Y., W.W. Schultz, and R.F. Beck, "Inner-angle wavepackets in an unsteady wake," accepted for presentation at 19th Symposium on Naval Hydrodynamics, Seoul, Korea, Aug. 1992.

LIST OF HONORS/AWARDS

W.W. Schultz, Alexander von Humboldt Fellowship, 1991.
W.W. Schultz, University of Michigan, promoted to Assoc. Prof. with tenure, 1991.

LIST OF PARTICIPANTS

W.W. Schultz, Associate Professor
R.F. Beck, Professor
A.F. Messiter, Professor
Y. Cao, Ph.D. in August 1991
S. Gou, Ph.D. Candidate

3.3.2. Interaction of Vorticity and Free Surface Flows

Principal Investigator: G. Tryggvason

Research Summary

Description of Scientific 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 generalized vortex methods 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: The focus of our work during last year has been on the effect of contaminants on viscous flows and wave generation due to three dimensional flows. We have examined in detail the collision of a vortex pair with a flat (waveless) free surface, for various amounts of surface contaminants. The full viscous fluid equations are solved with a finite difference technique. At the 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 relatively small amounts of surface contaminant can cause the vortical flow to behave as a no-slip boundary, in agreement with Willmarth's experiments. Computations for various Reynolds numbers and equations of state for the contaminants have been done. A paper has been submitted to the *Physics of Fluids.*

Other major activities during the last year are presented in a thesis by M. Song (co-chaired by Tryggvason and Meadows) that was completed in the spring of 1991. Part of the thesis describes experiments on a large vortex ring in the towing tank. The experimental work has identified the nature of the three-dimensional surface signatures that appear rather early after the ring collides with the surface. Accompanying numerical modeling shows that up to the appearance of three-dimensional disturbances, the evolution can be explained by an inviscid axisymmetric model. The vorticity is taken as a single ring, and the full nonlinear free surface conditions are used. Other parts of the thesis focused on the three-dimensional interaction of both inviscid as well as viscous vortex rings with a free surface. Simulations using an "essentially" inviscid vorton model followed the ring as it "opens-up" (or reconnects) at the surface. Linearized free surface boundary conditions allow the prediction of the accompanying wave generation. In some cases the simulations show a secondary "opening-up" in agreement with experiments. Viscous simulations using a waveless free surface show the same process, but due to low Reynolds number only the first reconnection can be simulated. Preliminary calculations have been used to investigate the effect of surface contaminants on three-dimensional flow. A paper describing the experiments and accompanying modeling has been submitted to the *Physics of Fluids*, and a paper on the wave generation due to vortex reconnection, as well as the modeling of more complicated flows by many "interactions" where each interaction is described by a low order approximation of a single interaction, is in preparation.

Full simulations of the collision of viscous vortex rings with a fully deformable surface are currently underway. The focus is on understanding the vorticity dynamics in terms of baroclinicly generated vorticity produced at the free surface. A preliminary report was given by T. Faical (self supported) at the 1991 summer ASME Applied Mechanics Meeting in Ohio this summer.

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, 1990. A manuscript accompanying the talk will appear in *Lectures in Applied Mathematics.*

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers in Referred Proceedings/Journals

Yu, D. and G. Tryggvason, "The free surface signature of unsteady, two-dimensional vortex flows," *J. Fluid Mech.*, **218**: 547-572, 1990.

Tryggvason, G., J. Abdollahi-Alibeik, W. Willmarth, and A. Hirsa, "Collision of a vortex pair with a contaminated free surface," submitted to *Phys. Fluids*, Nov 1990, (also available as URI Technical Report 90-1).

Song, M. and G. Tryggvason, "Free surface waves due to the "opening up" of a vortex ring," *Bull. Am. Phys. Soc,* **35**:10:2247, 1990. (Abstract only)

Krasny, R., "A method for computing vortex sheet separation," 43rd Meeting of the American Physical Society, Division of Fluid Dynamics, Nov. 19-21, Cornell University, Ithaca, N.Y., Abstracts in *Bull. Amer. Phys. Soc.* **35**:2269, Nov. 1990.

Song, M., "Vortex ring interactions with a free surface," Ph.D. Thesis, University of Michigan, 1991.

Song, M., L.P. Bernal, and G. Tryggvason, "Head-on collision of a large vortex ring with a free surface," submitted to *Phys. Fluids*, April 1991.

Faical, T., M. Song, S.O. Unverdi, and G. Tryggvason, "Collision of viscous vortices with a free surface and density interfaces," *Proceedings* of Symp. on Dynamics of Bubbles and Vortices Near a Free Surface", 1991 ASME Applied Mechanics Meeting, ed. Sahin and Tryggvason, Columbus, OH, 31-37, June 16-19, 1991.

