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END-OF-FISCAL YEAR REPORT

Robert F. Beck, Project Director
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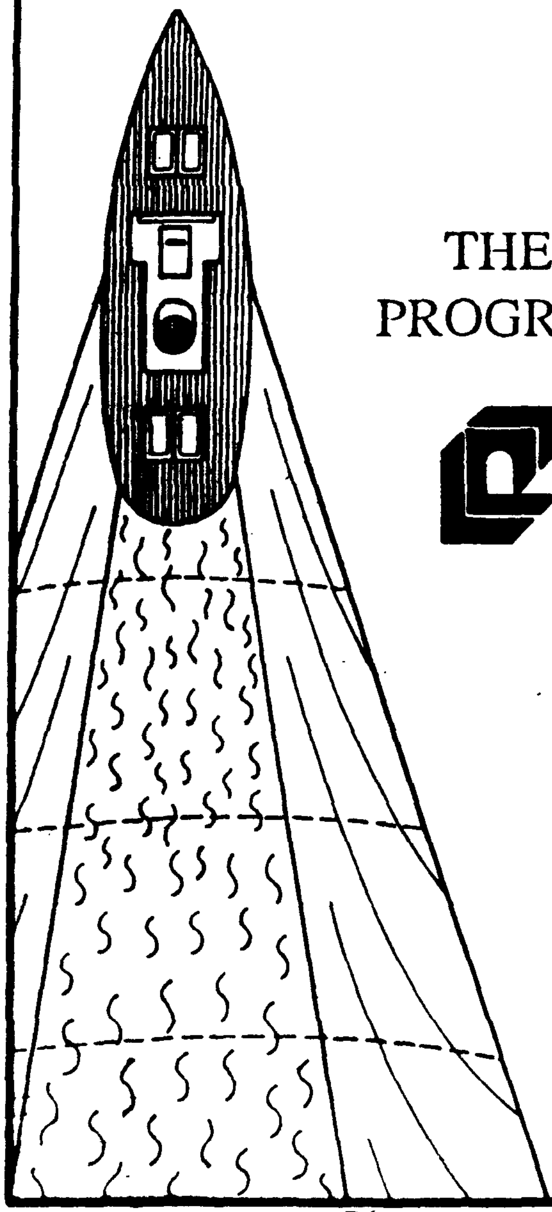

THE UNIVERSITY OF MICHIGAN PROGRAM IN SHIP HYDRODYNAMICS

COLLEGE OF ENGINEERING

NAVAL ARCHITECTURE & MARINE ENGINEERING

AEROSPACE ENGINEERING

MECHANICAL ENGINEERING & APPLIED MECHANICS

SHIP HYDRODYNAMIC LABORATORY

SPACE PHYSICS RESEARCH LABORATORY

ERIM

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PROGRAM FOR SHIP HYDRODYNAMICS

Executive Summary Report

by

Robert F. Beck, Project Director

The first year of the Program for Ship Hydrodynamics has been very successful. There were the usual start up problems, but on average the research is progressing well. Appendix I lists the year-end reports written by the principal investigators for each of the research projects. The 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 the second appendix are the abstracts from the papers submitted for publication.

During the past year, significant progress has been made in the acquisition of the major pieces of experimental equipment, which were part of the original proposal. The Hydrodynamic Monitoring Facility (HMF) being built by the Space Physics Research Laboratory (project 3.1.1) was originally scheduled for completion by October,1987. It now appears that initial testing in the towing tank will commence in December. The design and engineering phases of the wave slope, wave height, surface velocity sensors and data acquisition systems have been completed. Delivery of critical components from the vendors and the purchasing authorization process were the major causes of the delay.

As a result of an extra allocation of funds from ONR, the major components for the Laser Doppler Anemometer (LDA) being designed and built by Prof. Willmarth (project 3.2.3) for use in the towing tank have been ordered. This is six months ahead of the schedule in the revised proposal. The system is unique in that it uses fiber optics and wet mirrors. In order to minimize the flow interference, the measurement volume will be approximately 1500 mm from the underwater pod. The optics should be delivered from TSI in March, 1987.

The third major equipment purchase this year was a copper vapor laser and supporting equipment for flow visualization. This system is being used by Prof. Bernal (project 3.2.6) to make speckle photographs and study the vortical structure of the wake.

In the original proposal, the Micro Radiation Laboratory of The University of Michigan was to develop a set of calibrated scatterometers for use in the towing tank. A mid-year budget cut forced the cancellation of that project. In its place, ERIM (project 3.1.2) has agreed to the use of its set of calibrated scatterometers on an as available basis. An extensive series of radar measurements are being conducted in the towing tank to study backscattering from various disturbances on the water surface and the effects of different polarizations. A demonstration is planned during the October External Advisory Committee meeting. When the HMF is available, the radar measurements will be correlated with the precise free surface measurements of the HMF.

In order to develop experimental techniques to study ship wakes, Prof. Bernal (project 3.2.6) has investigated the much simpler problem of a turbulent round jet interacting with a free surface. Flow visualization experiments were conducted using shadowgraph techniques and laser-induced fluorescence. These experiments showed a well-defined pattern of surface waves emanating at the interaction point of the jet with the free surface. Simultaneous visualization of the jet fluid and surface deformation further showed the waves to be generated by the interaction of the large scale turbulent structure of the jet with the free surface. Temporal variations at a fixed point of the water surface curvature were also obtained using a collimated beam and a photodiode arrangement. The results show a spatial pattern of the rms value of the fluctuation consistent with the wave pattern observed in the flow visualization study. Also, the power spectral density of the surface curvature shows changes in the frequency content consistent with that pattern.

