REVIEW OF RESEARCH
AT THE INSTITUTE

ACCELERATED FLOWS

Motivated by problems encountered in shock absorbers, a research effort which lasted almost 10 years was concentrated on the hydrodynamics of rapidly accelerated liquids. At the time the investigation was started, only calculations based on incompressible fluid flows had been developed. Based on the trends shown by experimental records, a first analytical method was set up which would take into full account the compressibility of the hydraulic fluids used in the shock absorbers. This method proved to be very accurate, but also extremely complicated, except for simplified situations (Reprint 175). A simulation of the accelerated flow of the compressible liquid was therefore based on the hypothesis that except for extremely rapid phenomena, the wave propagation would be unimportant. The compressibility was not eliminated, however, but was incorporated only in the continuity equations (IIHR Misc. Paper by Macagno and Ho, 1962; Report 113). The results for realistic impulse-time diagrams were in satisfactory agreement with the more exact theory and with the experimental records.

For a shock absorber in which a steel spring was included, a hydraulic analogy was used to develop a model for the spring, which was known to be subject to severe loading conditions for which the coils would coalesce into a solid mass. The model was confirmed by laboratory experiments. The results of these last studies have been described in detail only in laboratory reports (IIHR Reports 112, 113).

BIOMECHANICS

Among the Institute endeavours in the area of Biomechanics, the hydrodynamics of flow in the lower urinary tract is presently the subject of a joint research effort with the Department of Urology of the College of Medicine (Report 122). In a different field, a study of swimming, jointly with the Department of Physical Education, is now getting under way.

For the past two years an investigation of the fluid mechanics of the human small intestine has been conducted by personnel from both the Institute and the College of Medicine. This project had its origins in a
general interest in biologically related fluid-mechanics problems and preliminary studies at the Institute of possible pumping mechanisms similar to those found in biological systems. The scope of this research has been narrowed and it is now supported by grants from the National Institutes of Health.

There are currently two main facets to this project. The first is an investigation of the movement of the wall of the small bowel. This involves studies of the size and shape of contractions as well as their distributions in time and space. The second, and more important to the Institute, is a description of the relationships between these contraction patterns and the resulting flow of the intestinal contents. This is being studied both analytically and experimentally. A computer-operated model of the small bowel has been constructed. The model can be controlled to simulate various contraction distributions, while the resulting transport and dispersion are studied.

Results to date include an estimate of the minimum length of contractions. The frequency distribution of contractions, as well as the joint frequency distribution of groups of contractions with rest periods, also have been obtained, by Christensen, Glover, Macagno, Singerman and Weisbrodt. Preliminary model studies have been conducted using single contraction and pseudo-random and simulated peristaltic contraction patterns, with the resulting fluid motion being observed. Future studies will involve the statistical spatial distributions of contractions. A detailed model study will also be undertaken, accompanied by a matching analytic model.

**Boundary-Layer Studies**

Studies of flat-plate boundary layers in the previous decade culminated in a reanalysis of flat-plate boundary-layer data by Landweber (Reprint 182), and an attempt to resolve a controversy concerning the calibration of Preston tubes. Following this work, and that on the effect of transverse curvature by Yu (Reprint 161), some three-dimensional boundary-layer measurements were undertaken. These consisted of shear stress and velocity-distribution measurements on an ellipsoid of three unequal axes, by Pavamani (see M.S. thesis).

For most of the remainder of the decade boundary-layer studies were displaced by investigations of wakes and jets in the wind-tunnel facility. In 1969, however, the facility once again became available for boundary-layer research, and a study of the thick boundary layer at the tail of a body of revolution was undertaken by Landweber and Satija (see 1971...
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Ph.D. dissertation). Several procedures for computing three-dimensional boundary layers have been proposed, some of which have been applied to calculate ship boundary layers. Some of the assumptions of these procedures were reviewed by Landweber in the paper "Characteristics of Ship Boundary Layers", presented at the Eighth Symposium on Naval Hydrodynamics (IIHR Misc. Paper, 1970), and were found to be inconsistent with Pavamani's data mentioned above, as well as the available data on ship forms. The frequently employed small-cross-flow assumption is inconsistent with the generation of secondary flow and the occurrence of separation along the hull at the free surface discovered by Chow (see Ph.D. dissertation) and verified by Tzou (see M.S. thesis), and with the generation of the so-called bilge vortices near the bow, investigated by Tatinclaux (Reports 102, 107, 117, Reprint 270).

Cavitatin

Studies of cavitation have proceeded along the lines of a number of earlier investigations. Bulletin 32, a postwar report on cavitation around various torpedo head forms at zero yaw, was supplemented by Bulletin 42, describing tests on many of the same head forms at various angles of yaw. The relation between cavitation and pressure fluctuation was determined for flow around bodies by Newsham (see M.S. thesis) and through conduit expansions (Reprint No. 204).

Classical Papers in Fluid Mechanics

By special arrangement with the French journal, La Houille Blanche, a series of selected works of classical authors is being published. The series is directed by Professor E. Macagno, who represents the Institute. Mr. Valembois (Chatou National Laboratory of France) is the French counterpart in the selection of authors to be included. Landmarks in dimensional analysis due to Fourier and Vaschy have already been published, matched by those of Galileo and Newton in similitude theory. Theoretical works have been represented so far by excerpts from Euler, Navier and Stokes, while experimental contributions of permanent classical value comprise publications due to Pitot and Smeaton.