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*, 1991.

2. Technical Reports

none

3. Presentations

Tryggvason, G., "Vortex Ring Interaction with a Free Surface," Invited presentation ONR 1991 Free Surface Vorticity Workshop, San Diego, Feb. 25-26, 1991.

Faical, T., M. Song, S.O. Unverdi, and G. Tryggvason, "Collision of viscous vortices with a free surface and density interfaces," 1991 ASME Applied Mechanics Meeting, Columbus, OH, June 16-19, 1991.

LIST OF HONORS/AWARDS

R. Krasny, University of Michigan, Faculty Recognition Award, 1991.
G. Tryggvason, University of Michigan, promoted to Assoc. Prof. with tenure, 1991.

LIST OF PARTICIPANTS

Gretar Tryggvason, Associate Professor
R. Krasny, Associate Professor
Museok Song, Ph.D. in May 1991
Javad Abdollahi-Alibeik, M.S. Student (no longer with the project)
T. Faical, Ph.D. Student (self supported)

3.3.7. 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. In the past year, the scope of this project has been increased to include a more canonical flow, the free-surface jet and continuing development of the HMF.

Significant Results in the Past Year: Progress has been made on several fronts since the last report. The initial study of the qualitative features of the wake of the Quapaw model have been completed. A new large-scale jet apparatus has been designed and tested, and initial flow visualization studies, as well as turbulent structure measurements, have been conducted. And development of the HMF hardware and software has continued.

Our previous visualization studies of the Quapaw wake have revealed the existence of a thin layer of fluid near the free surface with a strong outward (away from the wake centerline) velocity. This surface-current layer has been identified in both turbulent surface jets and wall jets. Stern vortices which interact to carry a significant portion of the wake fluid downward, away from the free surface, were identified for the unpropelled model. This interaction was modified by the swirl introduced by the addition of a propeller. While the detailed behavior of the stern vortices in the propelled case is unclear, visualization has shown that these vortices no longer carry turbulent wake fluid away from the free surface. This may account, in part, for the increased turbulent activity observed near the free surface in the wake of the propelled model. Shadowgraph visualization of the free surface had previously identified the existence of irregular, but somewhat organized, short waves along the edges of the turbulent wake. Fourier analysis of these images has revealed a strong directional component in the spectrum. This spectral peak appears to correspond to the inner edges of the steady Kelvin wave system and is not related to the waves at the edge of the turbulent wake. A complete analysis of all the Quapaw results is now being prepared for publication.

The turbulent wake of the Quapaw model exhibits many of the same features seen in turbulent jets near a free surface. The jet has the advantage of being experimentally simpler to investigate than a wake, however previous jet studies have been confined to very low Reynolds number. To examine turbulent shear flow near a free surface at high Reynolds number for a more basic geometry than a model ship wake a new large-scale jet apparatus has been designed (by W.W. Willmarth) and tested. The jet has a 10 cm diameter exit nozzle and is capable of operating at a maximum Reynolds number 300,000. To minimize confinement effects, the jet is operated in the Naval Architecture Department's large tow tank (approx. 22 ft x 10 ft cross section). This jet is propeller driven and has screens and a honeycomb section for flow straightening and turbulence management and a 9:1 area-ratio exit contraction. Measurements show a maximum exit velocity of 3 m/s and a turbulence intensity of less than 0.1 percent. Measurements showed no streamwise vorticity existed at the jet exit.

In late June, a two-week study of the qualitative characteristics of the large-scale jet was undertaken in the large tow tank. For comparison purposes, the small-scale jets used in the work of W.W. Willmarth and D.G. Anthony were examined at the same time. Visualization of the surface current showed that the lateral spreading of the surface current becomes independent of the Reynolds number above ***Re*** = 15,000 and is independent of Froude number. Comparison with the jet issuing beneath a solid wall shows the two types of flow to be qualitatively similar; however, the surface-current layer for the free-surface jet was thinner and spread more rapidly than that for the wall jet. Shadowgraph images of the free surface show considerable differences in the free-surface signatures over the range of Reynolds and Froude numbers examined. These differences, and in particular, their Froude-number dependence, are currently being examined. At the high Reynolds numbers (> 100,000) attainable using the new jet apparatus, considerably more small-scale activity appears in the free-surface visualizations. This is due to the larger range of length and velocity scales present at higher Reynolds number.

