SHIP HYDRODYNAMICS RESEARCH AT IOWA INSTITUTE OF HYDRAULIC RESEARCH
1982-1987

by

V. C. Patel, L. Landweber, A. T. Chwang,
F. Stern, and H. C. Chen

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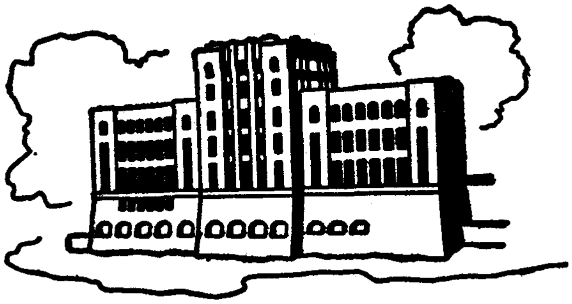

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Iowa Institute of Hydraulic Research
The University of Iowa
Iowa City, Iowa 52242-1585

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This Final Technical Report presents an overview of research conducted under ONR sponsorship during the period November 1982 through May 1987, and provides a guide to the many publications which describe the results of the research in detail. The principal areas of research have included irrotational flows and free-surface waves, interactions between viscous and inviscid phenomena in ship hydrodynamics, and numerical methods for the solution of viscous-flow equations with special reference to applications in ship hydrodynamics.

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I. INTRODUCTION

The principal purpose of the Special Focus Research Program, later termed Accelerated Research Initiative Program, in Ship Hydrodynamics at the Institute of Hydraulic Research (IIHR) was to address a number of very basic fluid flow phenomena which are peculiar to ship hydrodynamics and which remained poorly understood. Among the topics identified for special attention were flow phenomena at the bow, the effects of the free surface on the hull boundary layer, and the complex turbulent shear flow over the stern and in the wake. The results of the research in these areas are summarized below.

II. RESEARCH HIGHLIGHTS

A. Irrotational Flow and Surface Waves

1. Forces and moments on bodies

Several contributions were made in continuation of research previously supported by ONR under a separate contract. Among these are the following:

a) A previously published paper (Landweber and Miloh, "Unsteady Lagally Theorem for Multipoles and Deformable Bodies," J.Fluid Mech., Vol. 96, Part 1, 1980) did not include the derivations of residues of multipole integrals required in the treatment. These were presented at a 1985 Symposium at the University of Michigan, in Honor of Professor C.S. Yih, and published as an IIHR Report [1].

b) A new, asymptotic formula for the force on a body in a weakly nonuniform flow has been derived. The result, expressed in terms of added masses, is similar to the one-dimensional formulas of G.I. Taylor and J.N. Newman for steady, one-dimensional motion, but is generalized to include body rotation and unsteady flow. This work has not yet been published.

c) Formulas, expressing added masses and added moments of inertia of a single body, moving in an otherwise undisturbed fluid in terms of singularities within the body, have been extended to the case of a pair of bodies. A paper on this subject has been prepared [2].

2. Wave-trapping due to a porous plate

The reflection and transmission of small-amplitude surface waves by a vertical porous plate fixed in an infinitely long channel of constant depth, and the wave-trapping by a thin porous plate fixed near the end of a semi-infinitely long open channel of constant depth have been investigated. Analytical solutions in closed forms were obtained for the surface wave profile and the net hydrodynamic force acting on the plate. A porous-effect parameter and a Reynolds number associated with the flow passing through the plate were introduced. It was found that, when the distance between the plate and the channel end-wall is equal to a quarter-wavelength plus a multiple of half-wavelength of the incident wave, the reflected wave amplitude reduces to a minimum. Thus, the porous plate together with the fluid between it and the channel end-wall acts as a wave absorber or eliminator. The effect of nonlinear porous flow, governed by the square law of resistance, on the resulting surface waves was also studied. It is found that higher harmonic waves are generated by the nonlinearity. The results of these studies are reported in publications [3], [4] and [5].

3. Free-surface around a vertical cylinder

Analytical and experimental investigations have been carried out to study the nonlinear free-surface flow around an impulsively started vertical cylinder [6-9]. The analytical solutions for the velocity potential and free-surface elevation were derived up to the third order by the small-time-expansion method. The hydrodynamic pressure acting on the cylinder wall was also obtained. It was found that, during the initial stage of this impulsive motion, no travelling free-surface waves are present. The fluid simply piles up on the upwind face and a reverse motion appears on the downwind face. In the experiments, measurements of the free-surface elevation ahead of the cylinder and pressure distributions on the cylinder were made in an open channel of constant water depth. The experimental results of the free-surface elevation agreed fairly well with the analytical solutions, particularly in the far field. The pressure distributions on the cylinder were also in satisfactory agreement with the theoretical predictions.