The titles of the classical papers published in La Houille Blanche are listed in this Bulletin (p. 173).

Computational Modeling of Viscous Flows

Because sudden expansion presents the most striking situation of internal flow separation, both two-dimensional and axisymmetric flows through
expansions have been investigated numerically. Complete forms of the Navier-Stokes equations were treated by numerical techniques based on the discretization of the equations. The captive annular eddy, resulting in the case of flow through an axisymmetric expansion, was studied in great detail, and the results of the calculation were compared with flow visualizations; the agreement between the analysis and the experimental result was very striking.

A second effort in this area referred to accelerated flows of viscous fluids through expansions; a third concerned the flows generated by moving a wall in a rectangular domain, or rotating a base in a region of fluid confined within a circular cylinder. An application was made to a case in which the fluid possessed a continuous density stratification.

**Density-Stratified Flow**

The first studies of flow of fluids with density stratification were undertaken at the Institute during World War II. In the past decade the emphasis was mainly on flows with mass transfer which resulted in irreversible mixing. An investigation on the interfacial instability and on the subsequent mixing of two fluid layers of different density was carried out by Macagno and Rouse (Reprint 173). The thickness of the mixing zone and the rate of mass transfer across the interface were investigated as the Froude and Reynolds numbers of the flow were varied.

The stability of an enclosed stratified flow in the region of flow establishment was also found to depend on the Froude and Reynolds numbers of the flow. Macagno and Hinwood studied experimentally the interfacial instability and the subsequent mixing of the two fluids, which flowed from a large reservoir into a rectangular duct (Reprint 192). Hinwood developed a numerical simulation of this phenomenon, based on complete forms of the Navier-Stokes equations (Ph.D. dissertation, Reprint 241).

The behavior of a stratified fluid system, otherwise at rest, when a transverse flow cutting across the isopycnic lines is induced in the field, has been the subject of two investigations: Alonso (see M.S. thesis) studied experimentally the free-surface rotationally symmetric flow developed in a continuously stratified fluid contained in a cylinder with a rotating bottom; Aguirre-Pe (see M.S. thesis) extended this investigation to the case of a two-layered system. (See also paper by Aguirre and Macagno, 1969).

The flow in a rectangular cavity with a fluid with uniform density
gradient was studied by means of numerical models, which would reproduce only the initial phases of the flow, as was confirmed by experiments. A study which referred to the mixing induced by the secondary flow in a 90° curve in an open channel was also completed during this decade.

In many estuarine harbours, under certain flow conditions, the ocean salt water flows upstream for an appreciable distance and forms a wedge of salt water underlying the river water. This salt-water wedge may greatly affect the pattern of sediment deposition in an estuary. This process was the object of an experimental study carried out by Hinwood, while working at the University of New South Wales (Reprint 196).

**Environmental Fluid Mechanics**

New areas of research at the Institute have developed in response to the growing national concern over the deterioration of the natural environment. The Federal Water Quality Administration has sponsored experimental studies on longitudinal dispersion and lateral mixing in meandering channels (see 1971 Ph.D. dissertations by Fukuoka and Chang). Various aspects of stratified flows have been investigated by Macagno, Rajagopal, and Alonso; they studied internal hydraulic jumps and stratified flow in a channel bend.

In the area of thermal pollution, the Marley Company has for several years sponsored an investigation on the performance of induced draft cooling towers, with particular emphasis on eliminating recirculation and optimization of the geometrical arrangement of clusters of cooling towers. The National Science Foundation and the Iowa State Water Resources Research Institute are supporting a basic investigation of the mixing of heated effluents in open-channel flow. More recently a thermal model study of the proposed condenser-cooling-water outfall system for the Quad Cities Nuclear Power Plant has been undertaken. Related to this is a field study on the effect of thermal discharge from the Quad Cities Plant on the distribution of temperatures and ice thicknesses in the Mississippi River.

An extensive thermal model study for the Commonwealth Edison Company of the cooling-water discharge system for the Quad Cities Nuclear Power Plant is currently underway. The originally proposed scheme, which involved the use of a wing dam as a training wall, was tested in a model of a reach of the Mississippi River and found to be unsatisfactory. This led to the design and testing of a diffuser pipe system, which involves two 16-foot-diameter pipes, with multiple ports,
that extend nearly across the Mississippi River. Dr. Jain, Professors Kennedy, Sayre and McDougall, and Dr. Akyeampong have all been heavily involved in this project.

Related to the Quad Cities Nuclear Power Plant study is a field study of temperature and ice conditions in the reach of the Mississippi River to be affected by the thermal discharges from the plant. This investigation is under the joint direction of Professors Sayre and Kennedy.

The processes by which heated effluents are mixed with an ambient open-channel flow are being investigated in basic research studies sponsored by the National Science Foundation and the Iowa State Water Resources Research Institute. The main study objective is the region, downstream from the initial mixing zone, where ambient turbulence and velocity distribution play a key role in the mixing process. Professor Sayre is in charge of this investigation.

**Educational Films on the Mechanics of Fluids**

Near the beginning of the decade, with the aid of a grant from the National Science Foundation, the Institute undertook the preparation of a series of six motion pictures for use in teaching fluid mechanics to undergraduate engineers. The project was conceived and supervised by Hunter Rouse; he was assisted by members of the Institute staff and
that of the Audiovisual Center of the University. Particular mention is due Lucien Brush, who collaborated on the first three films, and Emmett O'Loughlin, who did most of the camera work on the last three.