Detailed measurements of turbulent structure in the large-scale jet are have been performed and are now being analyzed. These experiments involved efforts by D.G. Anthony and W.W. Willmarth, as well as C.-Y. Chen, a graduate student who has recently joined the project. Measurements of turbulence structure in the large scale jet were acquired for locations 16 and 32 diameters downstream of the exit for a Reynolds number of 101,000. These results show considerable differences when compared with those of Willmarth and Anthony in a similar jet at ***Re*** = 12,700. The near-surface layer is more strongly influenced by the presence of the free surface at the higher Reynolds number. This may be due to the increased small-scale structure present. These results are now in preparation for submission to the 19th Symposium on Naval Hydrodynamics in Seoul, Korea.

For these jet experiments, the three-component laser velocimeter developed by W.W. Willmarth was operated at a fixed location in the tow tank. During testing of the laser velocimeter prior to installation in the tow tank, it was found that the optical fibers had suffered significant optical degradation during the last year. Degradation of the fibers was expected, and is a natural consequence of using the instrument. Due to the present state of knowledge for this type of fiber, the rate at which this degradation would occur could not be accurately predicted, *a priori*. The laser velocimeter probe was returned to TSI Inc.for installation of new fibers. The new fibers are a different, non-degrading material and should last indefinitely. The new fibers are also individually jacketed, rather than bundled. This should minimize spurious velocities introduced by differential fiber straining which results from vibration of the bundled fibers. Design has proceeded on a moving carriage on which to mount the laser velocimeter, and construction will begin shortly.

Development has proceeded on the two other systems which, along with the laser velocimeter, comprise the HMF. Software has been developed for determining surface velocities by tracking tagged fluid regions. Due to limitations on the achievable number density of tagged regions obtainable using a scanning infrared laser, alternative approaches have been investigated. Using particles to mark the surface will allow a higher density of velocity measurements. The processing approach used determines the velocity field from particle displacements between two successive video frames. This software, initially written by L.A. Meadows, and further developed by Ph.D. student K. Thiagarajan, implements an approach similar to that used in digital particle-image velocimetry. The analysis system is currently being used to examine subsurface flow near the edge of an oscillating disk. One of the problems associated with particle-imaging methods for velocity measurements is getting consistently accurate results. Spurious velocity vectors appear in the measured velocity field, seemingly without cause. The usual approach taken is to manually eliminate these "bad" vectors and then fill the resulting voids in the data set by interpolation. We are currently developing rational approaches to error detection for this measurement technique. Once these are implemented, the technique will be applied to the investigation of surface velocities for the turbulent jet flow described above.

This processing approach is currently being adapted for use in stereo image-pair surface-height measurements. For a stereo pair, surface elevations are related to the apparent displacement of particles between the two images which comprise the pair. Implementation of this technique requires accurate synchronization of two video cameras and real-time recording of two simultaneous images. These preliminary tasks have been completed by E.A. Wright who has developed a method for storing two monochrome video images in one video frame using color coding. The above described analysis software for velocity measurements has been modified for this application and testing of the entire system is underway. Combination of these two approaches should yield high-density measurements of both surface velocities and elevations.

Development is on hold for the scanning laser system used for multipoint, refractive free-surface slope measurements. The primary difficulty in making this system both operational and reliable has been the imaging photomultiplier, or mepsicron, used for determining the location of the laser beam on a screen suspended above the water surface. Due to signal-to-noise-ratio problems, the mepsicron was converted from a photon-counting mode of operation to a continuous mode. This required new processing electronics and data acquisition hardware and software. During testing of these systems, the mepsicron sensor became inoperable. At this time, it was learned that the Electro-optics Division of ITT Corp., the manufacturers of the mepsicron, had closed its doors. This development, plus the mepsicron's $26,000 replacement cost, have led to a suspension of work on this system. If the above-outlined particle-imaging-based, stereo-pair surface elevation measurement system proves successful, the slope measurement system will be somewhat redundant. A decision to resume work on the slope system will require possibly the adaptation of another sensing device, in place of the mepsicron. That decision will be made based on the outcome and evaluation of the stereo pair elevation measurement system.

LIST OF PUBLICATIONS, REPORTS, PRESENTATIONS

1. Papers in Refereed Proceedings/Journals

Johnston, V.G. and D.T. Walker, "Observations of turbulence near the free surface in the wake of a model ship," *Proceedings* Symposium on Dynamics of Bubbles and Vortices Near a Free Surface, 1991 ASME Applied Mechanics Meeting, Columbus, OH, June 16-19, 1991.

