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DAVID W. TAYLOR NAVAL SHIP
RESEARCH AND DEVELOPMENT CENTER
Bethesda, Md. 20084

FIVE YEARS OF NUMERICAL NAVAL SHIP HYDRODYNAMICS AT DTNSRDC

by

Nils Salvesen

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SHIP PERFORMANCE DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

November 1979

DTNSRDC-79/082

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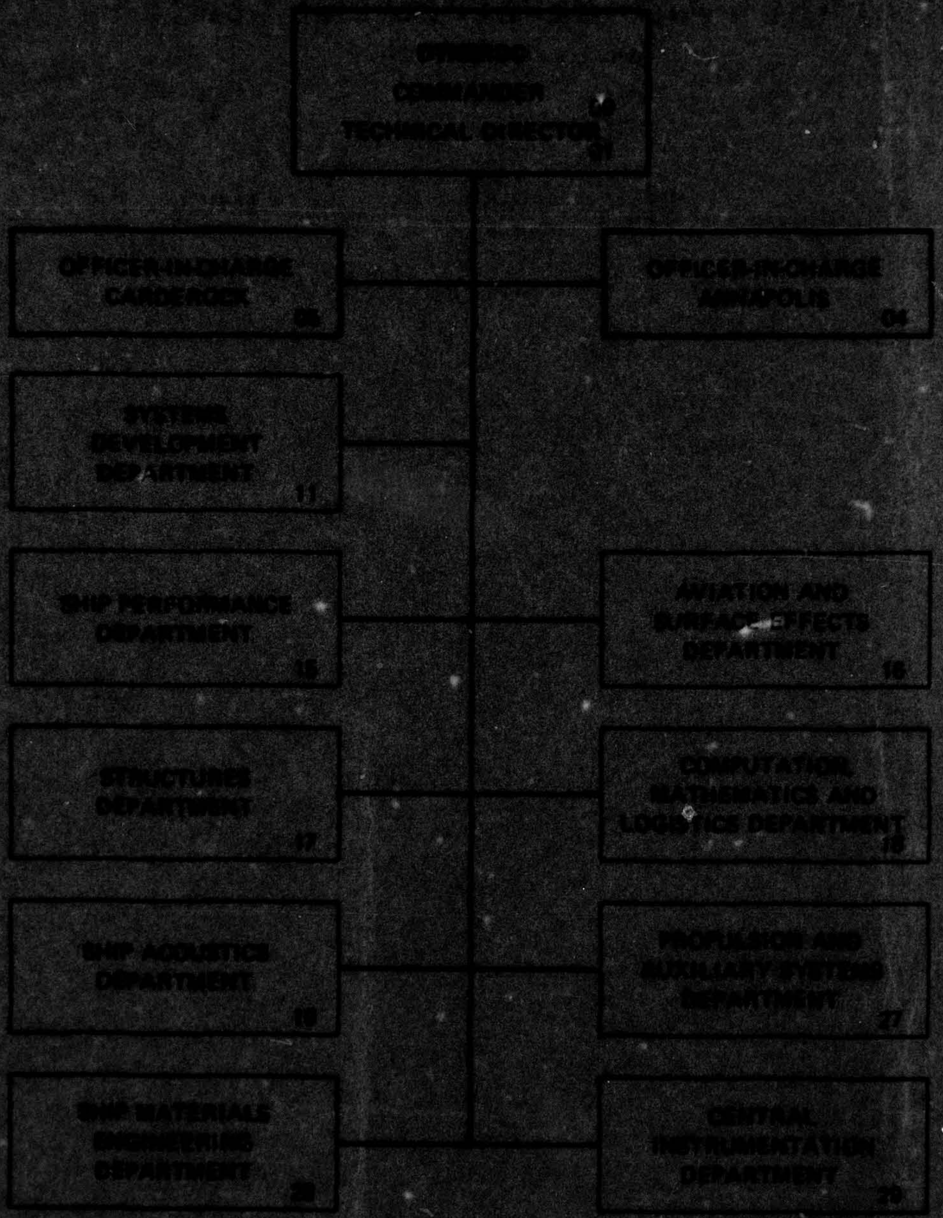

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In 1974 the Numerical Naval Ship Hydrodynamics Program was established at the David W. Taylor Naval Ship Research and Development Center. The objective of the program is to develop new numerical methods which can be used to evaluate those hydrodynamic performance characteristics which cannot be satisfactorily predicted by traditional methods. In this report, the accomplishments during the first five-year period (1974-1979) are discussed. → next page

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cont. During this initial period, the effort was devoted entirely to naval ship free-surface problems. Several successful methods have been developed for solving fully three-dimensional ship-motions, ship-wave-resistance and local-flow problems using linearized free-surface boundary conditions. Numerical methods have also been developed for unsteady and steady two-dimensional problems where the exact free-surface conditions are satisfied. These new numerical methods are more accurate than the conventional computational methods and they can be used to analyze several naval free-surface problems which previously could only be investigated experimentally. It is concluded that the Numerical Naval Ship Hydrodynamics Program should include consideration of all areas in naval ship hydrodynamics where it is believed that the application of advanced numerical techniques and computers can result in better solution techniques.