The six films are as follows: *Introduction to the Study of Fluid Motion*, which stresses the great breadth of the subject, the necessarily close tie between theory and experiment, the role of the scale model in engineering analysis and design, and methods of flow measurement in laboratory and field; *Fundamental Principles of Flow*, including continuity, momentum and energy, and their application to typical problems in many professional fields; *Fluid Motion in a Gravitational Field*, which deals with jets, nappes, channel transitions, waves, surges and effects of density stratification; *Characteristics of Laminar and Turbulent Flow*, showing effects of viscosity, examples of laminar flow, characteristics of fluid turbulence and problems of surface resistance; *Form Drag, Lift, and Propulsion*, stressing phenomena of separation, their influence upon profile lift and drag, and application of the latter to principles of fluid machinery; *Effects of Fluid Compressibility*, such as water hammer, gravity-wave and sound-wave analogies, and supersonic drag.

All films are 16-millimeter, in full color, and carry an optical sound track. Their average length is some 20 minutes. An illustrated copy of the script accompanies each print; these films may be rented from The

Figure 12. Frame from educational film comparing the rheological behavior of fluids.
University of Iowa Audiovisual Center or purchased singly or together. To date 321 prints of one or another of the six films have been purchased by 114 institutions in 29 different countries. In several countries foreign-language sound tracks have been added magnetically to the films for alternative use.

Figure 13. Frame from educational film showing streamlines at an airfoil tip.

Hydrology

The recession characteristics of Iowa streams were studied by J. W. Howe late in the decade (Bulletin 43). The investigation was undertaken to help the State Water Commissioner predict the low-water flow of streams subject to minimum-flow regulations. Low-water periods from May to September were studied on all rivers having flow records with a recession period of 10 days or more in length. Recession constants were calculated at all stations and plotted on state maps for the different months. The variation in coefficients in large regions was small. A study was also made on the flow at the beginning of such recession periods, multiple correlations being made with area, preceding precipitation, mean air temperature and soil characteristics. Correlation coefficients varying from 0.95 to 0.97 were obtained with standard errors of estimate ranging from 0.25 to 0.59. Antecedent rainfall was found to have an extremely small effect; it could be eliminated from the regression equations with but slight modification of the exponents of
the other parameters. The project was financed by the Iowa State Water Resources Research Institute.

The Ralston Creek hydrologic data-gathering project has been in continuous operation since June 1924. In the past decade, however, the south branch was put under observation by the U.S.G.S., who installed a control and recording gage at Muscatine Avenue in east Iowa City. The area above this gage was three square miles, the same as the area above the gage on the north branch. Thereafter, the Agricultural Research Service, noting the rapid spread of urbanization on the south branch, asked that rainfall observations on the south branch be collected, as has been done on the north branch. Accordingly, three recording rain gages were placed at points in the south branch drainage, so that a good coverage of rainfall on both branches could be secured. It happened that two of the rain gages on the north branch were on the divide between the two branches. These gages, thus, adequately covered both basins. This made it possible to put the new gages south of the stream itself, giving rather uniform Thiesen polygons for the entire area. The new gages went into operation in June 1967. In January 1971 the Weather Bureau agreed to publish the records of the three new rain gages, along with those on the north branch, so that, in the latter years of the decade, the flow and rain gage records are published by the U.S. Geological Survey and by the U.S. Weather Service in its monthly bulletins. The Institute's annual report includes the full spectrum of data beginning with 1967.

With the new coverage, a policy of securing annual photographs from a number of vantage points was initiated, and each May pictures are taken from identical locations looking across the valley. This gives a pictorial record of the increasing urbanization of the area. Pictures were also started on the north branch, in those areas where urbanization seemed likely. The annual reports contain 36 such pictures.

Ice Research

The Institute's ice research program began in 1968, when a grant was received from the National Science Foundation for construction of a recirculating flume housed in a temperature controlled environment (see Research Facilities). Design and construction of the facility, both carried out by Institute staff, required approximately 18 months. Research utilizing the facility began in early 1970.
THE FIRST HALF CENTURY

Figure 14. Recirculating flume in low-temperature facility.

Figure 15. Inverted ice slab showing ice ripples

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During the winter of 1969-70 a program of field research was conducted on Cedar River and Iowa River. Vertical and lateral temperature and velocity distributions, and ice thickness and configuration, were measured at frequent intervals during the ice season. The vertical variation of temperature was found to be extremely small, while lateral variations across the river channel frequently amounted to as much as 0.1°C. These lateral variations apparently resulted from geothermal input in the form of ground-water flow. The under surface of the ice

Figure 16. Model of ice jam development using square wooden blocks.
was observed to remain plane as the ice thickened and to become wavy as the ice melted. Just prior to breakup the ice cover was observed to become very porous over its lower reaches. Ice melting was found to proceed more rapidly from below than above.

Two other investigations of ice were also initiated in 1969. The first was directed toward the mechanics of ice jams, while the second involved a theoretical investigation of the stability of the interface between an ice boundary and a turbulent flow.