Anthony, D. and W.W. Willmarth, "Measurements of jet turbulence beneath a free surface," *Bull. Am. Phys. Soc,* 35:10:2313, 1990. (Abstract only)

Willmarth, W.W., D. Anthony and A. Hirsa, "Flow field of a submerged turbulent jet interacting with a clean free surface," *Bull. Am. Phys. Soc,* 35:10:2322, 1990. (Abstract only)

2. Technical Reports

none

3. Presentations

Walker, D.T., "Turbulence near the free surface in model ship wakes," Second ONR Free-Surface Vorticity Workshop, La Jolla, CA, Feb. 16-19, 1991.

Walker, D.T., "The near-wake of the Quapaw model," ONR Code 12 Ship Wake Consortium, 1991 Spring Workshop, Ann Arbor, MI, May 1991.

Anthony, D.G., D.T. Walker, W.W. Willmarth, and C.Y. Chen, "Turbulence measurements in a jet discharging beneath a free surface," to be presented at the 44th Annual American Physical Society Division of Fluid Dynamics Meeting, Tempe, AZ, Nov. 24-26, 1991.

Walker, D.T., D.G. Anthony, and W.W. Willmarth, "Observations of the interaction of turbulent jets with a free surface," to be presented at the 44th Annual American Physical Society Division of Fluid Dynamics Meeting, Tempe, AZ, Nov. 24-26, 1991.

LIST OF HONORS, AWARDS

none

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K. Thiagarajan, Ph.D. Candidate

APPENDIX II

Proceedings IEEE Oceans 1991

A Remote Sensing Technique For the Estimation of a Moving Ship's Velocity and Length From Its Wave Spectra

by
Z. Wu and G. Meadows

A remote sensing technique to estimate a moving ship's speed, direction and length from its one or two dimensional wave spectra is presented. The estimation of ship speed is related to the ship generated free wave spectra and the direction is related to the position of spectrum loci in the wave number space. These relationships and the algorithm for the estimation are discussed. The prediction of ship length is based on the ship wave amplitude function, which can be derived from the free wave spectra. Results of a theoretical and experiment analysis indicate that the wave amplitude function has an obvious periodic character when it is described as a function of the longitudinal wave number. Hence, ship length information, inherent in this periodicity, can be recovered. The instantaneous "frequency" or "period" of the wave amplitude function may change with wave number related to the shape of the ship's bow and stern. Thus, the methods to avoid over- or under-estimation of ship length caused by this frequency modulation phenomenon are also proposed together with the analysis of the periodicity. It is shown that high estimation accuracy of ship speed and length can be achieved for theoretically calculated wave data and tow tank experimental data. Relative errors are generally less than two percent for ship speed and slightly higher for ship length.

In review, *Ocean Engineering*, 1991

LaGrangian Velocity Profiles in the Wake of a High Speed Vessel

by
L. Meadows, G. Meadows, A. Troesch, S. Cohen, K.P. Beier, G. Root, O.M. Griffin, and T.F. Swean Jr.

A video imaging technique is employed in a towing basin to obtain high resolution surface LaGrangian velocity observations in the centerline wake region of a high speed, twin screw surface vessel. Approximately 30,000 surface velocity realizations within the wake region extending from the stern to approximately six model ship lengths aft are used for comparison with both recent full-scale and numerical model results. Analysis of this data set reveals spacial decay rates in the mean and fluctuating velocity components which serve to identify relevant scales of motion and define candidate mechanisms for the persistence of these wakes in remotely sensed ocean surface data.

Ph.D. Thesis, University of Michigan, 1991

On the Estimation of a Moving Ship's Velocity and Hull Geometry Information from its Wave Spectra

by
Z. Wu

The wake generated by a moving ship may extend for many tens of kilometers in the open ocean, and can be remotely sensed. Through indirect methods, the detection of a ship and its related characteristics, is generally obtained by measuring the ship generated waves or their spectra. From the viewpoint of remote sensing, interesting problems exist related to the detection of a ship's presence and the acquisition of dynamic and static information about it. This problem can be divided into two basic aspects. First, how to obtain a moving ship's wave spectra from remotely sensed images, and second, how to extract the desired ship information from the imaged wave spectra. This thesis concentrates on the latter aspect, in particular, how to estimate a moving ship's direction, speed, length and hull shape from its wave spectra.

The extraction of ship information is based on the relations of the ship's wave spectra, wave amplitude function and hull geometry. In this thesis, an analytic representation of wave elevation is introduced with the use of the Hilbert transform, and the derivation is given for the calculation of the wave amplitude function from the Fourier spectrum of one and two dimensional complex-valued wave elevations. Methods and formulas are given for estimating a ship's speed and direction from the spectrum of a two-dimensional wave patch, a single wave cut or two wave cuts. A theoretical model of wave amplitude function is developed, and three methods are designed for the estimation of a ship's length from the wave amplitude function. Under the assumption of thin-ship theory, an inversion technique to predict the geometry of a ship's hull from the wave amplitude function or its magnitude is developed through the application of a spectral method and the constrained maximum likelihood method. Examples comparing theoretically calculated data and tow tank experimental data are given to demonstrate the methods developed and estimate performance.