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ABSTRACT

In 1974 the Numerical Naval Ship Hydrodynamics Program was established at the David W. Taylor Naval Ship Research and Development Center. The objective of the program is to develop new numerical methods which can be used to evaluate those hydrodynamic performance characteristics which cannot be satisfactorily predicted by traditional methods. In this report, the accomplishments during the first five-year period (1974-1979) are discussed. During this initial period, the effort was devoted entirely to naval ship free-surface problems. Several successful methods have been developed for solving fully three-dimensional ship-motions, ship-wave-resistance and local-flow problems using linearized free-surface boundary conditions. Numerical methods have also been developed for unsteady and steady two-dimensional problems where the exact free-surface conditions are satisfied. These new numerical methods are more accurate than the conventional computational methods and they can be used to analyze several naval free-surface problems which previously could only be investigated experimentally. It is concluded that the Numerical Naval Ship Hydrodynamics Program should include consideration of all areas in naval ship hydrodynamics where it is believed that the application of advanced numerical techniques and computers can result in better solution techinques.

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INTRODUCTION

Over the last two decades, there have been impressive advancements in the development of computational methods for predicting ship-hydrodynamic performance characteristics. Many of these computational tools are now being used routinely in the design of new naval ships and in improving the hydrodynamic performance of existing ships. However, these existing tools have some severe limitations since they are based on theories where drastic approximations have been applied in order to reduce the computational effort. New computational methods with superior accuracy are needed in order to solve many of today's challenging ship-design problems. It is believed that many of the ship-hydrodynamic problems can be solved more effectively by applying advanced numerical methods rather than by traditional analytical methods. Numerical methods are defined as methods which rely heavily on large-scale numerical computations where the governing differential equations and boundary conditions or governing integral equations may be solved directly by, for example, finite difference, finite element, spectral, or panel methods. During the last couple of decades there has been remarkable progress in the general fields of numerical aerodynamics and hydrodynamics and numerical methods are now being used successfully in solving many practical engineering problems. For example, sophisticated numerical methods are playing a large role in the design of modern fuel-efficient airplanes.

The David W. Taylor Naval Ship Research and Development Center (DTNSRDC) recognized the demand for advanced numerical methods to predict the hydrodynamic performance characteristics of naval ships and in 1973 a report entitled "Recommendations for Advancing the Capability in Numerical Naval Hydrodynamics at DTNSRDC" was prepared by Salvesen and Schot (NP 1973).* The Navy supported the recommendations stated in this report and in July 1974 the Numerical Naval Ship Hydrodynamics Program was established at the DTNSRDC. The objective of the program is to develop new numerical methods which can be used to evaluate hydrodynamic performance characteristics which cannot be satisfactorily predicted by traditional methods. The program has been jointly supported by the Office of Naval Research, the

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*Bibliographic items are listed in alphabetical order at the end of the report. In the text they are identified by author's name and year of publication with NP (Numerical Program) indicating that the work was supported by the Numerical Naval Ship Hydrodynamics Program.

Naval Sea Systems Command, and DTNSRDC through its Independent Research Program. In this report, the progress on the research carried out under this program during the five-year period from July 1974 through July 1979 is discussed.

The first five years' effort in numerical naval ship hydrodynamics was devoted to the reexamination of inviscid free-surface problems such as the problems of ship wave resistance and ship motions in waves. These free-surface problems have a long history of development using classical analysis which eschews substantial computational efforts and relies on simplifying ship-hull boundary conditions and linearized free-surface conditions. These classical methods have resulted in several useful computer codes which are in use today for predicting certain ship-hydrodynamic performance characteristics. However, the classical computational methods have some severe limitations which greatly restrict their application to naval ship design. For example, the strip theory of ship motions (Salvesen et al., 1970) which has been in use for several years, is inaccurate at high ship speeds. In strip theory, the complicated three-dimensional hydrodynamic problem of a ship advancing in waves is replaced by a summation of simplified two-dimensional cross-sectional problems. Furthermore, most of the analytical/computational methods used for predicting wave resistance (see, for example, Pien and Strom-Tejsen, 1968) cannot be applied for prediction of the flow in the immediate neighborhood of the ship hull due to approximations used in satisfying the hull boundary conditions. These theories are also inadequate for predicting the wave resistance of high-speed naval ships with transom sterns.

