1989 End-of-Fiscal Year Report

Robert F. Beck, Project Director

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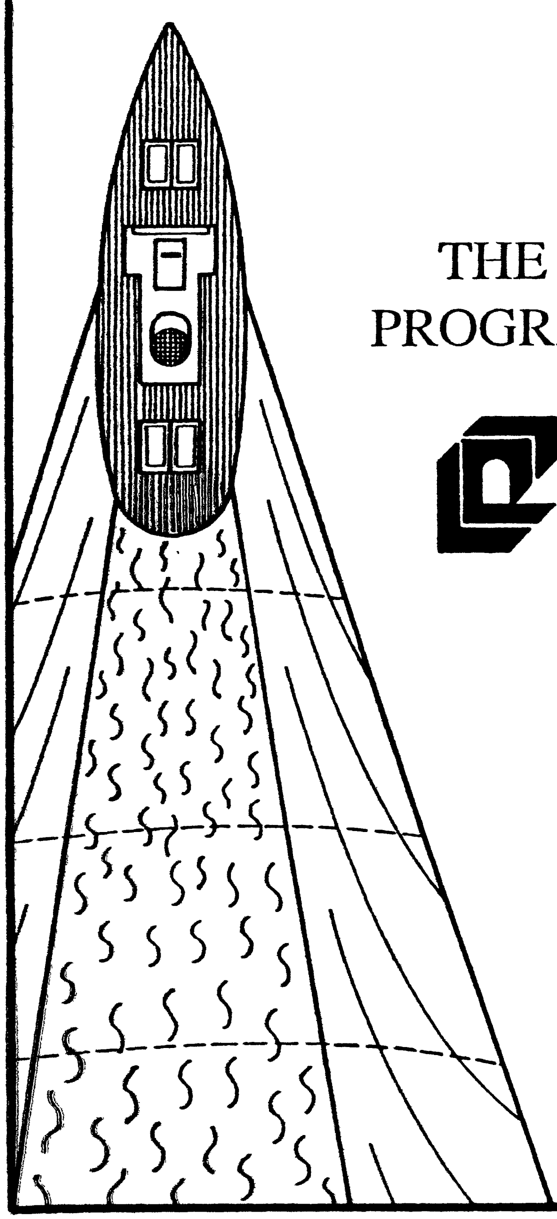

THE UNIVERSITY OF MICHIGAN
PROGRAM IN SHIP HYDRODYNAMICS

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PROGRAM IN SHIP HYDRODYNAMICS
Executive Summary Report

by
Robert F. Beck, Project Director

The third year of the Program in Ship Hydrodynamics has seen a marked increase in the amount of scientific research results and the delivery of the two major scientific instruments. Both the Hydrodynamic Monitoring Facility (HMF) and the Laser Doppler Anemometer (LDA) have been delivered and are presently undergoing calibration testing. 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.

The Space Physics Research Laboratory has finished their work on the development of the HMF. Profs. Perlin and Walker, two new faculty members with expertise in optics and fluid flow measurements, have been hired by the College of Engineering. They both started working this summer on the HMF and have made substantial contributions. The HMF is presently undergoing calibration and initial testing. Table I on page 5 lists the demonstrated capabilities of the HMF as obtained during the August trials, as well as the desired capabilities. As can be seen, the slope measuring system is functioning well. Its main problem is the unacceptably large standard deviations in the angle measurements due to insufficient light intensity to the Mepsicron detector. In October, modifications to the optical and mechanical systems have resulted in a factor of ten increase in optical efficiency. The improved system is currently being reinstalled in the towing tank. The thermal imaging system that measures the surface velocity and height by tracking warm spots created by a CO_2 laser is having difficulties with warm spot size and persistence of the spots. Investigations are presently underway into the physics of laser induced warm spots to determine the optimum balance between on-time and laser power. It appears that surface tension induced flows are the cause of the problem.

The first set of experiments to use the HMF will be part of the ERIM cooperative research program. ERIM has recently modified their calibrated radar scatterometers to measure doppler shift as well as the magnitude of the backscattered signal. The HMF along with the ERIM radars will be used to investigate wave/current interactions and radar backscatter processes using bubble-generated currents in the towing tank. The primary purpose of the experiments is to gain insight into the interactions between short waves and currents. However, they may also yield information on the role of air bubbles in maintaining the dark centerline wake which is a persistent and frequently dominant feature in SAR images of ship wakes.

The LDA was delivered by TSI in the beginning of April. The system is unique in the fact that it uses fiber optics, wet mirrors and has a 1200mm stand-off distance of the measurement volume. Initial assembly and testing has been done in a small tank. The system is now ready to move into the small towing tank in the Gas Dynamics Laboratory. The first set of experiments using the LDA will involve measurements of a turbulent jet both deeply submerged and near a free surface. These experiments will yield a complete set of baseline data. The system will then be used to further investigate the interactions of vorticity and the free surface using vortex rings and trailing vortices from a delta wing. Finally, by the end of FY90 the LDA should be installed in the large towing tank at the Ship Hydrodynamics Laboratory.

Much work this past year has centered on the critical problem area of interactions of vorticity with the free surface. These interactions generate short waves on the free surface that are thought to be a major source of radar backscatter. Both numerical and experimental investigations have been carried out. Prof. Bernal finished his investigation into the interaction of a round jet with the free surface. He has determined the primary scaling parameters of the flow and found that surface waves are produced by the large scale structures in the jet as they approach the free surface. The results show significant differences between a jet flowing beneath a wall and the free surface jet. Prof. Bernal also examined the break-up of a vortex ring as it impinges on the free surface. The vortex ring was made by a mechanical puffer device that could be oriented at an arbitrary angle to the free surface. It was found that the break-up is strongly influenced by the angle of incidence and the amount of surfactant on the free surface. Surfactants cause generation of secondary vorticity that limit the outward motion of the primary vortex ring core. At inclined angles of incidence the vortex ring breaks and reattaches so that the resulting flow consists of two half vortex rings each having vortex lines beginning and terminating at the free surface propagating away from each other.

Prof. Willmarth has been experimentally investigating the interaction of a pair of vortices with the free surface. The pair is generated either by a delta wing traveling below the free surface or by a specially designed flapper device. Special attention has been paid to the role of surfactants. It has been found 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 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 is not the same as) the path a vortex pair would take if the surface boundary were solid and allowed no slip. If the proper amount of surfactant is present, a pair of Reynolds ridges are formed on either side of the plane of symmetry of the surface wake produced by a vortex pair. A Reynolds ridge occurs at the interface where there is a rapid change in surfactant concentration. It normally involves a short wavelength fluctuation in surface elevation and may be involved in the narrow V wake seen in SAR images.

To compliment the experimental investigations into vortex/free surface interactions, Prof Tryggvason has been using numerical techniques to simulate the interactions. Comparisons between the numerical results and the experiments for several simple flows have been good. In particular, interactions involving a vortex pair or a vortex ring interacting with a free surface have been investigated using an inviscid model. Recently, a viscous flow code has been written to examine the effects of viscosity and surfactants on the interaction process. It is felt that full viscous simulations, although limited to low Reynolds numbers, may lead to a better understanding of the reconnection process that takes place when a vortex ring encounters a free surface.

Under the project entitled Nonlinear Ship Waves, Professors Beck, Krasny, Messiter, Olson, and Schultz have worked on a variety of different subprojects, the goals of which are to develop both numerical and analytical techniques to solve nonlinear wave problems. One of the major projects investigated the damping of short wavelength waves by applying a formal multiple scale procedure to capillary-gravity waves with small viscosity. Spectrally accurate computations of the resulting nonlinear Schrödinger-equation showed the effects of viscosity and capillary resonance.

A second major project developed a desingularized method to solve three-dimensional nonlinear free surface problems. The algorithm has been shown to be much more efficient and accurate than conventional singular techniques for simple potential flow problems. For a time marching water wave problem, the method has given very good preliminary results for nonlinear waves when compared to linearized results obtained using the time dependent free surface Green function. The desingularized method requires the solution of very large matrices. An iterative solution method has been developed which has shown improvements over the conjugate gradient method used previously.