4. An optimal finite-difference method

An "optimal" finite-difference (FD) method for two-dimensional potential flows was studied. The nine-point FD coefficients for Laplace equations were derived for rectangular cells with an arbitrary length-to-width ratio r. When the value of r^2 is between 5 and 1/5, the present nine-point formula agrees exactly with the corresponding formula of Manohar and Stephenson, with a sixth-order truncation error. It reduces to the best nine-point formula of Bickley, Kantorovich and Krylov, and Greenspan for square cells with an eighth-order truncation error. For r^2 greater than 5 or less than 1/5, the truncation error of the present formula is of the fourth order. The accuracy and performance of the present optimal FD formula was compared with the finite-analytic (FA) formula of Chen and Li and an alternative FA formula with trigonometric boundary approximations [10, 11]. It is found that the present FD formula gives the best result regardless of the value of r. An example of potential flow in a channel with an abrupt change in its width is also given.

B. Viscous-Inviscid Interaction

1. Viscous effects on ship wavemaking resistance

The primary goal of this project was to incorporate viscous effects into the calculation of ship wavemaking resistance. This has led to enhancements of both irrotational-flow theory, and experimental and numerical work on ship boundary layers. The Wigley parabolic ship form was selected for this study.

Measurements of the boundary-layer characteristics of a 10-ft Wigley model at various Froude numbers were undertaken in the Iowa Towing Tank. These were required in a procedure for correcting wave-resistance calculations for viscous effects, proposed by Landweber in his David Taylor and Georg Weinblum Lectures, and would also serve as a data base for evaluating algorithms for computing ship boundary layers. This work resulted in a paper on the boundary layer on the hull near the free surface [12] and culminated in the Ph.D. thesis by A. Shahshahan [13] and an IIHR report by Shahshahan and Landweber [14]. It was found that the correction for viscous effects greatly improved the agreement with the "measured" values of the wave resistance.

The aforementioned wavemaking-correction theory applies to a body with a centerplane singularity distribution. In order to use this theory, it was necessary to determine whether the Wigley form could be represented by a centerplane distribution. A new slender-body procedure, employing conformal mapping of ship sections, was developed to determine whether a centerplane distribution existed and to find it if it did exist [15, 16, 17]. It was found that the Wigley form did not have a centerplane distribution, but that a slightly modified form did. This new approach to slender-body theory has yielded the following additional results:

a) Ellipsoids have an exact, closed-form, slender-body centerplane distribution.

b) Ship forms with ogival sections have centerplane distributions.

c) Computed values of ship wavemaking resistance, with or without the viscous correction, are in better agreement with measurements with the slender-body rather than the Michell thin-ship centerplane distribution at Froude numbers up to 0.3. This result is in sharp contrast with that from the established slender-body theory which has been judged to be useless for wave-resistance calculations [15, 16, 17].

d) Since the integral equation for a centerplane distribution is of the first kind, a numerical solution by iteration may not converge to the exact solution even when it exists. It was shown [17], however, that one iteration, employing the slender-body solution as the previous approximation, yields an improved approximation over the entire body, especially near the bow and stern where the errors of the slender-body solution may be large.

2. Free-surface flow ahead of a two-dimensional body

This work is part of a continuing study of flow phenomena near a ship bow. At IIHR, the occurrence of a zone of separation ahead of surface piercing bodies and vortex formation around and along the bow had previously been reported in an M.S. thesis by A. Shahshahan in 1981. Analysis of the equations of viscous flow with the free-surface boundary conditions and the effects of surface tension yielded a prediction of the location of a stagnation point ahead of a bow and, by applying an integral method, the characteristics of the free-surface boundary layer. This work is reported in the paper by Patel et al. [18]. Subsequently, this work was refined by Tang, who also developed numerical methods for the solution of both the steady and unsteady two-dimensional Navier-Stokes equations with the exact boundary conditions. He applied his computer programs to the case of solitary waves and several two-dimensional surface-piercing bodies. This work is reported in his Ph.D. thesis [19].