In the next section, where the accomplishments under the Numerical Naval Ship Hydrodynamics Program are presented, several new numerical methods are discussed which have accuracy superior to the classical computational methods. For example, a new three-dimensional numerical method for predicting ship motions is now being completed (Chang, NP 1977). In this method, the complete three-dimensional oscillatory ship-motion problem, including all forward-speed effects is solved. The only assumptions made are that the free-surface boundary condition may be linearized, and the ship-hull boundary condition may be satisfied at the mean position of the ship. An ongoing evaluation of this new method indicates that it predicts motions accurately even at very high ship speeds. Furthermore, four different numerical methods for predicting the local flow (i.e., the flow in the immediate vicinity of the ship hull) and the wave resistance of ships advancing in calm water have been developed (Bai, NP 1977d; Dawson, NP 1977; Chang, NP 1977; and Ohring and Telste, NP 1977). All of these methods satisfy the exact ship-hull boundary condition and hold promise for accurately predicting the local flow field. It is expected that these numerical methods will have many useful applications since accurate prediction of the local flow is important for solving many hydrodynamic problems of naval ship design.

Some significant results also have been achieved in solving the complicated nonlinear ship-wave problem. Prior to the start of this Numerical Program, there existed no solution to the exact potential-flow formulation of any problem involving the free-surface flow past a partly or fully submerged body. During the last five years, several numerical methods have been developed, which solve the "exact" nonlinear formulation of two-dimensional problems pertaining to potential flow past bodies in or below the free surface. The work on the nonlinear two-dimensional problems is now in the process of being completed and the experience gained in solving such nonlinear problems is being applied to the fully three-dimensional nonlinear ship-wave problem.

The DTNSRDC has also played a major role in fostering an international community in numerical ship hydrodynamics. The First Numerical Ship Hydrodynamics Conference held in Gaithersburg, Md. in October 1975 was initiated and organized by the DTNSRDC and the Second Numerical Ship Hydrodynamics Conference held in Berkeley, Calif. in September 1977 was jointly organized by the University of California and the DTNSRDC. Presently, the DTNSRDC is organizing a Workshop on Ship Wave Resistance Computations to be held in November 1979 in Washington, D.C. The purpose of the Workshop is to evaluate existing computational methods for predicting the wave resistance and local flow field of ships.

When the Numerical Naval Ship Hydrodynamics Program was established five years ago, it was decided initially that the technical area covered by the program would be restricted to ship-wave problems which could be solved by potential-flow methods. This concentration of effort during the initial phase of the program has been very effective. It has resulted in a significant advance of the state-of-the-art of the prediction of ship hydrodynamics. Also, it has demonstrated that numerical approaches can have superior advantages over the more traditional methods in solving certain classes of ship hydrodynamics problems. The initial phase of the program can now be considered largely complete. The program now should include other problem areas in naval ship hydrodynamics where it can be expected that the development of advanced numerical methods for the solution of these problems will succeed and where it has been shown that pure analysis and simplified calculations have failed to give adequate solutions.

It is recommended that all of the following general problem areas in ship hydrodynamics should be included in the overall context of numerical naval ship hydrodynamics:

1. Ship wavemaking and viscous boundary layer interactions.
2. Ship boundary layers and large-scale separated flow, including vortex shedding.
3. Time-domain large-amplitude ship motions.
4. Nonlinear three-dimensional ship-wave problems.
5. Hydrodynamics of ship propulsion.

The application of advanced numerical techniques and computers for solving the equations of these important naval hydrodynamics problems should result in computer-based performance-prediction methods which are superior to the current prediction methods. However, this will be a difficult and challenging research effort. In many ship hydrodynamic problems the mathematical model is inadequate because the physics of the problem is poorly understood. Therefore, a combination of theoretical, experimental, and numerical research will be needed to achieve successful solution methods.

ACCOMPLISHMENTS

The main objective of the Numerical Naval Ship Hydrodynamics Program is to develop effective numerical methods which can be used to predict those ship hydrodynamic performance characteristics which cannot be satisfactorily predicted by classical methods. The limitations and inaccuracies of the classical methods, for the ship-wave problems chosen during the initial phase of the Numerical Program, are mainly due to four major assumptions. Therefore, the first aim of the Numerical Program has been to systematically remove or improve at least some of these four critical assumptions:

1. Small viscous/wave interactions. The interactions between the viscous effects and the gravity waves are assumed to be small so that potential-flow theory can be used in predicting, for example, ship motions and wave resistance.

2. Linearization of free-surface conditions. It is assumed that the wave slopes of the incoming and the ship-generated waves are sufficiently small so that the nonlinear free-surface boundary conditions can be replaced by the linearized conditions.

3. Hull-form approximation. The exact hull boundary condition is replaced by some approximate condition and the theories are usually categorized accordingly. Examples are thin-ship theory, strip theory, and slender-body theory.

4. Small amplitude ship motions. For ship motion problems, it is assumed that the unsteady body displacements are small so that the hull boundary condition can be satisfied at the mean position of the ship.

Prior to the start of the Numerical Program, practically all of the classical methods which were used for predicting the ship hydrodynamic performance characteristics were based on these assumptions. The effort of the initial phase of the Numerical Program has been concentrated on the improvement or removal of the last three assumptions.