Much of the research of the PSH involves large amounts of data which must analyzed. To assist researchers in this task, Prof. Beier has been developing advanced computer graphics methods. The methods will allow the researcher to visualize the data in a variety of ways including iso-surfaces, translucent surfaces, vector fields, and animation. Through a Department of Defense Research Instrumentation Grant and matching funds from the University, a Stellar GS1000 was purchased as the centerpiece of the newly created "Visualization Facility for Computational Fluid Dynamics" in the Department of Naval Architecture and Marine Engineering. The Stellar GS1000 provides extremely high computational power through its vector and parallel processing capabilities and fast three-dimensional color graphics. The visualization tools developed under Prof. Beier's project have already been used on several PSH projects.

There continues to be strong interaction between the Navy laboratories, the PSH and other research institutions. Professor Jerry Milgram of M.I.T. spent part of his sabbatical leave at The University of Michigan. He worked with PSH members and conducted experiments in the towing tank on the dissipation of short waves by turbulence. The Ship Wake Consortium had their annual meeting on the 11th and 12th of October, 1989, at The University of Michigan. The agenda for the Workshop is in Appendix III. As can be seen from the titles of the talks, there is a great deal of interrelationship between the various research topics that are being studied. The Consortium has played a very valuable role in bringing together the researchers who are working on the ship wake problem.

Prof. Guy Meadows and James Lyden have been involved in the Navy's full scale ship wake experiments. It is imperative that the hydrodynamic processes studied at model scale in the towing tank be correlated with full scale observations. The full scale data that are being collected will be invaluable in this regard. In fact, there will be three scales of data available to examine scaling questions. Very small scale data is being collected in the small tanks in the Gas Dynamics Laboratory. Intermediate scale data will be obtained from the Ship Hydrodynamics Laboratory towing tank and full scale data from the Navy's trials.

3.1.1 Hydrodynamic Monitoring Facility

Principal Investigator: G.A. Meadows

RESEARCH SUMMARY

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 with benchmark hydrodynamic studies and to eventually correlate these measurements with simultaneous radar scatterometer measurements. This data set will be unique. It will allow spatial and/or temporal correlations of the hydrodynamic surface, the radar signature and the infrared signature.

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 using refracted laser light. The surface height and surface velocities will be measured by tracking thermal images of "warm spots" which will be created on the free surface by a CO_2 laser pulse. The warm spots will be used to obtain velocity profiles, vorticity, and/or divergence on the free surface.

Significant Results in the Past Year: The Space Physics Research Laboratory has finished their work on the development of the HMF. Profs. Perlin and Walker, two new faculty members with expertise in optics and fluid flow measurements, have been hired by the College of Engineering. They both started working this summer on the HMF and have made substantial contributions. The HMF was in the towing tank during August and has recently been reinstalled. The purpose of these tests is operational checking and calibration of the three components of the HMF system.

During the August tests of the HMF in the tow tank, a static calibration of the instrument was performed. This procedure involves both manual and automated measurements of critical parameters to specify the viewing geometries of the three imaging systems. This static calibration defines the relative position of the quiescent surface with respect to each imagers' viewing perspective. Once the necessary measurements have been completed, a computer algorithm calculates the viewing geometry and solves (in a hindcast mode) for the position of the emanating laser beams. The criterion for a successful calibration is that these calculated closure positions be within 2mm of the measured positions in three-dimensional space. This numerical calculation is required prior to each series of experiments and is now automated.

The current capabilities of the HMF are summarized in the following table. The first column lists the originally proposed targets, as well as the minimum acceptable capabilities. These minimum acceptable capabilities were determined by an ad-hoc committee of both internal and external reviewers. This committee concluded that meeting these minimum acceptable requirements would allow substantial scientific advancements using the HMF. Columns two and three show the demonstrated capabilities of the HMF at the end of the August trials. Two major problems remain; one is related to laser power and the other to thermal spot persistence and size.

Although the slope measurement system is functional, measurements of a quiescent water surface (approximately zero slope) exhibit standard deviations of about 2.5 degrees. A significant contribution to this uncertainty results from low power in the laser beam as it exits the optical system. A thorough examination of this system has revealed several structural and optical modifications which could be made to improve the optical efficiency. During October, the system was structurally reinforced to minimize alignment problems, optical mounts have been redesigned for increased positioning flexibility, and minor optical design changes have been made. The result of these changes has been a factor of ten increase in optical efficiency. Bench-top experiments have indicated that this increase in efficiency may reduce the uncertainty in the measured slope to acceptable levels (≈.5°).

This improved system is currently being reinstalled in the tow tank where the effects of these changes can be fully evaluated. Satisfactory completion of this evaluation will allow measurements to be made with the instrument stationary. It will also enable testing of the measurement system while moving with the tow-tank carriage. This testing will determine the degree to which vibration and hydrodynamic loading of the instrument degrades performance.

With respect to the thermal imaging system, short persistence and large size of the tagged warm spots continue to be problems. Investigations are underway into the physics of laser induced warm spots to determine the optimum balance between on-time and laser power. Preliminary results show that heating the water surface causes a local surface depression which convects heat away from the spot center. This phenomenon results in warm spots of about 1cm diameter being created by a ~2mm diameter laser beam. Bench-top experiments have shown that the spot size is independent of laser on-time and laser power (in the range of times of interest). The spot persistence is approximately linear in laser on-time and laser power. For a given laser power this restricts the number of warm spots which may be created and tracked simultaneously.

Several items remain to be completed for the CO_2 system, including finishing the software to track the spots over time, automating the spot-location routine to step frame to frame, writing the code to compute the wave height, and linking these programs into an automated package. In addition, the CO_2 system has not been tested with a moving carriage and thus vibration problems may exist.

HYDRODYNAMIC MONITORING FACILITY CAPABILITIES

	Proposed Capabilities	Demonstrated Capabilities As of August, 1989	
	(acceptable)	slope (visible)	height, velocity (I.R. system)
Scan:	100x100 (10x10)	81x81	10x3
Time:	0.1s	0.1s	1.0s
Scan Area:	1x1m (.4x.4m)	23cm diam	25x18cm (AxB)
Height Resolution	1mm (2mm)	-----	~4mm (~B/50)
Maximum Height:	15cm	-----	??
Slope Resolution:	0.2	2.5°	-----
Maximum Slope:	35	~21°	-----
Velocity Resolution:	1mm/s	-----	5.4cm/s $B/100x30sec^{-1}$
Maximum Velocity	100cm/s	-----	300cm/s
Spot Size:	1mm (2mm)	1.5mm	10mm
Spot to Spot Centers:	2 to 10mm (5 to 10mm)	2mm	10mm

Plans for Next Year's Research: A set of experiments are being formulated to utilize the functioning elements of the HMF. These experiments integrate both the capabilities of the HMF and the theoretical and experimental work being conducted under the PSH. The general topics of these experiments will be: wave/current interactions and buoyancy driven flows, ring vortex-free surface interaction, water wave propagation transverse to counter-rotating vortices, and measurement of the sea-surface slope spectrum in the wake of a ship model.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers Published in Refereed Journals

   None

2. Technical Reports

   None

3. Presentations

   Meadows, G.A., "The Hydrodynamic Monitoring Facility", Ship Wake Consortium, Ann Arbor, MI, October 11-12, 1989.

LIST OF HONORS/AWARDS

None

LIST OF PARTICIPANTS

G.A. Meadows, Associate Professor
M. Perlin, Assistant Professor
D. Walker, Assistant Professor
J. Dombrowski, Research Engineer
B. Kennedy, Sr. Research Engineer
T. Litow, Sr. Research Associate
M. Song, Ph.D. Candidate
E. Wright, Research Associate
Z. Wu, Ph.D. Candidate

3.1.2 ERIM Cooperative Research Program

Principal Investigators: D.R. Lyzenga, J.D. Lyden and R.A. Shuchman

RESEARCH SUMMARY

Description of Scientific Research Goals: The long-term research goal of the Environmental Research Institute of Michigan's (ERIM's) involvement in the PSH is to gain a detailed understanding of the processes which govern the variations in radar backscatter associated with various ship wake phenomena including the Kelvin wake, the turbulent or vortex wake, and the "narrow-V" wake, all of which have been observed in synthetic aperture radar (SAR) images. This goal is being pursued through a set of multi-frequency and multi-polarization radar measurements made simultaneously with observations of the surface elevation, slope, and currents using the University's Hydrodynamic Monitoring Facility (HMF). We are planning to use the understanding gained from these measurements to explain the ship wake signatures observed in SAR images, and to that end will also carry out a set of image simulations to compare with actual SAR images.