![Figure 17. Ice breaker and navigation channel on Mississippi River.](http://ir.uiowa.edu/uisie/44)

**INSTRUMENTATION**

Electronic instrumentation during the past decade made the transition to a computer-based system. Transducer, signal-conditioning elements and specialized instruments, such as the hot-wire anemometer, are still as important as ever in supporting experimental research at the Institute. Now, however, they operate in conjunction with a digital computer, in order to permit more sophisticated analyses and faster reduction of experimental data. This latter capability permits the study of problems heretofore not possible, simply because of the effort needed to process the data.
The computer system is an IBM 1801 Data Acquisition System which operates in a time-sharing environment under control of IBM's TSX system. Process and control programs reside on disk and are queued for execution by an interrupt process. Signals from any of the instruments in the laboratory are connected to the computer through either a 32-point solid-state multiplexer or a 48-point relay multiplexer. Various multiplexer points are assigned to different locations in the laboratory, thereby providing access to the machine for many users.

Examples which illustrate the flexibility and advantage of the system include experimental studies which range from the processing of data representing contractions in the small intestine to the measurement of temperature in studies of thermal pollutants in rivers. A study in conjunction with the small intestine research is the computer operation of a model simulating flow conditions in the small bowel. The model is controlled by processed data obtained from volunteers who have swallowed specially designed transducers for recording contractions of the wall of the intestine.

The study of thermal-pollution effects in rivers is related to a problem of local concern. A nuclear power plant is being built at Cordova, Illinois, by Commonwealth Edison Company of Chicago and Iowa-Illinois Gas and Electric Company of Rock Island. When the unit is completed it will discharge as much as 2,270 cfs of heated water 23°F above ambient into the Mississippi River. Several models have been constructed at the Institute to study various aspects of thermal problems. Thermistors are used to measure the temperature at many different points in the models, and calibration and processing programs which compute temperatures and ratios of temperatures directly are executed on command.

Two new instruments which have been developed and which are extensively used with the computer are a multi-channel conductometer for measuring salinity concentrations in laboratory flumes and an electro-optical system for measuring mean and statistical properties of sediment suspensions. Conductivity rather than resistivity is measured to eliminate non-linear concentration-voltage relationships and special circuits were designed to reduce channel-to-channel influence and sensitivity to extraneous grounds. The electro-optical sediment instrument was developed for in situ measurement of suspended-sediment concentrations in alluvial channel flows. The transducer for the system consists of a P-N gallium arsenide diode as light source and an N-P-N planer silicon
phototransistor as light sensor. The source light detected by the light sensor is modulated by the suspended sediment in the gap between the source and sensor. The amplifier for the sensor output has been combined on one chassis with signal-analyzing circuits, which include an analog-to-frequency converter and multiplier. The resulting system is capable of measuring suspended-sediment concentrations down to 100 ppm, and can compute the mean concentration, the mean square of the concentration fluctuations, and the correlation between sediment con-

Figure 18. Control panel of the Institute's IBM 1801 computer.

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centrations and another signal supplied to the system.

Techniques for detecting turbulence and converting the resulting signals to a form suitable for analysis were an important phase of the Institute's operation for most of the first half century. Early work included turbulence measurements in the Mississippi River by A. A. Kalinske, using a midget current meter which could respond quickly to the secondary fluctuations. Recordings from this meter were reduced by hand to obtain values of the mean and fluctuating velocities at various elevations in the river. Several promising techniques were studied, including measurement of the forces upon submerged obstacles, such as very small spheres, and the diffusion of various substances (heat, dye, suspended particles) as a function of space downstream from the point of introduction.

One of the methods studied in the late 1940s was the Hot-Wire Anemometer. Its small size, very fast response and desirable directional characteristics were unmatched by any other technique. For gases, it was equally effective for measuring mean velocities or fluctuations and was readily linearized through electronic circuitry to yield signals which were directly proportional to the components of the velocity. In liquids, however, solid impurities tended to collect on the wire, so that its usefulness for mean velocities was substantially reduced. It worked reasonably well in clean water or other liquids, and special insulating coatings also improved the performance. This improvement, however, was at the expense of the extremely rapid response which marked the performance in air or other gases.

Techniques and equipment for analyzing the signals were developed simultaneously with the instruments for detecting the velocity components. Early instruments used heavily damped ammeters for recording mean velocities and thermal meters for determining the root-mean-square values of the fluctuations. At an intermediate stage of development, analog-to-frequency converters were used in conjunction with electronic counters to obtain mean values, and semiconductor devices were used to obtain instantaneous products of the various components of the fluctuations. The most recent instruments rely upon multiple-channel sample-and-hold amplifiers as interface components to the analog-to-digital converters. From this point the analysis could be accomplished by special-purpose digital computers.

Turbulent fluctuations in pressure were also the subject of intensive research, and several instruments were produced in which strain-gage
or crystal detectors were placed inside of a flat surface or a streamlined headform connected through small piezometric openings to the flow. As might be expected, these instruments could not be reduced to the very small size of hot-wire anemometers and, as a consequence, were useful only in larger systems. Signals from these transducers were analyzed using the instruments which had been developed for hot-wire anemometers.

Irrotational Flow

The methods of potential theory have been found useful in a variety of practical problems. These include the vibration of bodies in a liquid, the conformal mapping of ship sections and the determination of the flow about bodies moving through a fluid.

A method for mapping a ship section accurately into a circle is needed both for calculating the added mass of a vibrating ship and in a procedure for obtaining a parametric pair of equations of a ship form. A method, taking advantage of the maximum area property of the circle, developed by Landweber and Macagno (Reprint 227), was compared with other methods by Macagno (Reprint 247). When it was found that the area method failed for certain sections, another procedure, based on the Gershgorin integral equation, was developed by Landweber ("Mapping of Ship Sections," Seventh Symposium on Naval Hydrodynamics, Rome, 1968).