3. Effects of waves on the boundary layer of a surface-piercing body

This theoretical and experimental investigation was undertaken with the objectives of determining the fundamental aspects of the effects of waves on the boundary layer of a surface-piercing body and of developing a numerical method for calculating ship boundary layers for nonzero Froude numbers. The problem has been formulated in a rigorous manner in which proper consideration is given to the viscous free-surface boundary conditions. Order-of-magnitude estimates were derived for the body-boundary-layer/free-surface juncture region. These showed that this region is analogous to the flow in a streamwise corner in that a consistent formulation requires the solution of higher-order viscous-flow equations. Numerical results have been obtained for both laminar and turbulent flow for the model problem of a combination Stokes-wave/flat-plate [20-23]. For this initial investigation, the usual thin-boundary-layer equations were solved using a three-dimensional implicit finite-difference method. The calculations demonstrated and quantified the influence of waves on boundary layer development, including the occurrence of wave-induced separation. Calculations were made using both small-amplitude-wave and more approximate free-surface boundary conditions. Both the external-flow pressure gradients and the free-surface boundary conditions were shown to have a significant influence. The former penetrates to a depth of about half the wave length and the latter is confined to a region very close to the free surface. Extensions of the theoretical work have been made for more practical ship forms.

A towing-tank experiment has been performed for the purposes of documenting wave effects on boundary-layer development and validating the aforementioned theoretical work. The model geometry was designed specifically to simulate the Stokes-wave/flat-plate flow field. Detailed boundary-layer velocity-profile measurements have been made for three wave-steepness conditions. These experiments are the most detailed measurements, to date, documenting free-surface effects on boundary-layer development. The experimental and theoretical results are compared and discussed in [24].

4. Viscous-inviscid interaction with higher-order viscous-flow equations

The partially-parabolic Reynolds equations have been coupled with an inviscid-flow solution procedure to develop a viscous-inviscid interaction method to be used for three-dimensional flows which cannot be treated by means of the classical boundary-layer equations (e.g., ship sterns, bodies at incidence, interacting shear layers, and solid-solid and solid-fluid corners). The method has the following distinctive features: the governing equations are derived in nonorthogonal curvilinear coordinates with velocity components along the coordinate directions; an implicit finite-differnce scheme is used with the SIMPLER algorithm for pressure-velocity coupling; interaction between the viscous and inviscid regions is accounted for using the displacement-body concept; the inviscid flow is calculated using a conforming-panel, source panel method; the k-ε model is used for turbulent-flow applications; and both algebraic and numerically-generated grids are used. The method has been used to evaluate the relative merits of interactive and global solution procedures by comparing the viscous-inviscid interaction solutions with large-domain solutions of only the viscous-flow equations. The method has been tested, thus far, for two-dimensional, axisymmetric, and simple three-dimensional flows [25-29].

C. Development of a Numerical Method for Viscous Flow Around Ship Hulls

Considerable effort has been devoted since the inception of this research program to the development of a general numerical method for the computation of the viscous flow around ship hulls. Initially it was decided to confine our attention to the flow over the stern and in the wake because it was generally assumed that established boundary-layer methods could be used quite effectively for the flow at the bow and over the middle body, at least for the case without a free surface. This led to the development of a method for the solution of the so-called partially-parabolic, Reynolds-averaged Navier-Stokes equations. The generality of the approach used in the construction of this method, however, was such that it could be readily extended to solve the complete Reynolds equations. The achievements of the former and the progress made in the latter are summarized in the following two sections.

1. Stern and wake flows

Following a critical review of experimental information on thick boundary layers over ship sterns and on ship wakes, Patel [30] identified a number of important physical and numerical features which needed to be addressed and resolved in order to develop a comprehensive method for the prediction of such flows for practical configurations. As a result, a fully-emplicit, time-marching numerical method was developed for the solution of the partially-parabolic Reynolds-averaged Navier-Stokes equations. This method incorporated state-of-the-art numerical grid-generation techniques, the novel finite-analytic discretization scheme for the transport equations of momenta and turbulence parameters, the two-equation k-ϵ turbulence model with a special treatment of the wall boundary conditions, and a rapidly converging global velocity-pressure coupling algorithm. With this method, solutions could be routinely obtained on a minicomputer, such as a Prime 9950, in a matter of minutes. This method, which is described in detail in [31], has been applied to solve a variety of two-dimensional [31] and axisymmetric [31, 32] trailing-edge and wake flows. Its applications to three-dimensional bodies and ship forms are reported in [31, 33, 34]. The development of this time-marching, three-dimensional, partially-parabolic method also made it possible to undertake the separately funded research program in propeller-hull interaction (Contract N00014-85-K-0347).