To analyze the massive amounts of data which is expected from the experimental measurements, Prof. Beier (project 3.2.5) is developing techniques which use advanced computer graphics. The techniques are being perfected on an existing data set supplied by Dr. Richard Leighton from NRL for the turbulent flow in a rectangular channel. The turbulent bursting process is being analyzed using a combination of wire frame models and eventually translucent surfaces and animation.

The analytic research under the PSH has concentrated in the area of free surface hydrodynamics, with particular emphasis on nonlinear waves. Prof. Schultz (project 3.1.1) has examined the use of boundary integral techniques in solving nonlinear wave problems. An iterative least squares solver and explicit time marching have been implemented with significant savings in computer time. The difficulties associated with the intersection of the body surface and the free surface (the contact line) have also been studied. The mathematical problem in that region is ill-posed. Work is proceeding on finding ways that would regularize the solution in a simple way such that it mimics experimental observations.

Profs. Tryggvason and Graebel (project 3.3.2) have been studying the interactions of vorticity and the free surface . Work in the first year has concentrated on two-dimensional problems. These have included the collision of a vortex pair with the free surface, the effects of a co-rotating vortex pair, and the roll-up of a vortex sheet below a free surface. Work is proceeding on three-dimensional modelling including a free surface of vortex sheet roll-up of circular jets and the generation of vortex rings. These results will be compared to Bernal's experiments.

The project on Nonlinear Waves and Wave Interaction (project 3.3.3) has had two subprojects. Prof. Yih has used a ray type theory to develop formulas for the far field, constant phase lines behind a moving disturbance including the nonuniformity of the mean velocity field due to the presence of the viscous wake. Yih found that the wave pattern created by a ship with a wake is different from the usual Kelvin wave pattern. In the second problem area, Prof. Messiter and Ph.D. student, Steven Woodruff, developed a novel method for the solution of multi-scale problems. They applied the method to the problem of the two-dimensional weakly nonlinear interaction of short gravity-capillary waves and long fully nonlinear gravity waves. Next year the technique will be applied to capillary blockage, three-dimensional long and short waves at oblique angles relative to one another, stability questions concerning the growth or decay of the short waves, and possibly a study of the effects of surface contamination with concentrations varying slowly relative to short-wave scales.

During the past year significant interactions have been developed with the Navy Laboratories. There will be thermal wake experiments performed in the U of M towing tank by NRL and PSH personnel under joint funding. There have been three formal meetings between Navy personnel and PSH members. In November, 1986, there was a meeting in Washington with participants from the PSH, NRL, and DTNSRDC to discuss the wake scaling problem. Much useful information was exchanged. Several specific scaling problems were identified and full scale experiments which could be conducted in the controlled environment of the towing tank were proposed. Under funding from Code 12 of ONR, a consortium was set up between the PSH, NRL, and DTNSRDC. The first meeting of the consortium was held on May 4 and 5, 1987, at DTNSRDC Model Basin. The second was held in Ann Arbor on September 21 and 22. The attendance had to be limited to approximately 8 from each group. All participants have felt that the exchange of information has been very productive. As a direct result of the meetings there has been continuing contact on various research projects.

There has been two exchanges of personnel between the Navy laboratories and The University of Michigan. Prof. Troesch is spending his sabbatical year at DTNSRDC. Mr. Doug Anthony from DTNSRDC is now working towards a Ph.D. under Prof. Willmarth.

3.1.1 Hydrodynamic Monitoring Facility (HMF)

Principal Investigator: G.A. Meadows

RESEARCH SUMMARY

Description of Scientific Research Goals: To make substantial progress in the understanding of the hydrodynamic mechanisms which allow ship generated disturbances to be remotely sensed, experimental measurements which can correlate the hydrodynamic properties of the flow field with the electromagnetic properties of the sensing field are necessary.

To make these types of measurements, specialized facilities need to be developed. This research effort has concentrated on the development of new, extremely accurate instrumentation to measure the surface tangential velocities, surface displacements, and surface slopes of the water surface in the Ship Hydrodynamics Laboratory. The goal is to then correlate these measurements with simultaneous, radar scatterometer measurements. Such a complete set of data has never been gathered in a controlled environment. It will allow space and/or time correlations to be made of the hydrodynamic surface properties, the radar signature and the infrared signature.

Project 3.1.1 is developing a set of three instruments to measure the free surface height, slope and tangential velocities concurrently. The slope will be determined using refracted laser light. The surface height and tangential velocities will be measured using a thermal image to track "warm spots" which will be created on the free surface by a powerful laser pulse. The warm spots will be aligned in different patterns under computer control to obtain linear velocity profiles, vorticity, or divergence on the free surface.

Significant Results in the Past Year: In the first year of this effort, development of these three new instruments has proceeded from the concept stage through final design and fabrication. A design review was held on February 4, 1987, to discuss the proposed final design of the Hydrodynamic Monitoring Facility. Theoretical and operational considerations which allow the HFM to determine the height, slope and surface velocity of points on the free surface were demonstrated to ONR, and other Navy personnel. The data gathering region is a square which can expand from .2m x .2m to 1m x 1m. Each data point location may be accessed randomly; thus, arbitrary patterns of data acquisition may be obtained.

The entire instrument was designed to be transportable so that it can be bench tested outside the towing tank. In addition, it will be able to be moved to other laboratories to conduct specific experiments of joint interest. Since the design review of the HMF, all comments received have been incorporated into the instrument design. The design phase of the wave slope, wave height, surface velocity sensor and data acquisition systems, have been completed.