Submitted to *Physics of Fluids A*, 1991

Head-on Collision of a Large Vortex Ring with a Free Surface

by
M. Song, L.P. Bernal, and G. Tryggvason

The generation of free surface waves due to the interaction between a free surface and a vortex ring is studied experimentally and numerically. A well characterized vortex ring normal to the free surface is introduced. The interaction process is investigated by looking at the free surface evolution with the aid of a shadowgraph image, by measurement of the free surface elevation, and by visualizing the vortex ring with hydrogen bubbles. Three different free surface patterns are observed, depending on the strength of the vortex ring; a single circular depression of the free surface for weak vortex rings and very early times of strong vortex ring interaction, axisymmetric radially propagating waves in the early stage of strong vortex ring interaction, and fully three-dimensional waves that depend on the local structure of the vortex core. Numerical simulations are used to address the observed axisymmetric phenomena.

Submitted to Aerospace Sciences Meeting, AIAA Paper No. 92-0009

Resolution Characteristics of Holographic Particle Image Velocimetry

by
J. Scherer and L.P. Bernal

Holographic Particle Image Velocimetry (HPIV) uses holographic recording of a flow seeded with small particles to measure three-dimensional velocity fields. The use of high repetition rate lasers further extends the technique to measurement of three-dimensional velocity fields as a function of time. The spatial resolution characteristics of a typical system are analyzed. Basic requirements of the holographic recording and reconstruction systems are derived. HPIV velocity measurements of a vortex ring flow using a two axis holographic recording system are reported to illustrate the potential of the technique. Based on these results a spatial resolution of 2 mm and spatial dynamic range of 100 are expected for a typical HPIV system. These are comparable to typical resolution characteristics of LDV and conventional PIV systems.

Ph.D. Thesis, University of Michigan, 1991

The Interaction of a Vortex Ring with a Contaminated Free Surface

by
N.J. Kachman

The interaction between a vortex ring and a contaminated free surface is investigated experimentally using flow visualization and Particle Image Velocimetry (PIV). The surface tension was measured directly on the contaminated surfaces. A nondimensional contamination number, W, is introduced to characterize the effect of surface contamination. In the inclined incidence case, for low contamination numbers, $W < 5$ the flow evolution was similar to that of the clean free surface. At $W = 9$, the flow evolution changed compared to the clean surface. In the bottom vortex core interaction, the vortex no longer reconnected to the surface. It is shown that this was due to the generation of secondary vorticity by the surface-active agents at the surface. For all levels of contamination investigated, the top core interaction remained the same as for the clean case, with the vortex core reconnecting to the surface. For the normal incidence case, behavior similar to the inclined incidence case was observed. For W £ 5, the evolution of the flow near the surface was the same. For $10 < W < 20$, the secondary vorticity arrested the primary vortex core outward expansion, and forced it away from the surface. In addition both clean and contaminated regions existed on the surface. For $W > 20$, the underwater flow was the same as $10 < W < 20$ but the surface features were greatly reduced and no cleaned regions on the surface were produced. PIV measurements are described for the primary and secondary vorticity. A bias velocity was incorporated into the PIV to remove velocity directional ambiguity. The secondary vorticity rolled up into a discrete vortex with a circulation that increased for increasing W. The secondary vortex circulation was approximately 25% of the primary vortex. A rapid drop off in circulation was noted to occur when the ring reached the surface. The flow evolution and the amount of the secondary circulation measured was similar to that produced in a solid wall interaction. PIV measurements of the surface showed that the surface velocity decreased for increasing contamination number, but for the highest levels measured ($W > 360$), the surface was never immobilized.

Proceedings Symposium on Dynamics of Bubbles and Vortices Near a Free Surface
AMD **119** (Ed. Sahin and Tryggvason), ASME 1991

Vortex Ring Interaction with a Contaminated Surface at Inclined Incidence

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

The effect of surface contamination on the interaction of a vortex ring with the water surface at inclined incidence is discussed. A nondimensional contamination number is introduced to characterize the effect of surface contamination. At low contamination number the interaction process is very similar topologically to the interaction with a clean surface. At larger values of the contamination number the topology of the resulting vortical flow changes. The different behavior is the result of vorticity generation at the surface by the surface-active material. It is found that vortex reconnection always occurs as the upper part of the vortex ring core interacts with the free surface. In contrast, for contamination numbers higher than 5, vortex reconnection of the lower part of the vortex core does not occur. The results are also compared with the interaction of a vortex ring with a solid surface.