LINEAR SHIP-WAVE SOLUTIONS

It was decided that in developing the first generation of numerical methods for solving three-dimensional ship-wave problems, the two first assumptions cited above should be applied. In other words, potential-flow theory with linearized free-surface condition should be applied initially. The effort should be concentrated on improving or removing the last two assumptions applied to the hull boundary condition.

This decision was made not because viscous interaction effects or nonlinear free-surface effects are less important than the correct satisfaction of the hull boundary condition, but because it is much easier to improve the latter. Furthermore, by satisfying the exact hull-boundary condition, the local flow field can be computed with much better accuracy than by, for example, the conventional thin-ship theory. Accurate predictions of the local flow field are important in solving many important naval ship design problems, as, for example, bow cavitation, flow separation, and inlet/outlet flows. Accurate information about the local flow field is also a required input to existing computer codes for predicting three-dimensional viscous boundary layers.

Wave Resistance and Local Flow

The first problem which we shall consider is prediction of the wave resistance and the local flow field of a ship advancing at constant forward speed in calm water. Our initial objective has been to develop computational methods which satisfy the exact hull boundary condition and the linearized free-surface condition in an ideal fluid. There is good reason to believe that such an approach will yield accurate local-flow predictions over most of the hull and also improved wave-resistance predictions.

Four different numerical methods for predicting the wave resistance and the local flow field of a ship advancing in calm water have been developed, all of which satisfy the exact hull boundary condition:

1. The double-model linearization method (Dawson, NP 1977).
2. The Green's function method (Chang, NP 1977).
3. The finite-element method (Bai, NP 1977d).
4. The fast direct matrix solver method (Ohring and Telste, NP 1977).

Since detailed descriptions of these methods are included in the Proceedings of the Second International Conference on Numerical Ship Hydrodynamics, University of California, Berkeley, September 1977, we shall discuss these methods only briefly here.

In the double-model linearization method of Dawson, the free-surface boundary condition is linearized with respect to the double-model velocity potential. This method is similar to Baba's (1977) low-speed method, but there are distinct and important differences between the two methods (see the discussion by Newman, 1977). The solution is generated by a source-density distribution on the body surface and on the local part of the undisturbed free surface. A typical arrangement of the quadrilateral panels is shown in Figure 1.

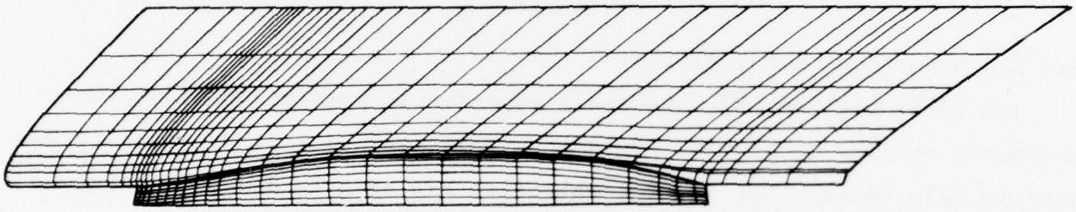
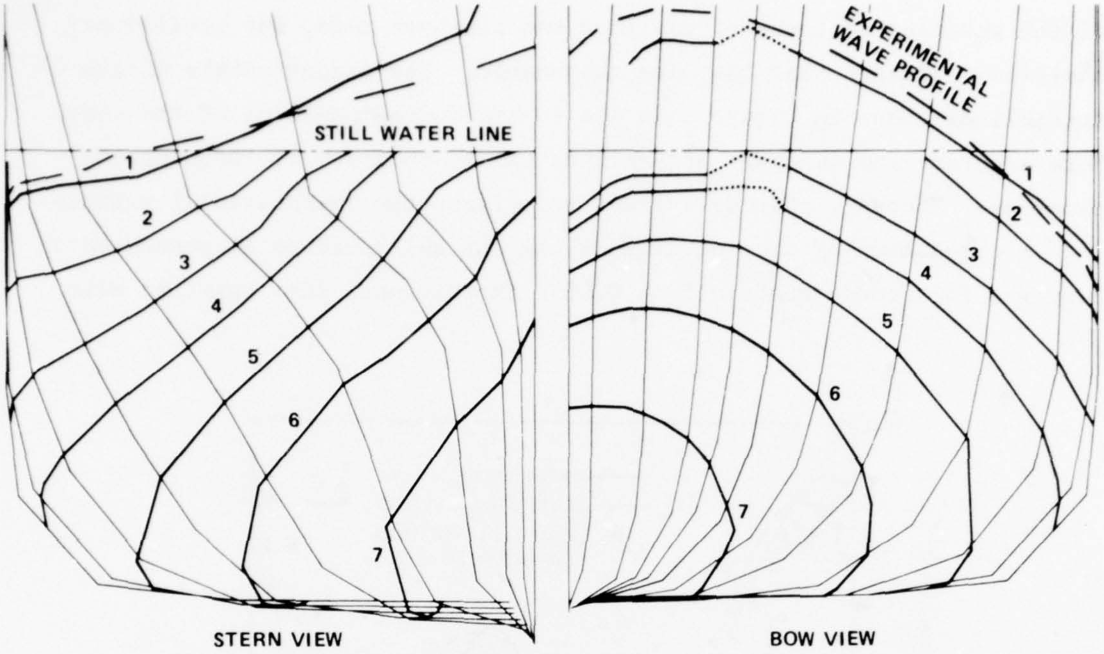