The acquisition and programming of both the control and analysis computer systems is nearing completion. These computers not only control the active sensors of the systems but also eliminate carriage motion to cast the data in a true inertial reference frame independent of model speed. The data acquisition and analysis computer, a MicroVax, was chosen to provide complete compatibility with Navy laboratories to foster data exchange.

Thermal imagery of laser induced warm spots has been demonstrated to be feasible through a number of laboratory experiments. Processing of these images utilizing enhancement techniques, has resulted in successful tracking of tens of warm spots in complex flows with mean downstream velocities of greater than 50 cm/sec and cross-stream components with deviations of 30°.

Major efforts at this point in time are concentrating on: i) software development for both control, data acquisition, analysis, and ii) on mechanical fabrication and assembly. The current HMF schedule shows the engineering phase of the program complete and at the tow tank in December rather than the originally planned mid-October. The major drivers in the schedule slip are purchasing authorization delays and late procurement deliveries. Virtually all vendors have delivered later than promised or are currently slipping delivery schedules. Both the MicroVax computer and the 80386u processor board which controls the data acquisition and control (DAC) computer were late which in turn delayed the software effort. All the needed computer hardware has arrived and programming the MicroVax and (DAC) computers are top priority activities.

Plans for Next Years Research: It is anticipated that after initial testing of the HMF in the Ship Hydrodynamics Laboratory in December, a substantial calibration effort will be required. This effort, however, will be largely carried out by the research as opposed to the engineering staff. Once this activity has been completed, initial measurements of fundamental wave and current fields will begin. This effort will be designed to verify one-dimensional measurements made elsewhere by other researchers. The ERIM activities (project 3.1.2) have been scheduled to coincide with the date of operational status of the HMF. At that time coincident hydrodynamic and microwave measurements will begin. Once again, measurement of fundamental flows and wave structures will be initially attempted followed by more complex patterns.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers Published in Refereed Journals

   none

2. Technical Reports

   none

3. Presentations

   G.A. Meadows and B.C. Kennedy, first joint ONR, NRL, DTNSRDC, U of M workshop on Surface Ship Wakes, Washington, D.C., Nov. 1986.

   G.A. Meadows, "Free Surface Measurements using DARTS in Viscous Wake Region of Model 5356", second joint ONR, NRL, DTNSRDC, U of M workshop on Surface Ship Wakes, Ann Arbor, MI, Sept. 1987.

LIST OF HONORS/AWARDS

none

LIST OF PARTICIPANTS

G.A. Meadows, Associate Professor
Museok Song, Ph.D. student
Zhijian Wu, Ph.D. student

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Plans for Next Years Research: Our plans for next year are centered around the University's Hydrodynamic Monitoring Facility (HMF). We anticipate a comprehensive radar measurement program coincident with HMF measurements of towed model ship wakes and other wake-related phenomena. If our present analysis supports its applicability, we anticipate making 3-D laser scanner measurements of waves in the towing tank and using the HMF measurements as a calibration/validation source. Finally, we anticipate doing similar validation studies of the two optical techniques considered this year.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers Published in Refereed Journals

   none

2. Technical Reports

   none

3. Presentations

   J.D. Lyden, "SAR Detection of Surface Ship Wakes", Program in Ship Hydrodynamics, The University of Michigan, Ann Arbor, MI, May 22, 1987.

   J.D. Lyden, first joint ONR, NRL, DTNSRDC, University of Michigan workshop on Surface Ship Wakes, Washington, D.C., Nov. 1986.

LIST OF HONORS/AWARDS

none

LIST OF PARTICIPANTS

J. Lyden, ERIM
R. Shuchman, ERIM
Steve Kilberg, graduate student
Mathew Peters, graduate student, Ohio State University
Scott Dupuie, graduate student, Ohio State Unversity

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 ships. The investigation will provide basic information about the unsteady flow field in the vicinity of the ship hull and propulsion system and the resulting unsteady turbulent flow far downstream. It should then be possible to determine the principal flow processes responsible for the acoustic signature and wake surface motion signatures of a ship.

The facilities and equipment for this research are being developed and used jointly with Professor Bernal in his parallel investigation under the PSH entitled, "Vortical Structure of Ship Wakes".

Significant Results in the Past Year: Equipment - During the time from September, 1986 to May, 1987 the work that has been done has been concentrated on the purchasing and putting into operation instrumentation that is now being used for experimental measurements in the related program 3.2.6 Vortical Structure in Ship Wakes. The major items of equipment are a 2..5 x 2.5 x 5 foot tank with glass walls (constructed by Professor Bernal and his R.A. Kroosh Madnia), a Copper Vapor Laser for flow visualization, hot-film probes and a traversing system for them and an IBM PC/AT with Le Croy data acquisition equipment for future use with a laser Doppler anemometer (LDA) as discussed below. As mentioned in part a) above, the two projects (3.2.3 and 3.2.6) are closely related and most of the equipment will be shared and used for experimental measurements on either project.

Laser Doppler Anemometer:

Much time and effort has also gone into initial design and pricing for a 3-Component fiber optic laser Doppler anemometer. After looking into the state of the art of construction of a large fiber optic LDA by commercial suppliers it was found that no existing design corresponded to our needs. Existing designs were either too small (DANTEK) or too cumbersome and difficult to traverse (TSI). An acceptable design has been developed and two bids for it have been received from TSI and DANTEK. In the course of developing specifications for the LDA system it has become clear that Professors Bernal and Willmarth have the expertise to put together an LDA system in which considerable savings can be realized by building our own traverse system (Willmarth) and designing the LDA interface to the controlling computer (Bernal) and the FORTRAN software (Bernal, Willmarth and students) for the system. The economies are so great that we have been able to afford to purchase a Copper Vapor laser and a very good analog to digital converter (Le Croy). It has recently been determined that the LDA system proposed by TSI is superior and less expensive than the LDA system proposed by DANTEK. The LDA system proposed by TSI has been ordered. Willmarth (1987) describes the proposed LDA system in a paper to be presented in October at the Towing Tank Conference in Tokyo, Japan.