Significant Results in the Past Year: During the second year of the PSH, preliminary measurements of the C-band (5 GHz) backscatter were made in the towing tank to investigate the effects of surface films and to gain experience operating in the towing tank environment. Subsequently, we have modified the X-bank (10 GHz) and C-band (5 GHz) radars to measure the Doppler shift as well as the magnitude of the backscattered signal. We have also formulated a set of experiments to investigate the wave-current interaction and radar backscatter processes using bubble-generated currents in the towing tank. Since these experiments require simultaneous measurements of the surface conditions using the University's HMF, we have intentionally delayed the experiments and conserved our resources until the HMF became operational. We now plan to set up and begin measurements during the first week of November, 1989.

Plans for Next Year's Research: The first experiment we intend to carry out using the newly developed HMF and Doppler radar facilities is an investigation of the interaction of short surface waves with an upwelling current generated by air bubbles injected near the bottom of the towing tank. This is not only a convenient means of generating currents for such interaction studies, but may also yield insight into the role of bubbles in maintaining the dark centerline wake which is a persistent and frequently the dominant feature in synthetic aperture radar images of ship wakes. In conjunction with the measurements, we will also carry out a series of calculations using a combined wave-current interaction and radar backscatter model which has recently been developed at ERIM.

In addition to the wave-current interaction experiment, we anticipate making radar and HMF measurements of towed model ship wakes and long wave/short wave interactions. We also anticipate incorporating the results of our laboratory measurements into a SAR image simulation model and comparing the results with images collected during the ONR surface ship wake detection program which is studying these phenomena at full scale.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers in Referred Journals

   None

2. Technical Memoranda

   Lyzenga, D., "Effects of bubbles on maintaining the 'turbulent wake'", ERIM Tech. Memo. RR-89-205, 18 July 1989.

Lyzenga, D., "A simple wave-current interaction experiment", ERIM Tech. Memo RR-89-243, 17 August 1989.

3. Presentations

None

LIST OF PARTICIPANTS

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

RESEARCH SUMMARY

Description of Scientific Research 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 far downstream. It should then be possible to identify the flow processes responsible for the wake signatures of surface ships. The experimental facilities and equipment used for this research are being developed and shared with Professor Bernal in his parallel investigations of the "Vortical Structure of Ship Wakes" (3.2.6) under this URI Research effort.

The present investigation of the flow beneath the surface is actively proceeding in collaboration with Gretar Tryggvason, who is developing numerical methods for calculations of the interaction of vorticity with the free surface. We are also working in close cooperation with Professor Luis Bernal and his students who are doing similar experiments in the three-dimensional case. We plan to correlate our results with the results of measurements of the surface flow field in the wake using the Hydrodynamic Monitoring Facility equipment developed by G. Meadows in section 3.1.1 of the URI/Ship Hydrodynamics research program.

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:

i) Delta wing and vortex pair wake flows:

Amir Hirsa has designed and constructed an improved version of our computer controlled vortex pair generation system. The new version uses larger flaps with a wide spacing. When the flaps, which are initially vertical, are rotated towards each other until they touch a pair of vortices is generated which then rises to the free surface. The system as it is presently configured is capable of generating laminar and/or turbulent vortex pairs. A consistent series of measurements has been made with this new system. We have been able to obtain trajectory and surface signature data for vortex pairs approximating the same circulation and Reynolds number for vortex pairs found in the wake of an underwater delta wing model that was previously tested. The flow field of the vortex pairs generated by the new system clearly shows the formation of a Kelvin oval of fluid which is transported to the surface with the vortex pair. In addition, we are also able to observe and study 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.

Very encouraging progress has been made in observing and understanding the interaction of vorticity with a free surface when surface active agents are present on the surface. We have found 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 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 is 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 Prof. 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. A Reynolds ridge (see Scott[1]) occurs at the interface where there is a rapid change in surfactant concentration. It normally involves a short wavelength fluctuation in surface elevation and may be involved in the narrow V wake seen in SAR images. 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 vortex pair studies is that when a given amount of surface active agent is present on the surface we find the same large scale, surface wake phenomena and flow structures using a vortex pair as was first reported by Sarpkaya and Henderson in the wake of a delta wing towed beneath the surface. 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. It is possible that the term scar used by Sarpkaya and Henderson to denote a surface feature that they frequently observed may, in fact, be the Reynolds ridge. 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 by surface active agents is the same.

ii) Three component fiber optic laser Doppler anemometer (LDA)

Since the last progress report Bill Willmarth and Douglas Anthony spent three days at TSI (March 1, 2 &3, 1989) and were trained in many aspects of the operation and set-up of the LDA system. At the factory we observed the successful operation of the LDA in a tank of water.

The LDA was delivered in the beginning of April. Initially, the LDA modules were individually operated in air at the U of M and performed as expected and observed at the factory. This proved that the LDA modules were not damaged or their internal adjustments had not changed during shipment. When the entire LDA system was submerged in water, we found that the adjustment of the wet mirrors was incorrect. It is thought that the adjustment was changed by vibration or shock during shipment of packing/unpacking because the intersection/measuring points of the LDA measuring volumes produced by the two modules were very far apart (2 to 3 cm apart). The wet mirrors were then adjusted approximately (using a 40:1 underwater microscope objective supplied by TSI) and measurements in water were possible.

We were not satisfied with the adjustment of the wet mirrors because it was very difficult to observe complete overlap of the three measuring volumes using the microscope objective. An improved method was devised in which a sheet of grey plastic was positioned at the apparent center of the measuring volume and the resulting light pattern was observed with a 60 power stereo microscope. A "blink" test of the observed measuring volume was then devised (one or more beams were periodically interrupted by insertion of an obstacle in the input beam for each fiber). Using this technique the actual intersection or overlap region of each of the beams could more easily be observed. It was found that the wet mirrors were not correctly adjusted and the six

[1] Scott, J.C., "Flow Beneath a Stagnate Film on Water: The Reynolds Ridge", J. of Fluid Mechanics, 1982, Vol. 116, pp. 283-296.

input beams (two blue, two green and two violet) did not correctly overlap at a point where each beam had minimum diameter (the beam waist). At first we thought that the LDA modules were out of adjustment. Further study of the effect of the wet second surface mirrors established the fact that the index of refraction of the beams was different in the substrate (glass) of the second surface wet mirror. Since a change in the index of refraction affects the path length as well as the angle of refraction of a light ray there can be only one position of the measuring volume where the waist diameters are the same and the light beams intersect. We were not at that position. By trial and error, we "walked" the wet mirrors to the approximately correct position. The actual intersection for each position was observed under the microscope and the approximate correction to the tilt angle of each mirror was estimated from the displacement of a beam measured with the microscope and the known distance of the measuring volume from the "wet" mirror.

The final result of the adjustment of the mirrors was an approximately correct adjustment of the measuring volumes which gave very good simultaneous data for each velocity component when a small test jet containing seed particles was placed in the measuring volume.

A method of calibration to determine the magnitude a orientation of each of the three measured velocity components has been devised. The method uses an accurately positioned rotating disk which reflects the incident laser beams allowing the orientation of the three planes of symmetry which bisect each pair of blue, green or violet beam pairs to be determined. Following this, the fringe spacing for each of the three beam pair intersection volumes is determined from the Doppler signals produced in each channel of the LDA system by the rotating disk whose rotation rate and diameter are accurately known.

The traversing system for the first use of the LDA in the small tow tank is complete and the LDA system is presently mounted on this system. The LDA interface, computer and computer controlled LDA traversing system are operational. Software and hardware for on line production and display of histograms for each channel are in operation.

iii) Preliminary measurements with LDA in a jet flow near the free surface:

Following the above successful adjustment and calibration of the LDA, three jet nozzles (1/4, 1/2 and 1 inch diameter) and a settling chamber containing turbulence damping screens and a honeycomb were designed and fabricated. A preliminary series of measurements was then made of all three mean velocity components and of all 9 components of the Reynolds stress for one jet exit mass flow at two different distances downstream of the jet. These measurements were approximately correct and no major faults were found. However, as a result of the experiments that a large number of improvements were necessary, namely: the method of measurement, the data acquisition software, the LDA/Le Croy Memory/IBM-AT interface operation, the method of removing velocity bias, the estimate of required averaging time, the mean data rate and the quality of the jet flow.