In calculating the natural frequencies of a vibrating ship, a strip method which uses the two-dimensional added-mass coefficients at each transverse ship section with three-dimensional overall corrections, is usually employed. The aforementioned development of methods of mapping ship sections, from which the added-mass coefficients can be directly obtained, was motivated by this problem. Three-dimensional correction coefficients, derived from studies of the irrotational flow about spheroids, were reported by Macagno and Macagno (Reprint 171) and by Matilde Macagno (IIHR Misc. Paper, 1963). It was then suggested by Landweber (IIHR Misc. Paper, 1963) that the vibration frequencies could be obtained by combining the kinetic energies of the vibrating body and the fluid as a single quadratic form and calculating the eigenvalues of the potential energy matrix of the elastic body with respect to the kinetic energy matrix. This essentially replaced a diagonal matrix composed of the sectional added masses with a nondiagonal matrix. Trials of this method were reported by Warnock (Ph.D. thesis), Pita (Ph.D. thesis) and Landweber (Reprint 231). An application to a
vibrating body of revolution, given by Landweber (Report 111), will be published in modified form in the *Journal of Ship Research*, 1971.

The irrotational flow about a body can be expressed in terms of a vorticity distribution on its surface. For bodies of revolution in arbitrary states of translational and rotational motion, three basic Fredholm integral equations of the first kind were formulated and applied to obtain the pressure and velocity distributions of the DTMB Series 58 family of bodies of revolution (NSRDC Report 2505, 1967). A procedure for determining the vorticity distribution for arbitrary three-dimensional forms was included in the paper, "Characteristics of Ship Boundary Layers," by Landweber at the Eighth Symposium on Naval Hydrodynamics (IIHR Misc. Paper, 1970).

An alternative means of representing the irrotational flow about a form assumes a distribution of sources on the surface. The Fredholm integral equation of the second kind for determining such a distribution was treated by Landweber and Macagno (Report 123) for the case of a ship form, taking into account the presence of a free surface.

When a free surface is present, one usually treats the problem by linearizing not only the free-surface boundary condition, but also that on the surface of the body. An investigation by Farell of the flow about a spheroid near a free surface, in which the boundary condition on the surface of the spheroid is satisfied exactly, showed that the errors due to linearization of the boundary condition could be large (Ph.D. dissertation). Measurement of the total and viscous resistance of a spheroid (employing the wake-survey technique for the latter measurements) by Güven (M.S. thesis) have partly confirmed the analytical results. The analysis has also yielded values of the added mass of a spheroid moving near the free surface (to be published in the *Journal of Ship Research*).

An application of the Lagally theorem and the method of source images, by Landweber and Macagno (Reprint 194) yielded expressions for the image system within a spheroid and the hydrodynamic force acting upon it in an arbitrary axisymmetric potential flow. In a sense these results extended the *sphere theorem* for irrotational flow. For non-axisymmetric flows the image system was found to include series of multipoles. Consideration of these led to a generalization of the Lagally theorem for multipoles by Landweber (Reprint 225).

Three significant doctoral dissertations have involved the solution of potential-flow problems through refined combination of analytical and numerical (digital-computer) methods. That by Strelkoff yielded the
pattern of flow over a vertical sharp-crested weir ranging from zero to infinite head-height ratio. That by Cassidy dealt with the pattern of flow over a spillway of arbitrary profile curvature. Finally, that by Hunt superseded the earlier relaxation study by Abul-Fetouh of the axisymmetric jet from an orifice in the wall of a large tank.

**Jets and Wakes**

In connection with the then-new field of ground-effect machinery, a series of basic studies were undertaken with the support of the ONR.

![Image of wake](http://ir.uiowa.edu/uisie/44)

*Figure 19. Smoke study of the wake of a spheroid showing alteration of the wake due to the proximity of a boundary (lower photograph)*

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These included: (1) a stationary annular jet impinging against a rigid ground plate; (2) an annular jet impinging against a rigid ground plate in the presence of an ambient flow; (3) a stationary annular jet directed against a water surface; and (4) an annular jet traveling over water. (See Malsy M.S. thesis, Mack-Malsy 1960 report to ONR, Yen 1962 report to ONR.)

In connection with the use of expansion chambers for energy dissipation, tests were made in a series of pipe expansions of varying diameter ratio, including the jet in a semi-infinite fluid as the limiting case. The tests included both cavitation prediction and vibration evaluation. (Reprint 210.) In 1966 Rouse was invited to give a Freeman Lecture before the Boston Society of Civil Engineers; this reviewed the many Institute investigations of submerged jets. (Reprint 216.)

Figure 20. Pattern of flow past a stationary pair of bars of different heights (upper) and the pattern of eddies produced by a moving pair of bars (lower).
Wake studies have emphasized the analogy between flow around bodies and flow through conduits of comparable geometry, with particular emphasis upon the eddy patterns in zones of separation. (Reprints 170, 181.) Doctoral dissertations in this field included those by Carmody, on flow past a disk; by Chaturvedi, on flow in expansions; and by Narasimhan, on flow at conical afterbodies. (See also Reprints 197, 187.)