Small Towing/Wave Tank:

We have designed a small towing tank 2.5 x 2.5 x 24 feet which is fitted with a wave development tank 2.5 x 8 x 10 feet in the center part. The tank will have all glass walls and bottom. The material for the glass walls has been received. This tow/wave tank framework was constructed this summer in the same laboratory room that contains the copper vapor laser and Professor Bernal's small jet tank. The tank has been fitted with precision rails for a small carriage. We are awaiting the delivery of suction cups for installation of the

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LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers Published in Refereed Journals

   none

2. Technical Reports/Presentations

   A contributed Technical report has been written for presentation at the International Towing Tank Conference in Tokyo, Japan in October 1987: "The Design of Three Component Fiber Optic Laser Doppler Anemometer for Wake Measurements in a Towing Tank" by William W. Willmarth.

LIST OF HONORS/AWARDS

None

LIST OF PARTICIPANTS

W.W. Willmarth, Professor
L.P. Bernal, Professor
T. Wei, Post Doctoral student, no longer with project
C.-O. Lee, graduate student, no longer with project
A. Hirsa, graduate student
M. Feminio, undergraduate student, no longer with project
D. Bass, undergraduate student

3.2.5 Flow Visualization of Turbulent Burst

Principal Investigator: K.-P. Beier

RESEARCH SUMMARY

Description of the 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.

Significant Results in the Past Year: A new visualization concept for the graphical representation of a turbulent channel flow has been developed first. If the flow is described by its velocity vectors given on a spatial grid and as a function of time, the loci of constant velocity or pressure are three-dimensional surfaces. These surfaces are changing their shape in time. The surfaces can be calculated from the given data set and can be used to built an 'onion model' of several surface layers each representing a different constant velocity or pressure. The layers can be displayed as translucent surfaces and animated in time.

In a first step, an algorithm was developed to find a wire frame representation of the contour surfaces. For a given point in time, the volume of given velocities or pressure is intersected with various planes resulting in families of two-dimensional contour lines. These contour lines are assembled into a three-dimension mesh describing the surface as a wire-frame object. A special topological search algorithm and various interpolation methods have been developed for the finding of the contour surfaces. The technical report by Beier (1987) gives some details on the techniques used.

In a second step, a wire-frame viewing program was developed allowing the inspection of the resulting surfaces. The program makes use of the capabilities of an IRIS graphics workstation. For a given point in time, various surfaces can be displayed simultaneously using different colors. The interactive program allows to manipulate the perspective view using various techniques (rotate, translate, zoom, depth-cueing, etc.).

After testing these initial programs with dummy data, the usefulness of the visualization principle was examined by using a data set provided by R.I. Leighton who investigated turbulent burst in a channel flow simulation. Only one set of data for one given point in time was used. A few days ago, the first surfaces were displayed and inspected. The initial test proved the correctness of the algorithms developed. The resulting surfaces have never been seen before and require intensive study for their correct interpretation. The time consuming generation of more surfaces and discussions with various members of the PSH is presently going on. The first results indicate that the occurrence of turbulent burst can be detected from the special shape of the contour surfaces in local areas.

Plans for Next Year's Research: The research results from the past year are only preliminary, but are already very promising. The major tasks for the next and the coming years can be described as follows: The geometric properties of the three-dimensional surfaces will be studied with the goal to replace the wire-frame representation by a piecewise continuous mathematical surface, probably by a pattern of Linear Coons Surface patches. The mathematical surface representation allows to apply hidden surface removal and coloring/shading techniques as well as the display of translucent surfaces. Translucent surfaces are necessary to properly represent the different layers of the velocity or pressure surfaces which form the onion-like object. The final goal is to animate the onion model of the turbulent burst in time and, from there, to develop a systematic solution for the graphical representation of n-dimensional property distributions in space and time.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers Published in Refereed Journals

   none

2. Technical Reports

   K.-P. Beier: "VIEWX-ISOX, Version 3.2/3, Documentation", Department of Naval Architecture and Marine Engineering, The University of Michigan, October 1987.

3. Presentations

   none

LIST OF HONORS/AWARDS

none

LIST OF PARTICIPANTS

K.-P. Beier, Associate Professor
S. H. Han, graduate student
C. Churchill, System Research Programmer II

3.2.6 Vortical Structure of Ship Wakes

Principal Investigator: L.P. Bernal

RESEARCH SUMMARY

Description of the Scientific Research Goals: The main objective of this effort is to obtain a better understanding of the turbulent wakes behind ships by means of an experimental investigation of the underlying vortical structure and its dynamics. The research during the past year has focussed on two main areas: (1) Development of speckle photography for flow field velocity measurements, and (2) Investigation of the interaction of the free surface with a turbulent round jet moving parallel to the surface.

The speckle photography system for turbulent flow research currently under development consists of the following elements: the flow visualization system, optical processing system, digital image analysis system and flow data analysis system. Each one of these elements introduces limitations to the technique which must be understood. These elements must then be integrated in a consistent fashion to obtain the desired resolution and accuracy of the measurement. In the second area of research, the turbulent round jet is one of the simplest flow configurations to study the interaction of the free surface with a turbulent shear flow. Aspects of the problem being addressed are the surface motion/deformation caused by the jet and the modification of the turbulent structure of the jet by the free surface.