These improvements in the LDA system have by now been made or are almost complete. When everything is ready and an entirely satisfactory series of test measurements have been made we will move the jet and LDA system into the larger wave development tank for the investigation of the jet flow field when the jet is positioned at various distances beneath a free surface.

The first measurements to be made with the system are a complete set of (base line) data for the flow in a turbulent jet far beneath the free surface. Following this the jet will be positioned near the surface and the measurements repeated to determine the effect of the interaction of the mean and fluctuating flow field and vorticity with the free surface.

Plans for Next Years Research: The primary aim of next year's research is to establish the operation parameters of the LDA system so that installation of the LDA and measurements in the towing tank can begin with a minimum of delay and error. We plan to have the design drawings and purchasing of components and material for the traverse system to be used in the tow tank completed by December 1989. It is estimated that the construction will be complete by the end of February 1990. When initially installed in the towing tank, it is planned that the LDA be used for measurements of the interaction of large vortex rings with the free surface. This will be a supplement to the flow visualization experiments presently being conducted in the towing tank. It is planned to investigate the general features and the important parts of the interaction of the vortex ring with the free surface that cannot be determined from flow visualization or laser speckle-grams. Also proposed is an attempt to determine the flow field in the plane of symmetry using laser speckle-grams produced with the copper-vapor laser. This part of the work will be performed in cooperation with Prof. Bernal and his students.

We plan to continue the study of the flow and surface motions produced by the wake of a delta wing with and without the presence of surface active agents. The major thrust of this continuation of work on the delta wing wake will be to determine the effect of larger Reynolds and Froude numbers. For part of this work we plan to conduct experiments in the large towing tank. The studies will use flow visualization, possibly laser speckle-grams and near the end of the year we plan to make laser Doppler anemometer (LDA) measurements.

The study of vortex pairs propagating towards and interacting with the surface will be continued to determine the entire two-dimensional velocity field when known amounts of surface active agent are present on the surface. Numerical methods for computations of the vortex pair approaching the free surface of a viscous fluid with or without the presence of surface active agents have been developed by Prof. G. Tryggvason and his students. The computations assume periodic boundary conditions and negligible surface deformation by the vortex pair (i.e. very low Froude number). It is expected that this work will be completed by April 1990.

The final project for FY90 year is the study, flow visualization and measurement of the wake produced by a surface ship model. The actual "hopefully generic" ship model has not been selected at this date. Initially, flow visualization measurements will be made. The primary aim of this part of the program is to ascertain the large scale features and their cause. We plan to make measurements with the LDA held stationary on the side of the tow tank so that the long time, far downstream wake features can be measured.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers Published in Refereed Journals:

W. W. Willmarth, G. Tryggvason, A. Hirsa and D. Yu, "Vortex pair generation and interaction with a free surface", Phys. Fluids A ,1 (2), pp 170-172, Feb. 1989.

L. P. Bernal, A. Hirsa, J. T. Kwon and W. W. Willmarth, "On the interaction of vortex rings and pairs with a free surface for varying amounts of surface active agent", accepted for publication by Phys. Fluids A, Dec. 1989.

2. Technical Reports

none

3. Presentations

W. W. Willmarth and A. Hirsa, "Free surface motion produced by trailing vortices", Paper EH 3, Annual meeting of Fluid Dynamics Division of the American Physical Society, Buffalo New York, Nov. 21, 1988.

A. Hirsa, G. Tryggvason, W. W. Willmarth and D. Yu, "Interaction of a vortex pair with a free surface", Paper EH 4, Annual meeting of Fluid Dynamics Division of the American Physical Society, Buffalo New York, Nov. 21, 1988.

Willmarth, W.W., "LDA Measurements of Turbulence in a Jet Near a Free Surface", Ship Wake Consortium, Ann Arbor, MI, October 11-12, 1989.

LIST OF HONORS/AWARDS

W. W. Willmarth won American Physical Society 1989 Fluid Dynamics prize which is sponsored/supported by ONR.

LIST OF PARTICIPANTS

W.W. Willmarth, Professor and Principal Investigator
L.P. Bernal, Professor
G. Tryggvason, Professor
A. Hirsa, Graduate student and Research Assistant
D. Anthony, Graduate Student on leave from Taylor Model Basin
D. Yu, Graduate student and research assistant working with G. Tryggvason.

3.2.5 Flow Visualization of Turbulent Burst

Principal Investigator: Klaus-Peter Beier

RESEARCH SUMMARY

Description of Scientific Research Goals: The major goal of this project is 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 (such as 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: The arrival of the Stellar Graphics Supercomputer GS1000 had significant impact on the activities connected to this project. The system was installed in January 1989 as the centerpiece of the newly created "Visualization Facility for Computational Fluid Dynamics" at the NAME department. Funding for this facility was provided through a $150,000 grant from the Department of Defense University Research Instrumentation Program (DURIP) and through $81,115 in matching funds from various sources within The University of Michigan. The Stellar GS1000 provides extremely high computational power through its vector and parallel processing capabilities and fast three dimensional color graphics.

A significant amount of time was spent to port the existing visualizations tools from the IRIS workstation to the new hardware and software environment. A redesign of the visualization software was necessary in order to make efficient use of vector and parallel processing. While the creation and the display of a single iso-surface on the IRIS workstation took several minutes, the goal was to reduce the time for the same task to seconds or - if possible - to fractions of a second. This would allow a scientist to scan the data continuously for interesting flow structures in a relative short amount of time. A highly interactive user interface was designed to accomplish this goal. As a major control device, a sliding ruler was implemented which allows one to change the constant property value for an iso-surface continuously. As immediate feedback, the iso-surface displayed will adjust to the new value in either real-time response (for volumes with a small grid size) or in a delayed step-by-step response (for larger grids).

The accomplish the goal for a fast response time, the algorithm for iso-surface creation and display was implemented in several variations in order to study performance characteristics. All the variations (presently seven) are available to the user and the algorithm to be applied can be selected from a pull-down menu. The algorithms differ in the quality of the iso-surface representation and in the internal use of the vector and parallel processing capabilities of the Stellar. It seems that no single algorithm is best suited for all problems. Instead, different characteristics of the data influence the performance results. It is, therefore, appropriate to provide alternative algorithms to the scientist.

As a valuable side product of the work described, all algorithms in the scalar versions were kept and integrated into a portable iso-surface program which uses the graphics subprogram package M-PLOT for graphics output. This program is currently available on Macintosh computers and provides reasonable response time for the study of small or medium size problems.

As a major result of the past year's work, the transition from a wire frame representation of iso-surfaces to a surface-oriented representation has been successfully completed. Most of the complex geometric problems have been solved. The details of the algorithms developed and a proof that the resulting surfaces are continuous will be documented in the PhD thesis of Graduate Student Research Assistant S.H. Han and in related publications.

Presently, work is underway to apply the developed visualization tool to well known flow structures in order to gain a better understanding of the typical appearance of iso-surfaces. Several scientist have already used the developed visualization tool for their work. Professor Tryggvason studied the results of vortex ring simulation using iso-surfaces, Professor Bernitsas used iso-surfaces to visualize a singularity bounding surface from a non-linear dynamics problem, and Graduate Student B. Krol applied iso-surfaces to the study of n-dimensional optimization problems.

Plans for Next Year's Research: Several refinements in the iso-surface algorithm still need to be completed and more program optimization is necessary to improve the response time for the user. A faster computer model, the Stellar GS2000, and a new version of the PHIGS graphics software package is expected to arrive during the coming weeks and will help to accomplish these goals. A more effective link of the iso-surface generator with the Application Visualization Software (AVS) from Stellar need to be created. The AVS will be used for the rendering and shading of the surface representation. A macro language will be developed which allows for the definition of iso-surface generation and visualization sequences for the purpose of video recording. With these necessary improvements and additions, work will start to visualize the flow structures in a turbulent channel flow and their change in time.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers Published in Refereed Journals

   None

2. Technical Reports

   None

3. Presentations

   S.H. Han, "Computer-Aided Visualization of Simulated Turbulent Channel Flow," PhD Dissertation Prospectus, presented at the Department of Naval Architecture and Marine Engineering, The University of Michigan, Ann Arbor, Michigan, January 1989.

   K.-P. Beier, "Visualization in Scientific Computing," Seminar presented at the Naval Research Laboratory, Washington, D.C., February 1989.