Bull. Am. Phys. Soc. **35**:10:2238, 1991

Holographic Particle Image Velocimetry

by
L.P. Bernal and J. Scherer

Holographic recording of small particles has long been recognized as a technique to measure fully three-dimensional velocity fields. Here we report the results of several experiments aimed at extending the technique to four-dimensional space-time velocity field measurement. In the present approach a Copper Vapor Laser is used to record a sequence of doubly-exposed holograms of the seeded flow. Thus each hologram records the displacement of the particles at an instant in time. The holograms are then analyzed using digital image processing techniques to determine this displacement and thus the velocity field. Experiments have been conducted to determine fundamental limitations of the technique with regard to spatial and temporal resolution in typical flow configurations.

Bull. Am. Phys. Soc. **35**:10:2267, 1991

Interaction of a Vortex Ring with a Contaminated Free Surface

by
N.J. Kachman and L.P. 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.

Ship Technology Research 38:3-5, 1991

Nonlinear Computations for Wave Drag

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

The steady potential flow around an elongated spheroid under a free water surface is computed by various linear and nonlinear methods. Results are in good agreement and can serve as a validation test for future methods for computing wave resistance.

Ph.D. Thesis, University of Michigan, 1991

Computations of Nonlinear Gravity Waves by a Desingularized Boundary Integral Method

by
Y. Cao

A desingularized boundary integral equation method combined with an Eulerian-Lagrangian time-stepping technique is developed for nonlinear gravity wave problems. The desingularization distance between the boundary and the sources is related to the local mesh size to ensure convergence. Tests for some simple problems show that desingularization significantly reduces the computer time required to compute the influence matrix of the resulting algebraic system. The algebraic system is still adequately well-conditioned to allow fast iterative solutions. Accurate solutions can be obtained for a large range of desingularization distances on the order of the mesh size.

Several nonlinear water wave problems are then investigated. The first problem considers upstream runaway solitons due to a disturbance moving near critical speed in two-dimensional shallow water. Results from the desingularized method with the fully nonlinear free surface boundary condition agree well to those using the fKdV model for weak disturbances. The fully nonlinear model predicts larger solitons than the fKdV model for strong disturbances and also predicts the breaking of waves for some stronger disturbances. Next, the problem of three-dimensional waves due to a submerged moving spheroid show good comparison to those from other algorithms. Finally, the generation of inner-angle wavepackets in the wake of a ship is investigated. The three most probable causes of the wavepackets are examined: interference of the wave systems by the bow and stern; free-surface nonlinear effects; and wake unsteadiness due to translation and oscillation of the disturbance. The wake is studied with nonlinear calculations using the desingularized method and with linear calculations using a time-domain Green function and the stationary phase method. It is shown that nonlinear effects are not essential to the generation and persistence of inner-angle wavepackets; the phenomenon can be explained by unsteady linear theory.

Bull. Am. Phys. Soc. **35**:10:2290, 1991

Steep Free-Surface Standing Waves

by
W.W. Schultz and J.-M. Vanden-Broeck

A time-marching spectral boundary integral method is combined with a Newton iteration procedure to seek spatially and temporally periodic solutions of standing waves. At lower amplitudes, these solutions confirm the existing perturbation results. However, as in traveling waves, we find that the limiting form is not the highest wave. We discuss the limiting free-surface accelerations and show results with surface tension.

SNAME *Transactions* **98**:319-363, 1990

Hydrodynamics of Remotely Sensed Surface Ship Wakes

by
A. Reed, R. Beck, O. Griffin and R. 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 theses 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.

International Journal for Numerical Methods in Fluids **11**, 1990

Three-Dimensional Desingularized Boundary Integral Methods for Potential Problems

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

The concept of desingularization in three-dimensional boundary integral computations is re-examined. The boundary integral equation is desingularized by moving the singular points away from the boundary and outside the problem domain. We show that the desingularization gives better solutions to several problems. As a result of desingularization, the surface integrals can be evaluated by simpler techniques, speeding up the computation. The effects of the desingularization distance on the solution and the condition of the resulting system of algebraic equations are studied for both direct and indirect versions of the boundary integral method. Computations show that a broad range of desingularization distances gives accurate solutions with significant savings in the computation time. The desingularization distance must be carefully linked to the mesh size to avoid problems with uniqueness and ill-conditioning. As an example, the desingularized indirect approach is tested on unsteady nonlinear three-dimensional gravity waves generated by a moving submerged disturbance; minimal computational difficulties are encountered at the truncated boundary.