Significant Results in the Last Year: Speckle Photography - A copper vapor laser was purchased and is fully operational in our laboratory. This pulsed laser is being used for flow visualization and for velocity field measurements using the speckle technique. Several light pulse sequences have been demonstrated to be used in the various flow visualization tasks. The unit is currently being integrated in the jet-free surface facility flow visualization systems.

A fully automated technique was developed to measure the flow velocity, two components, at a large number of points using doubly-exposed speckle photographs. After the system is initialized no further operator action is required to scan a rectangular array of points in the flow. The technique was tested using a speckle photograph of a disk in solid body rotation. From these tests the accuracy of velocity measurement was better than one percent and that of vorticity measurement was better than ten percent.

Jet-Free Surface Interaction - A new free-surface water tank facility was designed and built to investigate the interaction of a turbulent jet with the free surface. The facility has automatic water level control and excellent optical access for flow visualization and optical diagnostics.

Flow visualization experiments were conducted using the shadowgraph technique and laser-induced fluorescence. These experiments showed a well-defined pattern of surface waves emanating at the interaction point of the jet with the free surface. Simultaneous visualization of the jet fluid and surface deformation further showed the waves to be generated by the interaction of the large scale turbulent structure of the jet with the free surface.

Temporal variations at a fixed point of the water surface curvature were also obtained using a collimated beam and a photodiode arrangement. The results show a spatial pattern of the rms value of the fluctuation consistent with the wave pattern observed in the flow visualization study. Also, the power spectral density of the surface curvature shows changes in the frequency content consistent with that pattern.

Plans for Next Year's Research: The effort this coming year will focus on measurements of the fluid velocity at the surface and within the flow in the jet-free surface interaction problem. Development work will continue to improve the resolution (noise level) of the vorticity measurement, to resolve the directional ambiguity of the technique, and to obtain field velocity measurements sequentially in time.

Jet-free Surface Interaction - A detailed flow visualization study to determine the mechanisms of wave generation at the interaction is currently underway. Velocity measurements using the hot film technique will be conducted to characterize the turbulent structure of the jet in the presence of the free surface. Simultaneous flow velocity and surface curvature measurements will also be conducted. A new surface slope measurement technique is under development for improved accuracy of the characterization of the surface motion.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers Published in Refereed Journals

L. Bernal and K. Madnia, Interaction of a Turbulent Round Jet with the Free Surface, Proceedings of the17th Symposium on Naval Hydrodynamics, August 1988.

K. Madnia and L. Bernal, Interaction of an Axisymmetric Turbulent Water Jet with the Free Surface, American Physical Society Bulletin, Division of Fluid Dynamics, November 1987.

L. Bernal, J.T. Kwon and J. Wolter, Digital Image Analysis Technique for Speckle Velocity Measurements, American Physical Society Bulletin, Division of Fluid Dynamics, November 1987.

2. Technical Papers

none

3. Presentations

J. Wolter, Measurements of In-Plane Fluid Motion Using Laser Speckle Photography, presented at the AIAA Student Conference, April 2-4, 1987, Dayton, Ohio.

L. Bernal, The Interaction of a Turbulent Jet with the Free Surface, presented at the 1st Ship Wake Consortium Workshop, May 4-5, 1987, DTNSRDC.

L. Bernal, Free Surface Deformation by a Turbulent Jet, presented at the 2nd Ship Wake Consortium Workshop, September 21-22, 1987.

LIST OF HONORS/AWARDS

none

LIST OF PARTICIPANTS

L.P. Bernal, Assistant Professor
W.W. Willmarth, Professor
K. Madnia, graduate student
J.-T. Kwon, graduate student
L. Jenaway, undergraduate student
J. Holcomb, undergraduate student, graduated May 1987
J. McConnell, undergraduate student, graduated May 1987
J. Wolter, undergraduate student, graduated May 1987

3.3.1 Nonlinear Ship Waves

Principal Investigator: W.W. Schultz

RESEARCH SUMMARY

Description of Scientific Research Goals: We intend to study the fully nonlinear ship wave problem using a boundary integral method with panels on the ship (with sinkage and trim) and on the actual free surface. Ultimately, we wish to be able to incorporate vorticity, subgrid models of capillary waves (from 3.3), and empiricism from tow tank data into the program to get a more accurate representation of the wake SAR signature.Toward that goal, we have concentrated on improving two-dimensional calculations: including a careful examination of boundary integral techniques and corner singularities where a solid wall pierces the free surface.

Significant results of the past year: An iterative least squares solver and explicit time marching have been implemented in the two-dimensional irrotational flow algorithm for nonlinear free-surfaces. The overdetermined system is solved in N squared operations using a conjugate gradient algorithm we developed. The solution typically requires two iterations and is significantly faster than the Householder formulation even for small N (say 20). The iterative solution time for the overdetermined system is less than twice that to compute the determinate system for the same N but has much higher accuracy. We find that the solution is numerically stable when time marching uses a Runge-Kutta-Gill solver. With these two improvements, we can decrease the computational time by approximately 1/100th. This will allow more extensive computations including those in three-dimensions. Some improvements to the boundary integral program have been added: 1) We have adapted the program to run on the NRL Cray, 2) we can use as initial conditions a very accurate representation of steadily progressing Stokes waves using the algorithm of Schwartz and Vanden Broeck, and 3) we have used a spline representation on the boundary integral method to get higher accuracy and sixth-order convergence.