2. Fully-elliptic method

The partially-parabolic approximations are sufficient for a very large class of flows encountered in practice, including ship stern and wake flows. However, as a result of the generality that was incorporated in the formulation of our partially-parabolic method, it soon became evident that its numerical components could be readily generalized for the solution of the complete, fully-elliptic, Reynolds-averaged Navier-Stokes equations without a significant penalty in computing times. The need for such fully-elliptic solutions arises in the treatment of separating and separated flows. Considerable progress has been made in refining the physical components of the method towards the goal of developing a method suitable for the solution of the flow around complete three-dimensional bodies, e.g., the flow around a ship form, or the flow past a body with appendages. Among the major accomplishments are the following:

a) The fully-elliptic capabilities of the numerical method have been demonstrated through its applications in two-dimensional [35] and axisymmetric [36] laminar flows. The latter reference describes flow separation on a spheroid and closure of the bubble in the wake. Applications to a variety of ship forms are described in [37].

b) There are many turbulent flows in which the popular wall-function approach of treating the boundary conditions on surfaces becomes unreliable. Among the most important are flows with regions of separation, and unsteady and three-dimensional flows. Previous attempts to formulate the so-called near-wall, or low Reynolds number, turbulence models have not been particularly successful. We have shown that this difficulty can be overcome in a very economical way by combining a simple turbulence model for the wall region with a more elaborate one for the flow farther from the wall. Several versions have been tested thus far [38, 39, 40, 41] together with the fully-elliptic numerical schemes. The results indicate that a major hurdle in the accurate resolution of complex three-dimensional flows can be removed by such two-layer treatments of turbulence models. Other model combinations are also possible.

c) The original partially-parabolic method, like many other modern numerical methods for three-dimensional flows, employed partially-transformed equations, namely those in which the velocity components are left in a convenient orthogonal coordinate system. Since this approach may prove restrictive for certain types of applications (e.g., in the treatment of strongly three-dimensional flows), the fully-transformed equations for three-dimensional laminar and turbulent flows in generalized nonorthogonal coordinates have been derived

[42]. The fully-transformed elliptic equations have been solved for a variety of two-dimensional flows with highly curved surfaces [40, 43] in order to explore the advantages and difficulties before attempting more general three-dimensional flows.

D. Development of IIHR Research Facilities

The CRAY-XMP supercomputer at the Naval Research Laboratory (NRL) has been used to perform some of the ship-stern calculations mentioned in the previous section. In addition, some computer time was obtained at the Illinois and San Diego Supercomputer Centers, sponsored by NSF, in support of our computational effort in ship hydrodynamics. A terminal dedicated to work requiring supercomputers has been installed at IIHR. The University of Iowa is now an Affiliate of the National Center for Supercomputer Applications (NCSA) and will soon acquire a node on the NSFNET or MIDNET. When this becomes available, it will provide us with a high-speed access to several supercomputers and greatly increase our computational capabilities in ship hydrodynamics.

The three-component, fiber-optics, LDA system, financed in part by the DoD-University Research Instrumentation Program (Grant No. N00014-84-G-0156) in support of the research being performed under the present contract, was delivered by TSI Inc. to IIHR in August 1986. The design of this unique system was the result of a close collaboration between IIHR and TSI engineers. This system, which has generated worldwide interest, is now undergoing sytematic evaluations. When these tests are completed, it will be available to conduct a variety of experiments in three-dimensional flows.

Construction of the Institute's 1.8 x 1.5 meter (6 x 5 ft) low-turbulence wind tunnel has been completed. The working section of this tunnel has been designed to facilitate the use of the three-component LDA system. Tunnel calibration is now in progress.

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IV. CONCLUDING REMARKS

Research in ship hydrodynamics undoubtedly received a major boost as a result of the innovative Accelerated Research Initiative (Special Focus) Program of ONR. The accomplishments in the research conducted have been summarized above. It is expected that the effect of this high level of activity will be felt for a long time in the academic and research programs at The University of Iowa.

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