Figure 1 - Typical Panel Arrangement (Dawson, NP 1977)

The streamlines along the hull surface of a Series 60, $C_B = 0.60$ ship computed by the Dawson numerical method are shown in Figure 2. The upper part of the figure shows the streamlines for the hull advancing in the free surface at Froude number, $F_n = 0.35$, and the lower part shows the streamlines for the double model infinite-flow case ($F_n = 0$). The solid lines numbered 1 through 7 are the computed streamlines, the uppermost streamline numbered 1 being the wave profile along the hull. The broken line is the experimentally measured wave profile. There is a considerable difference in the streamline trajectories between the free-surface case

STREAMLINES FOR SHIP IN FREE SURFACE
(INCLUDING WAVE EFFECTS)



STREAMLINES FOR DOUBLE MODEL
(NO WAVE EFFECTS)

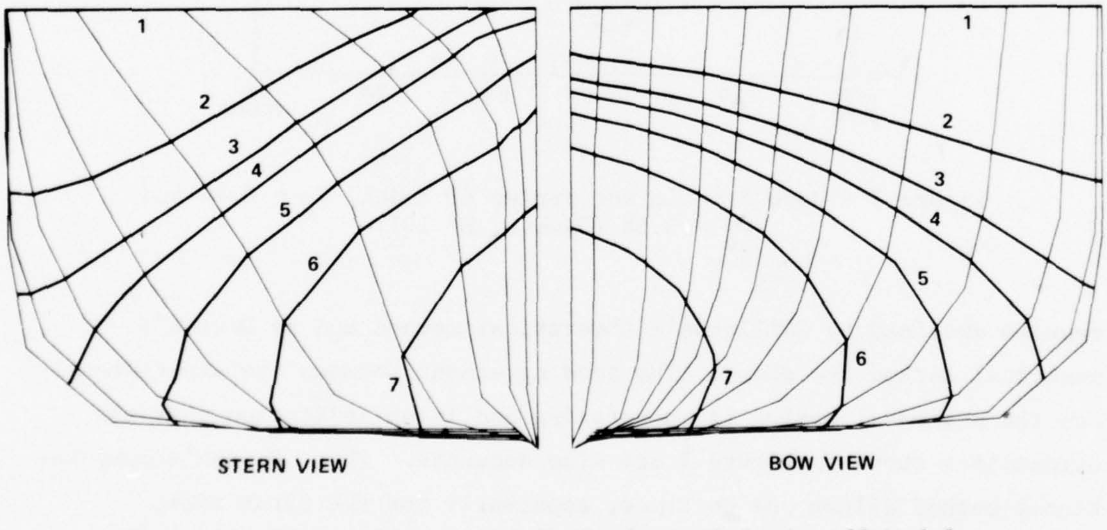


Figure 2 - Streamlines on Hull Surface of Series 60 Model, $C_B = 0.60$ at $F_n = 0.35$ (Dawson, NP 1979)

and the double model case. It clearly indicates that free-surface effects are important for accurate predictions of local flow at hull locations higher than about one-half of the ship's draft. The complete evaluation of the accuracy of these streamlines has not been made, but preliminary analysis indicates that they are reasonable. The jagged nature of the streamlines shown in Figure 2 is due to the course paneling of the body. More accurate and smoother streamlines can be obtained by refining the paneling. However, this will greatly increase the computational expense.

A comparison of wave profiles along the hull surface is presented in Figure 3 for Froude number, $F_n = 0.28$. Experimental data together with

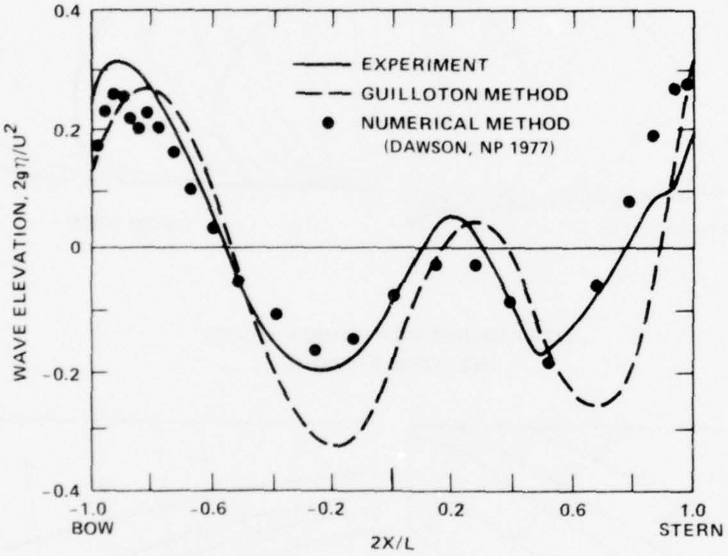


Figure 3 - Wave Profile for Series 60 Model, $C_B = 0.60$ and $F_n = 0.28$ (Dawson, NP 1977)