We have examined the wavemaker startup problem. We have found that the case where there is a step function in velocity of the wavemaker is ill-posed. In this case, there is a fundamental incompatibility between the homogeneous initial condition and the boundary condition along the entire wavemaker boundary. All small-time expansions to date (Peregrine, 1972; Greenhow and Lin, 1983; Roberts, 1987) are flawed. Surprisingly, we find that the ramp wavemaker velocity studied by Chwang (1983) and even smoother startups are ill-posed in that the singularity at the contact line immediately invalidates the linearization of the free-surface boundary condition. We are examining ways that would regularize the solution in a simple way such that it mimics experimental observations.

In some viscous computations solving the reduced vorticity equations by the finite element method, we are verifying the approach by examining Jeffrey-Hammel flow. For Reynolds numbers near 10 and a divergence angle of 45 degrees, we find errors of approximately 30 percent in vorticity. Work is continuing to refine these calculations.

Plans for next year's research: A computer algorithm for three dimensional waves in a container is complete is coded, but not debugged. We have abandoned this code and will, instead, examine the nonlinear wave pattern generated by impulsively started sphere. Initially, we will concentrate on developing an accurate and robust three-dimensional potential equation solver including an effort to develop an overdetermined system. The difficulty with radiation conditions will be postponed by placing the "infinite" boundary conditions suitably far from the impulsively started sphere.

The two-dimensional code will be further modified to examine: a) a spectral representation and parametric differentiation of the solution along the contour, b) the effects of surface tension and surface contamination (so that we may compare to the analytical results of Woodruff and Messiter (1987) in project 3.3, and c) the benefits of modelling singular behavior more precisely at corners of the contour.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers Published in Refereed Journals

Hong, S.W. and W.W. Schultz, "Solution of potential problems using an overdetermined complex boundary integral method", submitted to J. Comp. Physics.

S.W. Hong, W.W. Schultz and W.P. Graebel, "An alternate form of the complex boundary integral method for nonlinear free surface problems", to be submitted to Phys. of Fluids.

S.W. Hong, G. Trygvasson, and W.W. Schultz, "A note on the formulation of free surface problems: An integral equation for velocity", to be submitted Phys. of Fluids, October 1987.

2. Technical Reports

none

3. Presentations

Schultz, W.W. and S. Hong, "A boundary Integral formulation for velocity", Thirty-Ninth Meeting of the American Physical Society, Division of Fluid Mechanics, Columbus, Ohio, November 1986.

Schultz, W.W., "A complex-valued integral method for free surfaces with intersecting bodies", Second International Workshop on Water Waves and Floating Bodies, Bristol, England, March 1987.

LIST OF HONORS/AWARDS

"Periodic and Aperiodic Steep and Breaking Waves", Young Investigator Award, funded by the Office of Naval Research, Ocean Engineering Division, $265,000 for 36 months starting July 1987.

LIST OF PARTICIPANTS

W. Schultz, Assistant Professor
L. Olson , Assistant Professor
S.W. Hong, Ph.D. student
D. Rowley, graduate student
V. Rajarajadan, graduate student

3.3.2 Interaction of Vorticity and Free Surface Flows

Principal Investigators: G. Tryggvason and W.P. Graebel

RESEARCH SUMMARY

Description of Scientific Research Goals: The goal of this project is to contribute to the understanding of the interactions between vortical flows and free surfaces. 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, and boundary integral techniques, to study the problem. Where applicable, these methods are generally far superior to any other known method.

Significant Results in the Last Year: During the first year we have implemented a method for two dimensional simulations and considered a variety of problems involving relatively simple vortical flows. These include collision of a vortex pair with a free surface (also investigated by Telste, preprint) and the effect of a co-rotating vortex pair. We have investigated in considerable detail the roll-up of a vortex sheet below a free surface and shown that it is possible to distinguish between three different scenarios for the free surface evolution. Strong and shallow vortex sheets suck the free surface into the fluid, weaker and deeper sheets lead to breaking waves on the surface, and even deeper and weaker vortex sheets cause the generation of surface waves that are relatively short compared with the basic wavelength. This investigation is discussed briefly in Tryggvason (1987a). A more detailed description, discussion of the transition from one regime to another, as well as aspects of the numerics will be given in a future report. This latter report will also contain some of our efforts to represent the evolution by a simple model that may be analyzable by analytical tools.

A computer model for vortex shedding and wake formation due to a blunt body just under a free surface is presently being tested. An exact linearized solution for vortices traveling beneath a free surface has been obtained, and the computer code tested against it. The linearized model shows a single vortex to travel on a straight line path. Our nonlinear model shows this to be unstable, with ever growing oscillations in the vortex path.

We have also initiated work on three-dimensional modelling. A student has completed a axisymmetric vortex blob method to study vortex sheet roll-up of circular jets, and generation of vortex rings. Another student has a fully three-dimensional vortex filament method running. Neither of these methods incorporates a free surface as of yet, the addition to the axisymmetric code is a relatively minor task and is the next thing to do. This will enable us to study the interaction of vortex rings with a free surface. Full three-dimensional free surface simulations are a somewhat different matter. We will focus our fully three-dimensional studies on flow in the absence of a surface, or next to a rigid surface during next year. The justification for this is the observation from the two-dimensional investigations, that for a wide parameter range the free surface deformations are relatively small, and have small effects on the vortical flow itself. Full three-dimensional, free-surface vorticity interaction calculations are planned in subsequent years.

A joint study with a faculty member at the Worcester Polytechnic Institute is also underway, to generalize a two-dimensional vortex wake code with no free surface to a three-dimensional code which includes a free surface.