   K.-P. Beier, "Visualization in Scientific Computing, " presented at the 1989 Fall Workshop of the ONR Code 12 Ship Wake Consortium, The University of Michigan, Ann Arbor, Michigan, October 1989.

LIST OF HONORS / AWARDS

None

LIST OF PARTICIPANTS

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

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. The research has continued along two main areas: (1) An experimental investigation of the interaction of a turbulent round jet with the free surface, and (2) an experimental investigation of the interaction of a vortex ring with the free surface.

The investigation on the interaction of a turbulent jet with the free surface was initiated in an effort to obtain some basic data on the nature of the surface disturbances produced by a turbulent shear flow as well as to document the effect of the free surface on the dynamics of the turbulent flow. This flow configuration was chosen because of its simple geometry while it typifies the flow field associated with the propeller wake.

The study of the interaction of a vortex ring with the free surface was motivated by some earlier visualization results of the free surface jet flow which showed the appearance of vortices normal to the free surface at the surface. The vortex ring is a simple flow configuration in which these flow processes can be investigated in detail.

Significant Results in the Past Year:

<u>Free Surface Jet Results</u>

The study of the interaction of a round jet with a free surface was completed during this past year. The results are described in Dr. K. Madnia PhD Dissertation entitled "Interaction of a Turbulent Round Jet with The Free Surface." (See also PSH Technical Report no. 89-05) The main conclusions of the investigations are:

(i) Surface waves are generated at the interaction region of the jet with the free surface. The waves are produced by the large scale structures in the jet as they approach the free surface. The waves propagate at an angle with respect to the main flow direction. Along the centerplane of the flow waves do not propagate downstream due to the surface currents produced by the jet.

(ii) The main scaling parameters of this flow have been identified. It is shown that even at the relatively low Reynolds number of these experiments ($\approx 10^4$) the expected inviscid scaling is obtained. The characteristic length scale of the interaction is the distance from the jet centerline to the free surface. The appropriate velocity scale is the velocity derived from the jet momentum flux and the centerline depth. Mean flow properties collapse well for various conditions in these variables even at fairly low values of the depth to diameter ratio. It was further found that the maximum mean velocity decay of the free surface jet is reduced by a factor of $\sqrt{2}$ compared to the free jet result. The growth rate of the free surface jet is the same as for the free jet within experimental uncertainty.

(iii) Measurements were also made in a wall jet and the results have been compared with the free surface jet. The results show significant differences between these two flow fields. Most notably the growth rate of the wall jet is increased by a factor of 3.9 in the direction parallel to the surface and is reduced by a factor of 2 in the direction perpendicular to the surface compared to the free surface jet. A flow visualization study was conducted to investigate the possibility of persistent secondary flows in the plane perpendicular to the main flow direction in both of these flows (i.e., streamwise vortices.) The results indicate that the different growth rates of the wall jet and free surface jet are not caused by a steady secondary flow.

Vortex Ring Interaction with a Free Surface

A systematic study of the interaction of a vortex ring with a free surface was conducted. The results of this investigation are described in Dr. J.T. Kwon PhD Dissertation entitled "Experimental Investigation of Vortex Ring Interaction with a Free Surface." (Also PSH Technical Report no. 89-06.) Several configurations were investigated using flow visualization techniques and Laser Speckle Velocity measurements of the free surface flow. The vortex ring Reynolds number was in the range 2,000 to 7,000 and the Froude number was in the range 0.16 to 0.35. The main results of the investigation can be summarized as follows:

(1) Normal Incidence. The interaction of a vortex ring with the free surface when the vortex ring moves perpendicular to the free surface is strongly influenced by the presence of surface active agents on the surface. It was shown that surface active agents cause generation of vorticity at the free surface that rolls up in secondary vortex rings which limit the outward motion of the primary vortex ring core.

(2) Incline Incidence. When the vortex ring approaches the free surface at an angle two distinct interactions are observed as the upper and lower core of the ring interact with the free surface. During these interactions vortex lines parallel to the surface before the interaction brake and rotate so that the vortex lines terminate at the surface after the interaction. The resulting flow field consists of two half vortex rings each having vortex lines beginning and terminating at the free surface propagating away from each other. Viscous/Surfactant effects are more subtle for incline incidence case. The vortex reconnection time of the upper vortex core scales with the vortex circulation and the core size. It is independent of the Reynolds number. In contrast there is evidence suggesting that the interaction of the lower vortex core is influenced by viscous/surfactans effects. This aspect of the interaction needs further investigation.

Plans for Next Year Research:

(1) Vortex Ring / Free Surface Interaction. Fundamental studies of the interaction of vortex rings with the free surface will continue. Two new experiments will be conducted. First a larger scale vortex ring generator has been constructed and will be used in the Tow Tank at the Ship Hydrodynamics Laboratory to study scale effects on these vortical interactions. This work is being conducted in collaboration with Professors G. Meadows and G. Tryggvason. Second, the effect of surface active agents on the interaction will be further studied in experiments using known amounts of surface active agents.

(2) Fundamental Investigation of Turbulent Surface Wakes. Experiments are also planned in the Tow Tank to determine the structure of turbulent surface wakes. Among the issues to be investigated are: generation of surface waves by the wake turbulence, scaling characteristics of the turbulent wake and, vortical structure of the wake and its relation to forces acting on the hull.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers Published in Refereed Journals

Kwon, J.T. and Bernal, L.P. "Digital image analysis technique for speckle velocity measurements." In preparation to be submitted to Rev. Sci. Inst.

Madnia, K. and Bernal, L.P."Dynamics of turbulent jets near a free surface." Planned for submission to J. Fluid Mech.

Kwon, J.T. and Bernal, L.P."Vortex ring dynamics at a free surface." Planned for submission to J. Fluid Mech.

Bernal, L.P.; Hirsa, A.; Kwon, J.T. and Willmarth, W.W. "On the interaction of vortex rings and pairs with a free surface for various amounts of surface active agent," To appear Phys. Fluids A, Dec. 1989.

Bernal, L.P. and Kwon, J.T. "Surface flow velocity field measurement by laser speckle photography." Submitted to Exp. Fluids, July 1989.

Bernal, L.P. and Kwon, J.T. "Vortex ring dynamics at a free surface." Phys. Fluids A, vol. 1, no. 3, pp 449-451, March 1989.

2. Technical Reports

Madnia, K. and Bernal, L.P. "Interaction of a Turbulent Round Jet with the Free Surface," Program in Ship Hydrodynamics, The University of Michigan, Technical Report no 89-05, August 1989.

Kwon, J.T. "Experimental Study of Vortex Ring Interaction with a Free Surface," Program in Ship Hydrodynamics, The University of Michigan, Technical Report no 89-06, August 1989.

3. Presentations

Song, M.; Tryggvason, G. and Bernal, L.P. "Interaction of vortex rings with a free surface," Abstract submitted to 42nd Annual Meeting of the Division of Fluid Dynamics, American Physical Society, NASA Ames Research Center, November 19-21,1989.

Bernal, L.P. and Kwon, J.T. "Vortex line reconnection at a free surface," Abstract submitted to 42nd Annual Meeting of the Division of Fluid Dynamics, American Physical Society, NASA Ames Research Center, November 19-21,1989.

Madnia, K. and Bernal, L.P. "A comparative study of free-surface jets and wall jets," Abstract submitted to 42nd Annual Meeting of the Division of Fluid Dynamics, American Physical Society, NASA Ames Research Center, November 19-21,1989.

Bernal, L.P. and Kwon, J.T. "Vortex ring dynamics near a free surface." *Bull. Am. Phys. Soc.* vol. 33, no 10, p 2279, 1988.(Abstract only)

Madnia, K. and Bernal, L.P. "Dynamics of turbulent jets near a free surface." *Bull. Am. Phys. Soc.* vol. 33, no 10, p 2238, 1988.(Abstract only)

LIST OF HONORS/AWARDS

none

LIST OF PARTICIPANTS

L. P. Bernal, Assistant Professor
W.W. Willmarth, Professor
K. Madnia, PhD Student
J.T. Kwon, PhD Student
N. Kachman, PhD Student
E. Koshimoto, Master's Student

3.3.1 Nonlinear Ship Waves

Principal Investigator: W.W. Schultz

RESEARCH SUMMARY

Description of the Scientific Objectives: We intend to study the fully nonlinear ship wave problem using a boundary integral method with panels on the ship (with sinkage and trim) 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 concentrated on improving two-dimensional calculations to fully examine capillary-gravity wave behavior and developing boundary integral techniques to study nonlinear waves caused by moving bodies beneath the free surface.