results obtained by Guilloton's theoretical method and by Dawson's numerical method are shown. The good agreement between the experimental and the numerical method is encouraging and is an indication that the streamlines shown in Figure 2 are also accurate. Thus, Dawson's computational method allows one to trace, apparently for the first time, reasonably accurate streamlines on surface ships. Adee (1975) has also presented streamlines for the Series 60 hull including free-surface effects, but his results seem to be incorrect over the aft portion of the hull.

The Green's function method of Chang (NP 1977) which predicts the wave resistance and local flow about a ship is somewhat more traditional and makes use of more analytical results. In this method, the free-surface condition is linearized about the uniform stream velocity and the body-boundary condition is satisfied exactly by a distribution of Kelvin wave sources on the wetted surface of the hull. Again the resulting integral equation is solved by the panel method. It is believed that Chang's and Dawson's methods would give practically the same results at high ship speeds, whereas there may be some noticable differences at low speeds. Figure 4 shows a comparison of the wave-resistance coefficient of a Wigley

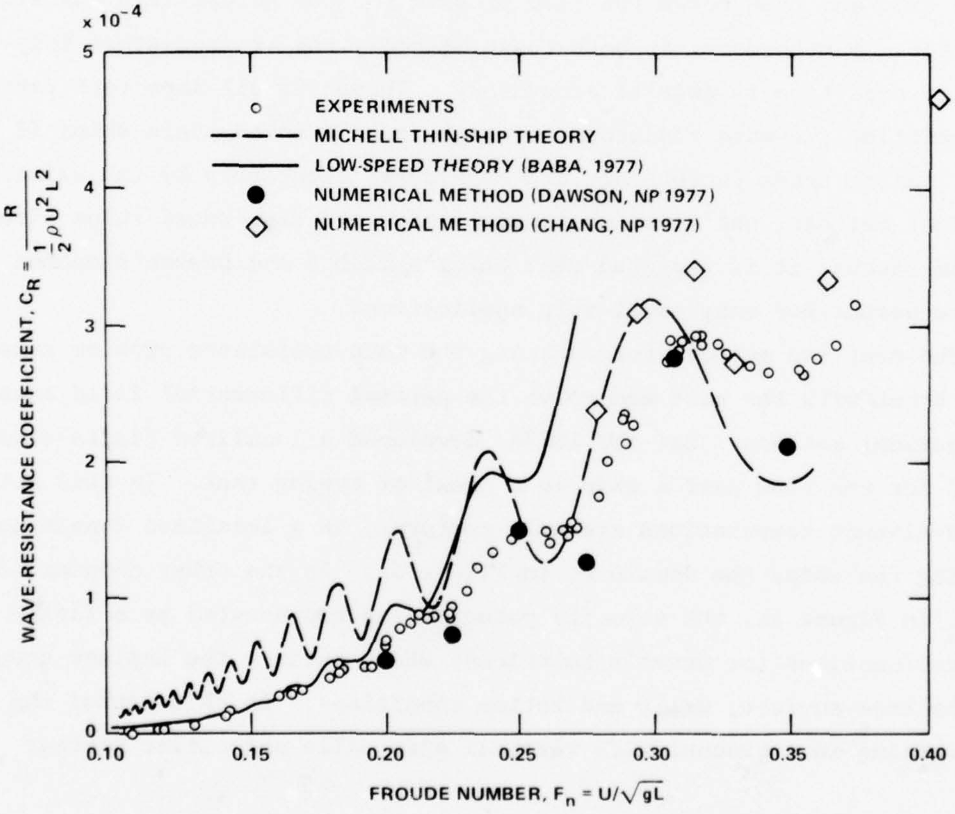


Figure 4 - Comparison of Calculated and Measured Wave Resistance of Wigley Parabolic Form (Baba, 1977)

parabolic hull obtained by various methods as a function of the Froude number. Some preliminary numerical results obtained by Dawson and by Chang are compared in this figure with experimental data and the wave resistance results obtained by Michell's thin-ship theory and by Baba's low-speed theory. The wave resistance computation of Dawson and Chang agree fairly well with the experimental data, whereas Baba's theory is fairly accurate only in the low speed range and the Michell theory only in the high speed range. Note that the wave resistance as here defined cannot be measured experimentally. The experimental data given in Figure 4 have been obtained by subtracting the flat plate resistance and an estimated form drag from the total measured drag. These preliminary results of Dawson and Chang are very encouraging and indicate that further development of these computational methods will be rewarding.