Journal of Fluid Mechanics **229**:135-158, 1991

Evolution of Weakly Nonlinear Water Waves in the Presence of Viscosity and Surfactant

by
S.W. Joo, A.F. Messiter and W.W. Schultz

A formal derivation of evolution equations is given for viscous gravity waves and viscous capillary-gravity waves with surfactants in water of infinite depth. Multiple scales are used to describe the slow modulation of a wave packet, and matched asymptotic expansions are introduced to represent the viscous boundary layer at the free surface. The resulting dissipative nonlinear Schrödinger equations show that the largest terms in the damping coefficients are unaltered from previous linear results up to third order in the amplitude expansions. The modulational instability of infinite wavetrains of small but finite amplitude is studies numerically. The results show the effect of viscosity and surfactants on the Benjamin-Feir instability and subsequent nonlinear evolution. In an inviscid limit for capillary-gravity waves, a small-amplitude recurrence is observed that is not directly related to the Benjamin-Feir instability.

Journal of Fluid Mechanics **218**:547-572, 1990

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 modeled 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 *Physics of Fluids A*, PSH Tech. Rpt. 90-1, 1990

Collision of a Vortex Pair with a Contaminated Free Surface

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

Collision of a viscous, two-dimensional vortex pair with a contaminated, free 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 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 vortices colliding with a no-slip boundary. For one case, the numerical results are 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.

Bull. Am. Phys. Soc. **35**:10:2269, 1991

A Method for Computing Vortex Sheet Separation

by
R. Krasny

A vortex blob method has been developed for computing vortex sheet separation and roll-up past a solid boundary with sharp edges. Flow tangency on the boundary is enforced by solving an integral equation for the bound vortex sheet strength. A version of the Kutta condition has been implemented to determine the circulation shedding rate at an edge. Time-dependent computations are in good agreement with Pullin's results for self-similar vortex sheet roll-up (*J. Fluid Mech.* 1978, **88**:401). Several applications will be presented including the instability of a jet being expelled from a narrow slot, and the roll-up of the wake behind an oscillating flat plate.

Bull. Am. Phys. Soc. **35**:10:2247, 1991

Free Surface Waves due to the "Opening-Up" of a Vortex Ring

by
M. Song and G. Tryggvason

Experimental studies of the free surface signature of underwater vortical flows suggest that the "opening-up" of vortex filaments is a major cause for short wave generation. To investigate this phenomena numerical simulations of the collision of a vortex ring of an oblique angle of incident to the free surface have been done. A nearly inviscid flow is assumed, and the vortex ring modeled by a collection of vortons. This introduces a small amount of dissipation and allows the ring to reconnect with its image at the free surface. In most experimental studies the free surface deformation is very small, and here the free surface motion is assumed to be linear. The governing equation for the free surface deformation is solved in an efficient way by a spectral method. Following the first reconnection with the surface, the rings sometimes reconnect again, forming two half-rings that propagate parallel to the surface. The computations are compared to recent experimental investigations.

Ph.D. Thesis, University of Michigan, 1991

Vortex Ring Interaction with a Free Surface

by
M. Song

The interaction between a vortex ring and a free surface is studied experimentally and numerically. Three separate, but relevant subjects are discussed. First, a head-on collision of a large vortex ring with the free surface is investigated experimentally. Three different free surface patterns, that depend on the strength of the vortex ring and the elapsed time, are observed: a single circular depression of the free surface for weak vortex rings, axisymmetric radially propagating waves in the early stage of a strong vortex ring interaction, and fully three-dimensional waves in the later stage for both weak and strong rings. The early stage of the interaction is well predicted by an inviscid, axisymmetric numerical model. Secondly, a generation of surface waves due to a vortex reconnection at the free surface is numerically investigated. Guided by experimental observations, Froude number is assumed to be small and hence free surface motion is assumed to be linear. The ring is modeled as a collection of vortons and the free surface evolution is solved by using a spectral method. The proposed model successfully captures the reconnection and the wave generation, and the results are comparable to available experimental observations. The short waves are generated as a depressed free surface is released when the vortex line changes its topology. Thirdly, effects of a surface contaminant on the oblique collision of a vortex ring with a flat surface are studied numerically. The Froude number is assumed to be so small that that the surface remains flat. The full Navier-Stokes equations and a conservation equation for the contaminant are solved by a finite difference method. For a clean surface, simulations at two Reynolds numbers (200 and 400) are done. For the contaminated surface, simulations with varying contamination parameter at the lower Reynolds number are performed. The results show a considerable modification of the underwater vortical flows due to the surface vorticity generated by the contaminant gradient. The distribution of the contaminant during the interaction depends on the strength of the contamination. Results are also compared to a collision with a no-slip surface.