Significant Results of the Past Year: PSH technical report 89-01 entitled, "Uniformly valid solutions to the initial wavemaker problem", by S.W. Joo, W.W. Schultz, and A.F. Messiter has been modified and accepted for publication in the J. Fluid Mech.

We have developed a desingularized method for three-dimensional nonlinear free surface problems. This algorithm has been shown to be much more efficient and accurate than Newman's and Hess and Smith's methods for simple potential problems representing the first time step as a sphere near a flat free surface impulsively moves toward or parallel to the free surface. We have also shown that the indirect method (solving for singularity strength rather than the velocity potential) is more effective when desingularizing three-dimensional potential problems. A PSH report entitled "Three-Dimensional Desingularized Boundary Integral-Method for Potential Problems", by Y. Cao, W.W. Schultz, and R.F. Beck is in the final editing process. The concerns about uniqueness and completeness of the desingularized method are addressed by letting the desingularization-distance depend on the mesh size. The method has given very good preliminary results for nonlinear time marching when compared to linearized results using the time dependent free surface Green's function. Very few problems were caused by using very simple radiation boundary conditions.

We have applied 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. Spectrally accurate computations of the nonlinear Schroedinger-equation show the effect of viscosity and capillary resonance. This topic constitutes the second part of the dissertation of S.W. Joo that was defended in June, 1989. 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 has been submitted to J. Fluid Mech.

A PSH report "Solution of Potential Problems Using a Spectral Boundary Integral Method", J. Huh and W.W. Schultz is in the process of modification for submittal for publication. This shows a strong advantage of desingularizing the kernel rather than using the standard trapezoidal rule with avoidance of the singular point. Time marching with this procedure has shown that some of the steady-progressing waves of Schwartz and Vanden-Broeck appear to be stable while others are not. We have also found that very accurate computations of overturning waves break down significantly sooner than that predicted by the piecewise-linear codes.

A PSH report "Potential energy in steep and breaking waves", coauthored by W.W. Schultz, O.M. Griffin and S.E. Ramberg, is in the final editing process. Two-dimensional breaking caused by an underwater disturbance and by wave focusing has been added to the effect of converging sidewalls.

A PSH report entitled, "GMRES Iterative Solution of Matrix Systems Derived form Boundary Element Techniques" has been completed by L.G. Olson. Further tests on the iterative method for the spectral integral equations have shown improvement over the conjugate gradient method used previously, especially for the desingularized three-dimensional computations.

Robert Krasny has published a PSH report entitled, "Wake patterns computed by a vortex method", and has submitted it for publication.

Plans for Next Year's Research: The thrust of the desingularized three-dimensional potential method is to apply it to nonlinear waves. We are modifying the method to consider breaking waves.

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. Work is continuing on a related manuscript by S. Woodruff and A. Messiter on long-short wave interaction. We are beginning to consider the effect of capillary-gravity resonances in a nonlinear Kelvin wave pattern to determine if these resonances could occur at SAR half-angles. We are also finding the effect of spatial variations of surfactant caused by a ship's passage.--starting with a Wiener-Hopf computation, to determine reflection coefficients at a surfactant boundary.

The spectral computations method are nearing completion. We are trying to implement the spectral viscosity method of Tadmor to allow the computations proceed to the nearly singular case.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers Published in Refereed Journals

Joo, S.W., W.W. Schultz, and A.F. Messiter, "An analysis of the initial wavemaker problem", to appear in Journal of Fluid Mechanics.

Schultz, W.W and S.-W. Hong, "A Complex Boundary Integral Method for two dimensional potential problems", to appear in Journal of Computational Physics.

2. Technical Reports

Schultz, W.W., Griffin, O.M., and Ramberg, S.E., "Potential Energy in Steep and Breaking Waves", Technical Report #89-10, October 1989.

Cao, Y., Schultz, W.W., and Beck, R.F., "Three-Dimensional Desingularized Boundary Integral Method for Potential Problems", Technical Report #89-09, October 1989.

Krasny, R., "Wake Patterns Computed by a Vortex Method", Technical Report #89-08, October 1989.

Joo, S., Messiter, A., and Schultz, W.W., "Evolution of Weakly Nonlinear Water Waves in the Presence of Viscosity and Surfactant", Technical Report #89-07, August 1989.

Olson, L., "GMRES Iterative Solution of Matrix Systems Derived from Boundary Techniques", Technical Report #89-04, June 1989.

Huh, J. and Schultz, W.W., "Solution of Potential Problems Using a Spectral Boundary Integral Method", Technical Report #89-02, March 1989.

Joo, S., Schultz, W.W., and Messiter, A. "Uniformly Valid Solutions to the Initial-Valve Wavemaker Problem", Technical Report #89-01, January 1989.

3. Presentations

Joo, S.-W., A.F. Messiter, and W.W. Schultz, "Surfactant effects on wave stability and damping", Forty-First Meeting of the American Physical Society, Division of Fluid Mechanics, Buffalo, N.Y., November 1988.

Joo, S.W., Schultz, W.W. and Messiter, A.F., "The Effect of Viscosity and Surfactant on Nonlinear Waves", Fourth International Workshop on Waves and Floating Bodies, Oystese, Norway, May 1989.

Schultz, W.W. and Huh, J., "Spectral Boundary Integral Method for Gravity-Capillary Waves", Fourth International Workshop on Waves and Floating Bodies, Oystese, Norway, May 1989.

Cao, Y., Schultz, W.W. and Beck, R.F., "Numerical Investigation on the Desingularization of the Boundary Integral Equation for Three-Dimensional Potential Problems", Fourth International Workshop on Waves and Floating Bodies, Oystese, Norway, May 1989.

Messiter, A. and Schultz, W., "Surfactant Effects on Wave Propagation", Ship Wake Consortium, Ann Arbor, MI, October 11-12, 1989.

LIST OF HONORS/AWARDS

None

LIST OF PARTICIPANTS

R. F. Beck
R. Krasny
A. F. Messiter
L. Olson
W. W. Schultz
Y. Cao
S. Gou
J. Huh
S. W. Joo

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 study employs generalized vortex methods, boundary integral, as well as finite difference techniques.

Significant Results in the Past Year: An account of our two-dimensional, inviscid studies (D. Yu and G. Tryggvason: "The free surface signature of unsteady, two-dimensional vortex flows") has been submitted to the Journal of Fluid Mechanics. This manuscript describes various models for vortical flows, in particular, vortex sheets, point vortices, and vortex "patches", and the signature of their motion on the free surface. Currently, the two-dimensional, inviscid model is being used to study the modification of waves propagating into a vortex generated current. To increase the number of computational elements, we have implemented the so-called Fast Multipole Method to speed up the calculations.

Since the two-dimensional inviscid simulations are relatively well under control, we have turned our attention to three-dimensional flows. A fully three-dimensional inviscid code has been completed and is presently being used to study the interaction of a simple vortex model with the free surface. The current version is somewhat demanding on computer time, and does not include any special treatment of outgoing waves (i.e., the far field boundary conditions). Therefore, some refinement is needed for the free surface treatment, in addition to more realistic vortex structures. Initially, we have used simple models employing vortex filaments in the vicinity of a flat surface to model the flow evolution. Among other things, a model accounting for the appearance of the 'striations' in delta wing experiments has been studied. To account for the 'opening up' mechanism seen in the experiments with vortex rings, we are currently experimenting with 'vorton' modelling of the vorticity field. We are also investigating the use of a linearized free surface model in combination with fully nonlinear vortex models. In addition, we are collaborating with Bernal and Meadows on experimental studies in the towing tank, and plan detailed comparisons between the numerical predictions and experimental observations.

Another line of research motivated by experimental results, is a study of viscous aspects of the vortex free surface interaction. Our current two-dimensional and axisymmetric finite difference code follows the evolution of a viscous vortex pair colliding with a rigid wall, free slip, or contaminated surface. In the case of a contaminated surface, an additional equation is solved on the free surface to calculate the induced shear stress. Work on a three-dimensional counterpart to these simulations is in progress. Full viscous simulations, although limited to low Reynolds numbers, may lead to a better understanding of the reconnection process that takes place when a three-dimensional vortex filament encounters a free surface.