The methods of Chang and Dawson first determine the trim and sinkage of the ship and then solve the flow problem for the actual trim and sinkage condition. Furthermore, in both these methods, the transom-stern body-boundary condition is modeled accurately. These are all important factors in predicting the wave resistance of high-speed transom-stern ships ($F_n >$ 0.35). Since these factors are not considered accurately by the existing classical methods, and since most naval ships are high-speed ships with transom sterns, it is expected that Chang's method and Dawson's method will be useful for many naval-ship applications.

The next two methods for treating the wave-resistance problem make a clear break with the past and solve the partial differential field equation by numerical methods. Bai (NP 1977d) developed a localized finite-element method for the flow past a ship in a canal or towing tank. In this method, finite-element computations are only performed in a localized domain surrounding the ship, the domain D_0 in Figure 5a. In the other domains, D_1 and D_2 in Figure 5a, the velocity potential is represented by a finite sum of eigenfunctions (or Green's functions) which satisfy the Laplace equation and the free-surface, wall, and bottom conditions. In this method the ship is advancing in a channel with vertical side walls and a flat bottom;

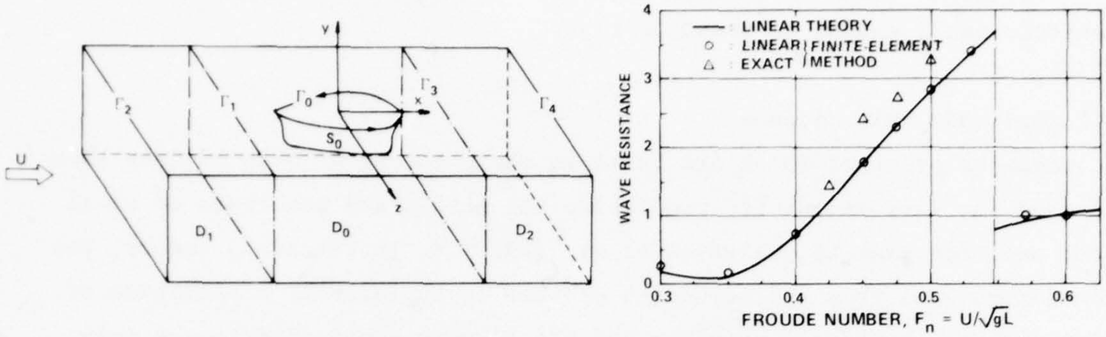


Figure 5a - The Three Subdivided Fluid Domains for the Localized Finite-Element Method

Figure 5b - Wave Resistance of a Wigley Parabolic Ship in a Canal

Figure 5 - Wave Resistance Computed by Localized Finite-Element Method (Bai, NP 1977d)

however, the method can also be applied to the problem of a ship advancing in open water if the walls and the bottom are placed at a sufficiently large distance away from the ship although in such a case the computational expense would be very large.

A typical wave resistance obtained by Bai's method is shown in Figure 5b. Bai's finite-element method has been used here to investigate blockage effects due to the finite dimensions of ship-model tanks (Bai, NP 1978b and NP 1979). A very significant result has been found; namely, that the main difference in the total resistance coefficient measured at high values of Froude number in a large and a small towing tank is primarily due to the difference in the wave resistances computed for the two tanks. As a result of this finding, a new mean-speed correction formula due to blockage has been proposed (Bai, NP 1978b).

The fourth method for solving the wave-resistance problem (Ohring and Telste, NP 1977) treats the time dependent problem of a ship which, for example, may be accelerating from rest to some given steady speed. This method will be discussed in a separate section on Transient Ship-Wave

Solutions where we shall see that this method predicts the steady-state condition as well as the transient conditions with good accuracy in a relatively small amount of computer time.

Small Amplitude Ship Motions

Computer programs which are based on strip theory of ship motions have been used the last decade for predicting the motion and sea loads of naval ships; see, for example, Salvesen et al. (1970).* In the strip theory, the three-dimensional ship hydrodynamics problem is replaced by a summation of two-dimensional sectional problems and the forward-speed effects are only satisfied approximately. The strip-theory approach gives good results for heave, pitch, and roll motions in moderate seas and moderate ship speeds for most conventional hull forms; however, the method gives inadequate results for low frequencies, higher ship speeds, local pressure distributions, and for the sway and yaw motions. The forward speed limitation is the most severe restriction for naval applications.