Proceedings Symposium on Dynamics of Bubbles and Vortices Near a Free Surface
AMD **119**:31-37 (Ed. Sahin and Tryggvason), ASME 1991

Collision of Viscous Vortices with a Free Surface and Density Interfaces

by
T. Faical, M. Song, S.O. Unverdi, and G.Tryggvason

Full numerical simulations of the collision of a viscous vortex ring with a fully deformable density interface are presented. Experiments and inviscid numerical simulations of a vortex ring or a vortex pair colliding with a free surface or a density interface show that the vortices penetrate partly through the initial interface for large Froude numbers, but are stopped when the Froude number is small. For small vortices, viscous effects can modify the motion, both by reduction of the strength of the vortex ring itself and by diffusion of baroclinically generated vorticity. For small Froude number the ring is deflected by the interface and the vortex ring reconnects with vorticity created baroclinically at the interface.

Submitted to *Lectures in Applied Mathematics*, 1991

Interaction of Vortices with a Free Surface and Density Interfaces

by
G. Tryggvason, S.O. Unverdi, M. Song, and 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.

Proceedings Symposium on Dynamics of Bubbles and Vortices Near a Free Surface
AMD **119** (Ed. Sahin and Tryggvason), ASME 1991

Observations of Turbulence Near the Free Surface in the Wake of a Model Ship

by
D.T. Walker and V.G. Johnston

Visualization of the flow in the boundary layer and wake of a model ship shows evidence of inboard-rotating stern vortices; however, the vortical structure persists only a short distance aft of the model before it is effectively diffused by turbulent mixing. A thin, rapidly growing, turbulent surface layer, similar to that seen in free-surface turbulent jets, is also identified. Observations of free-surface disturbances in the wake reveal that, near the ship, there is a region of unsteady, irregular surface disturbances which correspond to the subsurface region of turbulent flow. At the edges of this region, the small-scale disturbances created by the turbulence coalesce into relatively organized, but unsteady, waves. These waves propagate outward, away from the turbulent region, and into the irrotational free stream. Further aft, the disturbances caused by the turbulence become less pronounced; this is due to the general growth in the turbulent length scales and decrease in turbulent velocity scales with distance aft. At low speed, the addition of a rotating propeller causes the free surface in the center portion of the wake to exhibit markedly fewer disturbances and the swirl introduced by the propeller results in larger disturbances on one side of the wake. At higher speed, the effects of the propeller are much less pronounced on the free-surface.

Bull. Am. Phys. Soc. **35**:10:2313, 1991

Measurements of Jet Turbulence Beneath a Free Surface

by
D. Anthony and W. Willmarth

Simultaneous three-component measurements of the velocity field of a submerged turbulent jet issuing two diameters beneath and parallel to a clean free surface were made using a fiber optic Laser Doppler Velocimeter (LDV). The measurements reveal the existence of a strong outward current just beneath the free surface that is much wider than the turbulent jet flow beneath it. Within this shallow layer, turbulent velocity fluctuations normal to the free surface are significantly diminished while those parallel to the surface are enhanced. A flow visualization experiment reveals that the surface current contains fluid structures ejected from the jet, and that these structures propagate laterally to considerable distance when the water surface is free of surface-active agents.

Bull. Am. Phys. Soc. **35**:10:2322, 1991

Flow Field of a Submerged Turbulent Jet Interacting with a Clean Free Surface

by
W. Willmarth, D. Anthony and A. Hirsa

A 0.635 cm diameter turbulent jet discharging at a speed of 200 cm/sec in water parallel to and 2 diameters beneath a clean free surface is studied using laser induced fluorescence (LIF) at Re = 13,000 and Froude number = $U_{exit}(gh)^{-1/2}$ = 5.66. Three component turbulence measurements show that the jet spreads rapidly at a half angle = 35° with mean velocity = 10 cm/sec in a thin layer near the surface. LIF video images (to be shown) reveal coherent vortical structures containing dyed jet fluid propagating outward in this thin layer. We suggest that near the surface vertical mixing is inhibited and horizontal motion of vorticity parallel to the surface is enhanced owing to image vorticity above the free surface. The rapid spreading near the surface is suppressed when oleyl alcohol (a surfactant with 9 dynes/cm surface pressure) is placed on the surface. The suppression of horizontal spreading is attributed to secondary vorticity generated when coherent vortical structures approach and interact with the surfactant covered free surface.