In addition to these 'waveless free surface' models we are working on full simulations of viscous, multifluid simulations, and have simulated various sharply stratified flows both in two-dimensions (including surface tension) as well as fully three-dimensional flow.

Plans for Next Year's Research: The emphasis will be on three-dimensional interactions, both viscous and inviscid flows, the effects of surface contaminants, and continued interactions with the experimental studies of Willmarth and Bernal.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers in Referred Journals

Willmarth, W.W., Tryggvason, G., Hirsa, A. and Yu, D., "Vortex Pair Generation and Interaction with a Free Surface", Phys. Fluids, A1, pp. 170-172, 1989.

Yu, D. and Tryggvason, G., "The Surface Signature of Unsteady, Two-Dimensional Vortex Flows", submitted to the Journal of Fluid Mechanics.

2. Other Publications

Hong, Seok Won, "Unsteady Separated Flow Around a Two-Dimensional Bluff Body Near a Free Surface", Ph.D. Thesis 1988, Chairman Prof. W.P. Graebel.

3. Presentations

Tryggvason, G., "On the Boundary Integral Formulation of Sharply Stratified Flows", 40th Meeting of the American Physical Society, Division of Fluid Dynamics, Nov. 23-25, 1988, Buffalo, N.Y. Abstract in Bull. Amer. Phys. Soc. 33:2258.

Hirsa, A., Willmarth, W., Tryggvason, G., and Yu, D., "Interaction of a Vortex Pair with a Free Surface", 40th Meeting of the American Physical Society, Division of Fluid Dynamics, Nov. 23-25, 1988, Buffalo, N.Y. Abstract in Bull. Amer. Phys. Soc. 33:2278.

Song, M., Tryggvason, G. and Yu, D., "Vortex Interaction with a Free Surface", 40th Meeting of the American Physical Society, Division of Fluid Dynamics, Nov. 23-25, 1988, Buffalo, N.Y. Abstract in Bull. Amer. Phys. Soc. 33:2279.

Tryggvason, G., Computations of Vortex Interactions with a Free Surface and Density Interfaces", Naval Research Laboratory, May, 1989.

Tryggvason, G., "On the Boundary Integral Formulation of Free Surface Problems", 21st Midwestern Mechanics Conference, Aug. 13-16, Houghton, MI.

Tryggvason, G., "Computations of Vortex-Free Surface Interaction", Ship Wake Consortium, Ann Arbor, MI, October 11-12, 1989.

Abstracts have been submitted to several upcoming meetings.

LIST OF HONORS/AWARDS

none

LIST OF PARTICIPANTS

G. Tryggvason, Assistant Professor
Dequan Yu, Ph.D. Student
Museok Song, Ph.D. Student
Javad Abduallahi, Ph.D. Student

PSH Technical Report #89-10

Potential energy in steep and breaking waves

by
W W. Schultz, O.M. Griffin, S.E. Ramberg

A new criterion is proposed indicating that waves break as a function of the energy input level. We find that potential energy, rather than wave height is a better experimental criterion for determining wave breaking. A simple two-dimensional, periodic algorithm is developed and used to compare breaking criteria for three different kinds of energy input: from converging sidewalls, from a submerged disturbance and from wave focusing. These all show similar trends in the limit as the energy input rate becomes small.

PSH Technical Report #89-09

Three-dimensional desingularized boundary integral method for potential problems

by
Yusong Cao, William W. Schultz, and Robert 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.

PSH Technical Report #89-08

Wake patterns computed by a vortex method

by
Robert Krasny

A wake is modeled by a vortex sheet carrying positive and negative circulation. The sheet's evolution is computed by a vortex-blob method. Initial conditions and circulation density for the vortex sheet are chosen to simulate some of the wake patterns observed in the soap-film experiments of Couder et al.

PSH Technical Report #89-07

Evolution of weakly nonlinear water waves in the presence of viscosity and surfactant

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

Amplitude evolution equations are derived for viscous gravity waves and for 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 studied analytically and computationally. For capillary-gravity waves a band of Weber numbers is found in which the linear analysis guarantees neutral stability in the absence of viscous dissipation. The corresponding spectral computation shows modulation features that represent a small-amplitude recurrence not directly related to the Benjamin-Feir instability.

PSH Technical Report #89-06

Experimental study of vortex ring interaction with a free surface

by
Jung Tai Kwon

The results of an experimental investigation into the interaction of vortex rings with a free surface are presented. Laminar vortex rings with Reynolds numbers in the range $2x10^3$ to $10x10^3$ were formed underwater at several incidence angles to the free surface. When the vortex core closest to the surface interacts with it, vortex lines are found to disconnect and reconnect with the free surface resulting in open vortex lines beginning and terminating at the surface. Under certain conditions a second reconnection process is observed resulting in a vortex line topology consisting of two semicircles propagating away from each other on divergent paths. This double reconnection of vortex rings at a free surface is documented in detail by flow visualization and surface velocity field measurements. A new technique was developed to measure the velocity field at the free surface using Laser Speckle Photography and automated digital image analysis. Test results show the accuracy of the velocity measurement to better than 1%.

It is further shown that the interaction geometry when the vortex ring moves initially parallel to the surface is independent of the ring Reynolds number. The effect of Reynolds number on reconnection time is also investigated and showed to be independent of Reynolds number. It is, however, quite sensitive to the incidence angle.

The effect of free surface contamination is investigated at an incidence angle of 90°. The results show the formation of secondary and tertiary rings with a contaminated surface. With a cleaner surface the formation of a secondary ring is delayed.

PSH Technical Report #89-05

Interaction of a turbulent round jet with the free surface

by
K. Madnia and L.P. Bernal

An experimental study of the interaction of an underwater turbulent round jet with the free surface was conducted. Flow visualization, surface curvature measurements and hot film velocity measurements were used to study this flow. It is shown that surface waves are generated by the large scale vortical structures in the jet flow as they approach the free surface. These waves propagate at an angle with respect to the flow direction. The propagation angle increases as the strength of the interaction is increased by increasing the momentum flux of the jet or reducing the distance of the jet to the free surface or both. Propagation of these waves in the flow direction is suppressed by the surface current produced by the jet. Far downstream the surface motions are caused by the large scale vortical structures interacting directly with the surface. The fundamental scaling parameters of the free-surface jet have been determined. The velocity scale is the velocity obtained from the combination of jet momentum, density and depth of the jet and the length scale is the distance of the jet to the free surface. It is shown that the centerline velocity decay when scaled with these parameters collapses to a universal curve for different depths of the jet. The asymptotic decay in the far field is reduced by a factor of $\sqrt{2}$ compared to the free jet due to the confinement by the free surface. The growth rate of the free-surface jet is found in good agreement with the free jet. However, the eccentricity of the jet cross section caused by the displacement of the jet centerline persists for large distances downstream, beyond 40 times the initial depth of the jet centerline. Measurements are also reported in the flow field of a jet moving parallel to a solid surface. These results are compared with the results from the free-surface jet. It is found that the solid wall jet flow is fundamentally different from the free-surface jet flow. The growth rate of the wall jet in the direction parallel to the surface is approximately 3.9 times the growth rate of the free-surface jet. The growth rate of the wall jet in the direction perpendicular to the surface is half the free-surface jet growth rate. This is the result of the different dynamics of vorticity on the free surface compared to a solid wall. The skin friction at the solid wall and increased growth rate combined to give a different maximum velocity decay rate compared to the free-surface jet.

PSH Technical Report #89-04

GMRES iterative solution of matrix systems derived from boundary element techniques

by
L.G. Olson

We apply the Generalized Minimal Residual (GMRES) iterative equation solution technique to a set of full, unsymmetric matrix systems generated by a standard boundary element method. The test problems chosen produced well conditioned matrices. The GMRES technique, when used without preconditioning and with a sufficient number of trial vectors, solved the matrix system using as few as 23% of the operations required by a direct Gauss reduction. The class of partial LU decomposition preconditioners tested degraded the condition number of the matrices, and consequently did not reduce the GMRES solution time. In general, the GMRES technique does not appear to be of practical interest compared to the direct reduction unless other factors (availability of good approximation to the final solution, etc.) intervene.