Plans for Next Year's Research: Our planned investigations for next year will be two-fold. We will continue the development of numerical methods for three dimensions, described above, and also continue to study model problems in two dimensions, where we feel we have the numerics well under control.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers Published in Refereed Journals

G. Tryggvason, "Deformation of a Free Surface due to Vortical Flows", to be submitted as a letter to Physics of Fluids, (manuscript available in semifinal form) (1987a).

S.W. Hong, G. Tryggvason and W.W. Schultz, "A Note on the Formulation of Free Surface Problems. An Intregral Equation for Velocity", to be submitted as a letter to Physics of Fluids.

G. Tryggvason, D. Yu and S.W. Hong, "The Surface Signature of an Unsteady Submerged Vortex Sheet", in preparation.

2. Technical Reports

none

3. Presentations

G. Tryggvason, Ship Wake Consortium Workshop, at DTNSRDC, May 2-3, 1987, and at The University of Michigan, Ann Arbor, Sept. 20-21, 1987.

G. Tryggvason, Interaction of Vorticity Density Interfaces, upcoming presentations both at the SIAM Annual Meeting in October and on the APS (Division of Fluid Dynamics) in November).

LIST OF HONORS/AWARDS

none

LIST OF PARTICIPANTS

G. Tryggvason, Professor
W. Graebel, Professor

3.3.3 Nonlinear Waves and Wave Interaction

Principal Investigators: R.F. Beck, C.-S. Yih, A.F. Messiter

RESEARCH SUMMARY

Description of the Scientific Research Goals: The primary research goal is to develop analytic techniques which may be used to study hydrodynamic processes that occur in the wake of a ship. Particular emphasis is being placed on free surface flows and their interaction with the viscous wake.

During the first year two problem areas were investigated. The first was the propagation of gravity waves over a nonuniform stream. This is the process which is involved in the modification of the Kelvin wave pattern by the vicous wake. The second problem area was the study of wave/wave interactions. Using perturbation methods, the nonlinear interactions between waves of widely different time and or length scales was investigated.

Significant results of the past year: Using a ray type theory, Yih and Zhu (1987) developed formulas for the far field, constant phase lines behind a moving disturbance. The method is general and was applied to deep-water surface waves, surface waves in water of finite depth, and internal waves. Finally, the patterns of the surface waves in deep water created by a moving body are determined, with the nonuniformity of the mean velocity of the fluid in the wake taken into account. The vorticity in the direction along the phase lines is shown to be small, so that the wave motion can still be assumed irrotational in a first approximation . The wave patterns differ from the Kelvin-wave pattern, as a result of the nonuniformity of fluid velocity in the wake. In particular, the transverse waves show a pronounced V slope due to the retarded flow in the viscous wake.

In the second problem area, a Ph. D. thesis entitled "A singular perturbation analysis of the weakly nonlinear evolution of long and short water waves and waves in boundary layers," supported in part by the URI, was completed by Stephen L. Woodruff in August 1987. The thesis describes the development and application of a novel method for the solution of multiple-scale problems, as a possible alternative to conventional multiple-variable methods. One of the two primary areas of application discussed in the thesis concerns the two-dimensional weakly nonlinear interaction of short gravity-capillary waves and long, fully nonlinear gravity waves (the other area concerns weakly nonlinear boundary-layer stability and the possibility of active boundary-layer control). The results include a nonlinear second-order partial differential equation (of the Ginzburg-Landau type) for the slow changes in a short-wave packet as it moves over the long waves. Solutions obtained in special limiting cases were shown to agree with those found by others.

Two publications have resulted from Woodruff's work. Woodruff (1987a) describes the method and does simple example problems. Another paper, concerning the applications of the method to interactions of surface wave problems, is currently being prepared for submission to JFM by Woodruff and Messiter (1987b).

Plans for Next Year's Research: Several additional applications of Woodruff's method appear to be fairly direct, and will be explored briefly or in detail, depending on the difficulties encountered and the prospects for useful results. Currently an extension to capillary blockage is being considered, both to reproduce results of others and to obtain new information. Anticipated three-dimensional extensions include interactions where a short wave propagates obliquely relative to a long wave or propagates across a mean current. Stability questions, concerning possible growth or decay of short waves moving over long waves, will also be considered, in relation of course to the existing literature.
The method should also be applicable for studying effects of surface contamination with concentration

varying slowly relative to short-wave scales. Finally, we would like to make a tentative beginning toward an analytical formulation for interaction of short surface waves with large-scale wake turbulence; this will be more difficult, and represents a possible long-range goal rather than a one-year study.

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers Published in Refereed Journals

Woodruff, S. L. (1987a). The use of an invariance condition in the solution of multiple-scale problems. Submitted to the SIAM Journal of Applied Mathematics.

Woodruff, S. L. and Messiter, A. F. (1987b). Interaction of long and short water waves. Manuscript in preparation.

Yih, C-S. and Zhu, S. (1987). Patterns of ship waves. Accepted by Quarterly of Applied Mathematics.

2. Technical Reports

none

3. Presentations

none

LIST OF HONORS/AWARDS

none

LIST OF PARTICIPANTS

R. F. Beck, Professor
A. F. Messiter, Professor
C-S Yih, Professor
S. Woodruff, Ph.D. student, graduated August 1987
S. Zhu, Ph.D. student

American Physical Society Bulletin
November, 1987

Digital Image Analysis Technique for Speckle Velocity Measurement

by

Assistant Professor Luis P. Bernal
Ph.D. student, Jung T. Kwon
B.S.E. graduate, John D. Wolter
Department of Aerospace Engineering
The University of Michigan

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 512 x 512 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%.