In a 1962 paper (Reprint 179) Rouse extended the Bernoulli theorem to conditions of turbulent flow, especially in zones of separation. Four cases were evaluated by Chevray (see M.S. thesis) and covered further in Reprints 198, 205 and 265. Chevray also measured turbulence characteristics in the wake of a body of revolution (see Ph.D. dissertation) as had Chen and Gear several years earlier (see M.S. theses). These were related to studies on wakes with zero momentum flux (see M.S. thesis of Caruso, and Ph.D. dissertations by Ridjanovic and Wang).

A numerical study of wake deformation has determined the collapse shape and internal velocity field of an initially circular homogeneous fluid mass surrounded by a linearly stratified fluid. During the initial stage of collapse the fluid is assumed to be inviscid and the motion irrotational. For the later stages, when viscous effects assume a significant rate, the complete Navier-Stokes equations are solved. The final stage of collapse is analyzed by means of a viscous, long-wave theory. The pressure acting on the boundary of the mixed region is assumed to be hydrostatic throughout the collapse process. A new numerical method is described for obtaining solutions for the complete Navier-Stokes equations in problems involving moving boundaries (see Ph.D. dissertation by H. Padmanabhan and Reprint 268). The technique involves an extension of an approach due to Chorin.

Experimental information on various elementary types of free-turbulence shear flows, mainly on jets and wakes, has become almost as comprehensive in recent years as that on homogeneous turbulence. The flow in the wake of an axisymmetric body with hydrodynamic self-propulsion, a type of free-turbulence flow with widespread practical application, had received little attention in the past, however, and was therefore extensively investigated under the sponsorship of the Office of Naval Research. (Reprint 203, Caruso M.S. thesis, and doctoral dissertations by Ridjanovic and Wang.) Self-preservation hypotheses for plane-symmetric and axisymmetric free-turbulence shear flows were discussed in particular by Naudascher in the light of these data, data by
Ortega (see M.S. thesis) on the turbulent round jet in a coaxial stream, and other published data. (Reprint 203, Reports 106 and 110.) A by-product of these investigations was an analysis of turbulent flow past a grid, as the plane-source counterpart of flows past point and line sources of turbulence (Reprint 269). The effect that a linear density stratification has on the flow past a grid has also been investigated under ONR sponsorship (see 1971 Ph.D. dissertation by Tao).

Figure 21. Development of the eddy pattern behind a sill with increasing velocity.

Non-Newtonian Flows

Work on the analysis of viscous fluids with nonlinear constitutive equations was begun as an Institute project in 1965. The first publication, dealing with unsteady flow of non-Newtonian fluids, appeared in 1966.
Research in this general area was then extended to rotationally symmetric flow, to flow through an expansion, and to stability of plane and axisymmetric Poiseuille flows subject to finite disturbances. The work on flow expansion was based on a power law which would represent shear-thinning and shear-thickening fluids, but for the other investigations a polynomial model was introduced by E. Macagno based on a formulation for the rheological behavior in terms of the invariants of the strain-rate tensor (Reprints 214, 222, 250).

Open-Channel Resistance
Resistance studies for free-surface flow have incorporated those for surface and cross-sectional-shape effects of closed conduits and proceeded therefrom to effects involving various aspects of gravitational action. Surface roughness was the basis of the Roberson and O'Loughlin dissertations (Reprint 199, and IIHR Misc. Papers). Effects of cross-sectional shape were treated by E. Macagno in Reprint 208. Effects of channel non-uniformity were typified by bridge piers (see Hsieh thesis). Apparent resistance changes due to the onset of rollwaves were evaluated for both smooth and rough channels (see Koloseus dissertation and Reprint 185). All of the foregoing aspects of the problem, plus that of channel curvature, were reviewed in a summary paper by Rouse (Reprint 202).

Sediment Studies
Sediment studies continued, as in earlier years, to be directed toward clarification of the mechanics of transport, with the goal of developing more rational predictors for engineering applications. The types of studies conducted may be divided into four principal categories. The first has been concerned with the effects of sediment properties on transport characteristics. Diamandis (see M.S. thesis) found that the range of particle sizes present in the bed material limits the depth of scour, but has no effect upon the non-dimensional profiles. This work was continued by Hannan (see M.S. thesis) who conducted his experiments using two different sediments with the same mean diameter and same standard deviation, but with different skewness of size distribution. Again, the non-dimensional scour profile was found to be independent of both time and skewness. The effect of particle size distribution on the characteristics of the suspended load was considered by Lee (see M.S. thesis), who made systematic experiments using two different
sands of the same mean size and skewness but different standard deviations. The standard deviation of the bed material was found to have a significant effect upon both the mean concentration and size distribution of the suspended load.

The second main type of study has focused upon fluid-particle interaction. The effects of turbulence-induced random velocities on the settling velocities of particles was investigated by Ho (see Ph.D. thesis). His experiments with spheres settling in an oscillating fluid showed that the fluid oscillation reduces particle fall velocity significantly below the quiescent-fluid value. A numerical solution of the equation of motion yielded an estimate of the effect of fluid oscillation on the fall velocity. The relationship between the diffusivities for momentum and sediment has a significant effect on the available theoretical models for sediment suspension. Singamsetti (see Ph.D. thesis) investigated diffusion of sediment particles in a vertical, axisymmetric, sediment-laden submerged jet directed downward into stationary water. The diffusivity for sediment was found to be as much as 20 percent greater than that of momentum. The results were explained on the basis of heuristic arguments concerning the inertial and gravitational effects on the sediment-particle motion.