PSH Technical Report #89-03

The free surface signature of unsteady, two-dimensional vortex flows

by
D. Yu and G. Tryggvason

The 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 large amplitude Kelvin-Helmholtz instability of a submerged shear-layer and the head-on collision of a vortex pair with the free surface. The surface deformation is controlled by a Froude number, based on the vortical motion, and the geometrical parameters describing the initial vortex configuration. Large Froude numbers generally lead to strong interactions for sufficiently shallow vortices.

PSH Technical Report #89-02

Solution of potential problems using a spectral boundary integral method

by
J. Huh and W. W. Schultz

The advantages of solving two-dimensional potential problems using spectral boundary integral methods are examined. Using fast Fourier transforms, we expand the spatial coordinates x and y using an arclength parameter s. This spectral representation is very accurate when the geometry is smooth and nodal spacing is uniform. Two spectral formulations are outlined. One is based on the integration at every other node to avoid the kernel singularities of Baker, and the other is based on the kernel desingularization of Van der Vooren. An error analysis and convergence studies for several geometries are shown.

PSH Technical Report #89-01
To appear in Journal of Fluid Mechanics

Uniformly valid solutions to the initial-value wavemaker problem

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

A Fourier-integral method is developed to obtain transient solutions to potential wavemaker problems. This method yields solutions that are uniformly valid for wavemaker velocities which need not be given as powers of time. The results are compared with known small-time and local solutions. Examples considered include ramp, step and harmonic wavemaker velocities. As time becomes large, the behavior near the wave front is derived for the impulsive wavemaker, and for the harmonic wavemaker it is shown that the steady-state solution is recovered. The solution for a wavemaker velocity given as a Fourier cosine series compares favorably with the computational and experimental results of Dommermuth et al. (1988). Capillary effects are included and nonlinear effects are discussed.

Phys. Fluids A 1 (2), pp 170-172, Feb. 1989

Vortex pair generation and interaction with a free surface

by
W. W. Willmarth, G. Tryggvason, A. Hirsa and D. Yu

Two vertical, rotating flaps are used to generate a vortex pair beneath a free surface. Vortex pair formation, propagation and interaction with a free surface are described. Numerical simulations for inviscid flow about a constant upwash sheet of vorticity beneath a free surface agree with experiment up to the time that turbulent mixing occurs during interaction with the free surface. The spacing between the vortex pairs then becomes larger than the calculated spacing. The experiments and lines of marked particles included in the simulations show fluid ingestion and transport towards the free surface.

Accepted for publication by Phys. Fluids A., Dec. 1989

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

We report observations 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 $G/n \approx 3{,}800$ 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 $G/n \approx 18{,}000$ 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.

To be submitted to Reviews of Scientific Instrumentation

Digital image analysis technique for speckle velocity measurements

by
J.T. Kwon and L.P. Bernal

Speckle photography is a relatively simple technique to measure in-plane fluid motion. The local flow velocity is obtained from the spacing and direction of Young's fringes formed when a narrow laser beam is passed through the doubly-exposed speckle photograph. A technique was developed to measure the spacing and direction of the fringes. In this technique the fringe image is digitized into a 512x512 pixel array. Speckle noise is first removed by averaging along the fringe direction. This image is further processed to remove background nonuniformities and to increase contrast. The spacing and direction of the fringes is determined from the density distribution along two perpendicular directions. An autocorrelation technique is used to obtain the fringe spacing with an accuracy better of 1%. The accuracy of the vorticity derived from the measured velocities is better than 10%.

Submitted to the Journal of Fluid Mechanics

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, based on the vortical motion, and 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 remain almost flat, and the disturbances caused by the vortical flow decrease rapidly with Froude number.

Ph.D. Thesis, 1988

Unsteady Separated Flow Around A Two-Dimensional Bluff Body Near a Free Surface

by
Seok Won Hong

This thesis deals with unsteady two dimensional separated flows past bluff bodies under a free surface. The primary objective of this work is to develop a reliable mathematical and numerical model to accurately predict the important elements of these flows, such as the hydrodynamic loading on the body, vortex shedding frequency, and the shape of the free surface. Another objective is to study the interactions between the free surface and the body, the vortical wake, and the viscous boundary layer.

The mathematical model is developed using several assumptions for the flow and the free surface boundary condition. The flow is assumed to be incompressible and at a high Reynolds number, so that it is irrotational except within the very thin boundary layer around the body surface and the vortical wake behind the body. The vortical wake is further assumed to be an irrotational flow with a number of inviscid circular vortices of finite core size. The free surface between the water and air is assumed to satisfy the full nonlinear boundary conditions, but the effects of surface tension are ignored.

The numerical model is formulated by using the most appropriate numerical methods and schemes. A complex variable boundary integral method is used for the estimation of flow velocities. A boundary layer solver is used to define the location and rate of vorticity shedding at the flow separation point. A Lagrangian scheme is used to evolve the free surface and the vortical wake. A fourth-order Runge scheme is used for higher resolution time stepping.

The present numerical model is found to be successful for various numerical calculations and verifications. The hydrodynamic loading on the circular cylinder below a free surface is correctly estimated both with and without shed vortices. The vortex-free surface interactions are compared with the linearized solutions and are shown to agree accurately with them.

In Chapters I and II, the physical description of the problem is given together with a literature review. In Chapters III and IV, the mathematical and the numerical models are formulated. Verification of the developed numerical model is carried out in Chapter IV by solving various simple problems. In Chapter V, numerical calculations and discussion are presented for separated flow problems with or without a free surface. Finally, conclusions are drawn in Chapter VI.

REVISED

ONR CODE 12 SHIP WAKE CONSORTIUM

1989 FALL WORKSHOP

University of Michigan
David Taylor Research Center
Naval Research Laboratory

October 11 & 12, 1989

College of Engineering (North Campus)
University of Michigan
Ann Arbor, MI 48109

AGENDA

Wednesday, October 11 - East Room, North Campus Commons

0830	Introduction and Opening Remarks R. Beck, UM; J. Fein, ONR
0845	The Hydrodynamic Monitoring Facility G. Meadows, UM
0915	Propeller/Free Surface Interactions J. Blanton, S. Fish, DTRC
0945	LDA Measurements of Turbulence in a Jet Near a Free Surface W. Willmarth, UM
1015	Coffee Break
1030	DARTS Experiments and Comparison with Turbulent Wake Predictions L. Meadows, UM
1100	Near Field Wave Profile Computation Y. Kim, DTRC
1130	Lift/Transom Stern Computations J. Telste, DTRC
1200	Lunch
1315	Laboratory and Field Measurements of Surfactant Film Properties and Wake Effects R. Peltzer, J. Kaiser, NRL
1345	Surfactant Effects on Wave Propagation A. Messiter, W. Schultz, UM
1415	Bubble Scavenging and Surface Film Wave Damping R. Skop*, J. Brown, U. Miami; R. Peltzer, O. Griffin, NRL; *also SAIC, Annapolis, MD

1445	Coffee Break
1500	Diffusional Growth and Collapse of Bubbles in Time-Dependent Pressure Fields M. Cerza, NRL* *presently Code 1944, DTRC
1530	Turbulent Dissipation of Surface Waves J. Milgram, MIT
1600	MARIN Model Ship Wake Experiments W. Lindenmuth, DTRC
1630	Discussion and Comments

Thursday, October 12 - East Room, North Campus Commons

0900	ONR Full-Scale Ship Wake Experiments-SAR Data Collection J. Lyden, ERIM
0930	Numerical Simulation of Vortex-Free Surface Interaction R. Leighton, T.Swean, Jr., NRL
1000	Coffee Break
1030	Flow Field and Surface Interaction of a Vortex Pair A. Hirsa, UM
1100	Experimental Study of Unsteady 3-D Vortex Characteristics in a Stable Stratified Fluid with a Free Surface S. Cohen, A. Troesch, UM; M. Stewart, NRL
1130	Visualization in Scientific Computing P. Beier, UM
1200	Lunch
1315	Three-Dimensional Vortex Interactions at a Free Surface L. Bernal, UM
1345	Computations of Vortex-Free Surface Interaction G. Tryggvason, UM
1415	Future Plans and Prospects J. Fein and/or E. Rood, ONR
1430	Summary and Discussion, Informal Visits and Demonstrations Gas Dynamics Laboratory and Ship Hydrodynamics Laboratory