Interaction of an Axisymmetric Turbulent Water Jet with the Free Surface

by

Graduate student, Koorosh Madnia
Assistant Professor Luis P. Bernal
Department of Aerospace Engineering
The University of Michigan

A turbulent round jet moving parallel to the water surface is being investigated experimentally. Shadowgraph flow visualization was used to observe the surface motion at several jet exit velocities and depths. A region of strong interaction was observed where the jet reaches the free surface. In this region surface waves are generated at sufficiently high jet exit velocity for a fixed depth. These waves tend to propagate along preferred directions. Simultaneous visualization of jet fluid and surface motion indicated that the waves are generated by the underlying large scale structures of the jet. Downstream of the region of strong interaction the turbulent jet flow disturbs the free surface causing a characteristic surface motion. Time traces of the surface curvature fluctuations and their power spectra have been used to characterize the surface motion.

Proceedings of the 17th Symposium on Naval Hydrodynamics
August, 1988

Interaction of a Turbulent Round Jet with the Free Surface

by

Assistant Professor Luis P. Bernal
Graduate student, Koorosh Madnia

Initial work on the interaction of the free surface with turbulent shear flows has focussed on the interaction of the free surface with a turbulent round jet moving parallel to the surface. A new water jet facility was built to study this interaction as a function of the jet initial depth, jet exit diameter and jet momentum. The facility features automatic water level control and excellent optical access for laser diagnostics and flow visualization. Flow visualization experiments by laser induced fluorescence and shadowgraph techniques are being used to determine the main features of the interaction between turbulent jet and the free surface. Preliminary results indicate that for a given flow geometry at a sufficiently high jet momentum surface waves are generated by the interaction. Furthermore, these flow visualization pictures strongly suggest that these waves are caused by the large scale vortical structure of the jet. In some cases the waves are observed to propagate along preferred directions (±60°) relative to the jet direction.

AIAA Student Conference
April, 1987

Measurement of In-Plane Fluid Motion Using Laser Speckle Photography

by

B.S.E. graduate, John D. Wolter
Department of Aerospace Engineering
The University of Michigan

This paper describes a non-invasive image analysis method of measuring in-plane fluid motion by laser speckle photography. An image is generated by passing a laser beam through a double exposure laser specklegram of the flow field. This image consists of a random speckle interference fringe pattern superimposed on a random speckle field. The magnitude and direction of the local fluid motion is derived from the separation and orientation of the fringes. The image is directly magnified and digitized using a Newvicon camera. The random speckle pattern is removed from the digital image by averaging in the direction of the fringes. Then the separation and orientation of the fringes is obtained from the correlation coefficient between images shifted along the coordinate axes. This method will be used for velocity and vorticity measurements in fluid flow fields. It has been demonstrated using a solid rotating disk. Results of this experiment and accuracy of the technique are discussed.

Journal of Computational Physics

Solution of Potential Problems Using a Overdetermined Complex Boundary Integral Method

by

Ph.D. student, Seok Won Hong
Assistant Professor William W. Schultz
Department of Mechanical Engineering and Applied Mechanics
The University of Michigan

The advantages of solving potential problems using an overdetermined boundary integral element method are examined. Representing a two-dimensional potential solution as an analytic complex function and discretization of Cauchy's theorem gives rise to two algebraic systems: the real and imaginary parts. Depending on which boundary condition is prescribed, the real or the imaginary algebraic system is diagonally dominant. Computations show that the errors of strong system (diagonally dominant) often have almost the same value as those of weak system (diagonally non-dominant) with opposite sign. The overdetermined system (composed of the combination of the real and imaginary part) tends to average these errors. An error analysis and convergence studies for several geometries and solutions are performed. A methodology for handling computational difficulties with contour corners is outlined.

Physics of Fluids

An Alternative Form of Complex Boundary Element Method for Nonlinear Free Surface Problems

by

Ph.D. student, Seok Won Hong
Assistant Professor William W. Schultz
Professor William P. Graebel
Department of Mechanical Engineering and Applied Mechanics
The University of Michigan

A complex variable boundary element method is developed for potential flow problems by applying Cauchy's integral theorem to complex velocity. The resulting integral equation is given as a function of normal and tangential velocities on the boundary. A new form of full nonlinear dynamic free surface boundary condition is derived as a function of normal and tangential velocities.

The main advantage of the present method over the conventional potential method is that it can easily handle the case of the flow with field (free) singularities such as vortices and sources. Also, the present method gives the velocity field directly without doing any numerical differentiation. On the other hand, the dynamic free surface boundary condition becomes slightly complicated.

Quarterly of Applied Mathematics, 1987

Patterns of Ship Waves

by

Professor Chia-Shun Yih
Ph.D. student, Songping Zhu
Department of Mechanical Engineering and Applied Mechanics
The University of Michigan

Patterns of water waves created by a moving disturbance representing a moving body, floating or submerged, can be found by applying (1) the principle of stationary phase, (2) the principle that the phase lines are normal to the wave-number vector, and (3) the perception that the local phase velocity of the waves must be equal to the component of the velocity of the disturbance normal to the phase line. The three equations thus obtained are solved, and formulas for the phase lines are derived, which depend explicitly on the dispersion equation, and on that equation only. These formulas are applied to deep-water surface waves, surface waves in water of finite depth, and internal waves to obtain the wave patterns sufficiently far from the moving disturbance.

Finally, the patterns of the surface waves in deep water created by a moving body are determined, with the nonuniformity of the mean velocity of the fluid in the wake taken into account. The vorticity in the direction along the phase lines is shown to be small, so that the wave motion can still be assumed irrotational in a first approximation. The wave patterns differ from the Kelvin-wave pattern, as a result of the nonuniformity of fluid velocity in the wake.