Practically oriented investigations of scour constituted the third area of research. The study of Chu (see M.S. thesis) was concerned with effectiveness of rock sausages placed over filter layers to protect them from erosive attack. The various types of scour failure possible were observed, and the flow regimes over which each can occur were considered. Scale effects in model tests of rock-protected structures were explored in the M.S. theses of Mehrotra and Chang, in which scour-pocket experiments were made using glass spheres. In each set of experiments the Froude number was maintained constant and the Reynolds number was varied over a considerable range. The minimum value of Reynolds number above which the non-dimensional scour rate is insensitive to Reynolds number was then determined. The rate of scour was found to be extremely sensitive to upstream flow conditions. Chang sought to clarify the role of Reynolds number by measuring the spectra of the velocity fluctuations over a range of Reynolds numbers in a flow over a rigid geometry modeled after a scour pocket. The spectra showed no systematic effects of Reynolds number. The scour investigations were extended to wave-induced erosion by Hulman (see M.S. thesis), who undertook an experimental investigation of raveling of riprap embankments by obliquely breaking waves.
Flow in alluvial channels was the subject of the fourth category of study. In their Ph.D. theses Squarer and Annambhotla considered the relationship between friction factor and the geometrical characteristics of ripples and dunes on the beds of alluvial channels. Squarer’s investigation was conducted in the Institute’s larger, sinuous channel, while Annambhotla used data obtained in a field investigation conducted on the Missouri River near Omaha. Both sought to characterize the bed geometry by means of parameters based on the spectra of the boundary profiles, and both found a strong relationship between bed roughness and a measure of the bed-wave steepness (such as square root of variance of bed-undulation displacement divided by a characteristic wave length determined from the normalized spectrum).
In the past decade a notable development in the field of ship hydrodynamics is the appearance of methods for the separate determinations of the viscous and wave resistance of ship models. By applying the Betz-Tulin theory, viscous resistance can be calculated from measurements of the total-head and pressure distributions in the wake of a ship model. An experimental arrangement and procedure for obtaining and analyzing these measurements were reported by Wu (see M.S. thesis); refinements in the theory of the method were given by Landweber and Wu (Reprint 186) and by Landweber (Proc. Eleventh ITTC, Tokyo, 1966). The basic assumptions of the Betz-Tulin theory were examined by Wu (see Ph.D. dissertation) and Tzou (see Ph.D. dissertation). Application of the method to a Series-60 ship model showed that, contrary to the usual assumption, the viscous drag of a ship model varied in a sinuous way with Froude number (see Landweber and Wu, IIHR Misc. Paper, 1963). One of the basic assumptions, that the wave resistance is unaltered when the rotational wake is replaced by the analytical continuation of the external irrotational flow, was investigated by Tzou (see Ph.D. dissertation) and Landweber (Proc. Twelfth ITTC, Rome, 1969). With the Institute’s acquisition of an IBM 1801 computer and Scanivalve, a motorized device with many pressure nipples for measuring a sequence of pressures in controlled and rapid succession, it became possible to automate the wake-survey measurements and their analysis, as is described by Glover, Tzou and Landweber (IIHR Misc. Paper).

Several methods have been proposed for determining the wavemaking resistance of a ship model from surface-profile measurements. A basic assumption of the theory on which the data analysis is based is that, beyond about a model length downstream, the surface disturbance may be represented adequately by the far-field part of its theoretical mathematical representation. This assumption was examined for a source in a channel by Landweber (IIHR Misc. Paper, 1963) and by Landweber and Tzou (Reprint 243) for a particular source distribution when “transverse-cut” data are analyzed. Application of the method to a modified ogive in a channel by Kobus (see Ph.D. dissertation) showed large discrepancies between the theoretical and measured wave resistances. An explanation of this discrepancy in terms of wavemaking of the vorticity in the wake and a way of correcting the analysis of trans-
verse-cut data for the effect of the wake were given by Tatinclaux (Reprint 264).

On some ship bows there are streamlines which pass downwards and around the bilges to the underside of the hull. Because of the small radii of curvature at the turn of the bilge, a large cross flow may develop in the boundary layer which could give rise to a secondary flow and vortex generation. Such vortices, called bilge vortices, contribute appreciably to the total resistance. Measurements of their strength under various conditions, and estimates of their contribution to resistance were given by Tatinclaux in a series of papers (IIHR Misc. Paper, 1966; Reports 102, 107, 117; Reprint 270).

Figure 23. Ship model underway in the towing tank.

An old ship-model-testing problem is that of correcting ship-model data for the influence of the tank walls, the so-called blockage effect. It has been found that velocity corrections based on irrotational flow and the method of images are inadequate. A study of the pressure on the back face of a hemisphere in a wind tunnel with movable walls by Lin (see M.S. thesis) confirmed that the walls have a large effect on the base pressure. An analytical study by Landweber ("A Note on Blockage..."

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Effect," *Jubilee Memorial, W.P.A. van Lammeren, 1970*) indicated that the body-wall geometry determines the length of the separation bubble which, in turn, mainly determines the pressure at the separation point, and hence on the back face; a practical application of this mechanism was suggested.

**SHIP ROLLING**

Two investigations on ship rolling were completed during the decade. One, on the wavemaking of rolling ship forms by McLeod and Hsieh, verified a theory due to Ursell that a certain form was least desirable from the point of view of roll damping. The other, a study of the mechanism of roll damping due to bilge keels, extended the work by Martin (see Ph.D. dissertation). Ridjanovic (Reprint 174) studied the effect of the aspect ratio of flat plates oscillating normally to their planes; and Tseng (see M.S. thesis) included the effects of a superimposed stream, as well as examining the errors due to linearization in the analysis. It is common practice to employ turbulence stimulation in ship-model resistance tests, but not in ship-rolling studies; although, as shown by Martin, McLeod and Landweber (Reprint 167), turbulence stimulation is necessary in rolling tests, especially for forms without bilge keels.

**SIMILARITY REPRESENTATIONS**

An extensive study of similarity representations in fluid mechanics and related areas based on finite and infinitesimal groups has been carried out by H. J. Woodard and W. F. Ames. These authors presented the paper "Application of Lie Algebra to Similarity Theory," at the Summer 1970 Meeting of the Society for Industrial and Applied Mathematics. A second paper, "Infinitesimal Transformation and Similarity Variables in Fluid Mechanics," and report, "Similarity Solutions for Partial Differential Equations Generated by Finite and Infinitesimal Groups," describe the procedure in some detail for three examples in fluid mechanics.

Ever since the pioneering researches of Boltzmann and Blasius the similarity variable has played an important role in fluid mechanics. Improvement and implementation of a deductive method for determining similarity variables has been underway for three years with the support of the Office of Naval Research. The procedures, based on the theory of finite and infinitesimal groups, have been applied to general boundary-layer problems, nonlinear diffusion and Burgers' model of turbulence. Present studies are being carried out on the Reynolds equa-
tions for turbulent flow. These researches are under the direction of Professor Ames.

**Structural Vibrations**

A series of investigations started at the beginning of the decade contributed to a better understanding of the concepts and mechanisms responsible for flow-induced structural vibrations. (See Reprints 189 and 228.) Among the specific problems studied were the hydrodynamic forces on high-head gates. (See M.S. theses by H. Kobus, R.P.R. Rao, N. Gillisen and C. Farell; and Reprint 193.) The results of these investigations, primarily concerned with hydraulic downpull forces, have become useful in engineering practice for the design of prototype structures.

In addition to the mean force characteristics, the fluctuating components of the induced hydrodynamic loading received considerable attention as well. In particular, studies of vibration during simultaneous overflow and underflow of leaf gates (Reprint 172) and flow-induced vibration of high-head gates (see Ph.D. dissertation by F. A. Locher) should be mentioned, together with a number of investigations of pressure fluctuations as influenced by the geometry of the gate lip. (See M.S. theses by F. A. Locher, J. C. Tatinclaux, Y. Chu; and Reprint 234.) In conjunction with these studies, an investigation of the pressure fluctuations on low ogee-spillway crests was also conducted. (Report 130.)

A by-product of these investigations of flow-induced forces was a study of the effects of confining walls on the periodic wakes of cylinders and plates. (See M.S. theses by C. Farell, A. Toskas and Y. Chen.)

**Unsteady Hydraulic Phenomena**

Due to the special interest in Latin America on pressure waves in conduits and effects in surge-tank installations, the course Hydraulics of Unsteady Phenomena was open to special work in this area by students from that continent. This resulted in a number of papers by those students and their professor presented at the regional congresses of the IAHR in Latin America; and in the publication of a monograph on control of pressure waves in systems of conduits; plus a volume of notes on pressure waves, which were published by Federal University of Paraná (Brazil) and the Central University of Venezuela.
Waves Breakdown

Research on the breakdown in solutions of nonlinear wave equations has been completed and published by W. F. Ames (Reprint 257). The method is applied to a variety of problems, including the transonic flow of a gas, gas dynamics, shallow-water waves and transmission lines. When applicable, the procedure is simple to use, as compared with the unfolding method of Riemann invariants.
GRADUATE DEGREES

Following the granting of the first master's degree in 1922, over five hundred advanced degrees have been awarded for studies in hydrology and hydraulics, and in many areas of theoretical and applied fluid mechanics. Such areas range from accelerated flows to water waves and from aerodynamics of buildings to transport of sediments. In this educational endeavor, the Institute has worked in close cooperation with the Department of Mechanics and Hydraulics, and during certain periods also with the Department of Civil Engineering. Of the total of 503 advanced degrees, 89 were at the doctoral level, and were earned by students from Australia, Canada, China, Egypt, France, Germany, India, Iraq, Israel, Mexico, Turkey, United States, Uruguay, and Yugoslavia. Inclusion of the master's degrees adds thirty more countries to the list.

A detailed breakdown according to degree and the country of origin is presented in the accompanying table. It is certainly noteworthy that over half of the students have held appointments as Research Associates or Research Assistants at the Institute. Some of them also held appointments as Teaching Assistants in the Department of Mechanics and Hydraulics; these were usually students who already had teaching experience or were planning academic careers.

The name of each degree recipient, together with degree date and degree awarded is listed in alphabetical order in the Author Index of Theses and Dissertations, or in the Appendix if he earned a master's degree without thesis. Accompanying the names in the Author Index are page numbers referring the reader to the dissertation or thesis title, date, and adviser. If the degree was awarded within the decade 1961-70, an abstract of the dissertation or thesis is also included. The abstracts for those works presented in earlier years are to be found in other decade bulletins of this series cited in the Preface. Copies of all the dissertations and theses are kept at The University of Iowa Engineering Library. Requests concerning such documents should be addressed to the Research Library of the Institute, which can either loan a copy, prepare retention copies for sale, or refer to available publications containing the essential results of the thesis.

Graduate Degrees and Countries Represented, 1922 to 1970

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