Chang (NP 1977) has developed a new three-dimensional numerical method for predicting ship motions which solves the complete three-dimensional hydrodynamics problem and satisfies correctly all forward speed effects. The hydrodynamic problem is solved by distributing three-dimensional oscillating Kelvin sources (which satisfy the linearized free-surface boundary condition) on the wetted hull surface. The strength of these singularities is obtained by solving the hull boundary condition. It is assumed that the ship motions are small enough that the hull boundary condition can be satisfied at the mean position of the hull. Some preliminary computations of added-mass and damping coefficients obtained by Chang's three-dimensional method for a Series 60 model with block coefficient, $C_B = 0.70$ are shown in Figures 6a and 6b. The added-mass and damping coefficients, next to the exciting forces, are the most important hydrodynamic ingredients needed in predicting ship motions and wave induced loads. Figure 6a shows the added-mass and damping coefficients for pitch

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*Ship responses in irregular waves can be computed easily from the regular-wave responses by use of well-established linear superposition procedures.

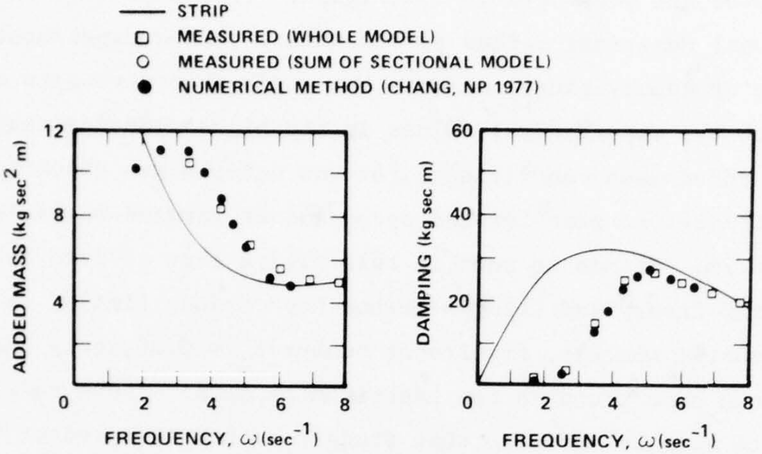


Figure 6a - Pitch Added-Mass and Damping Coefficients at F_n = 0

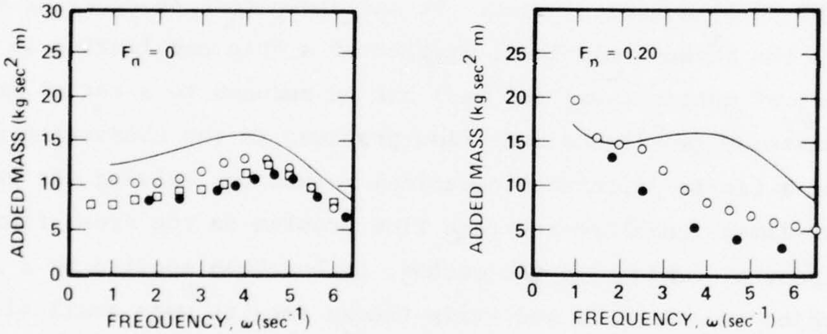


Figure 6b - Yaw Added-Mass Coefficients at F_n = 0 and F_n = 0.20

Figure 6 - Added-Mass and Damping Coefficients for Series 60 Model, C_B = 0.70 (Chang, NP 1977)

motions as a function of frequency of encounter for the Series 60 model at zero forward speed. Results obtained experimentally, by strip theory and by Chang's method are presented in the figure. It can be seen that Chang's three-dimensional numerical method agrees well with the experimental results throughout the frequency range, whereas the strip-theory results only agree well with the experimental values in the high-frequency range. In Figure 6b the added-mass coefficients for yaw motions are shown for the same Series 60 model at zero forward speed and at forward-speed Froude number, $F_n = 0.20$. It can be seen in this figure that at zero forward speed both strip theory and Chang's method have trends similar to the experimental results; whereas, for Froude number $F_n = 0.20$, only Chang's method shows the same trend as the experimental data. These results and similar results seem to indicate that Chang's method can predict the hydrodynamic coefficients used in predicting ship motions with better accuracy than the strip theory. A complete evaluation of the ship motions predicted by this method is in progress.

Another advance in the area of ship motions has resulted from Chapman's (NP 1975) numerical work. He has shown that by applying slender-body theory, the three-dimensional problem of a ship oscillating in the lateral modes of motion (sway and yaw) can be reduced to a series of transient unsteady two-dimensional flow problems in the transverse plane. He developed a finite-difference numerical method for solving the resulting unsteady two-dimensional free-surface flow problem in the cross-flow plane. For the purpose of evaluating the method, it has been applied to a flat plate for which experimental and strip-theory results were available. Figure 7 shows the sway added-mass coefficient as a function of frequency of oscillation for three Froude numbers, $F_n = 0.16$, 0.43, and 0.96. It can be seen that the results of Chapman's numerical method agree well with experiments, whereas the results of the conventional strip theory do not agree well with the experimental results. Although Chapman's method for predicting sway and yaw hydrodynamic characteristics makes somewhat more drastic approximations than Chang's method, it does give satisfactory

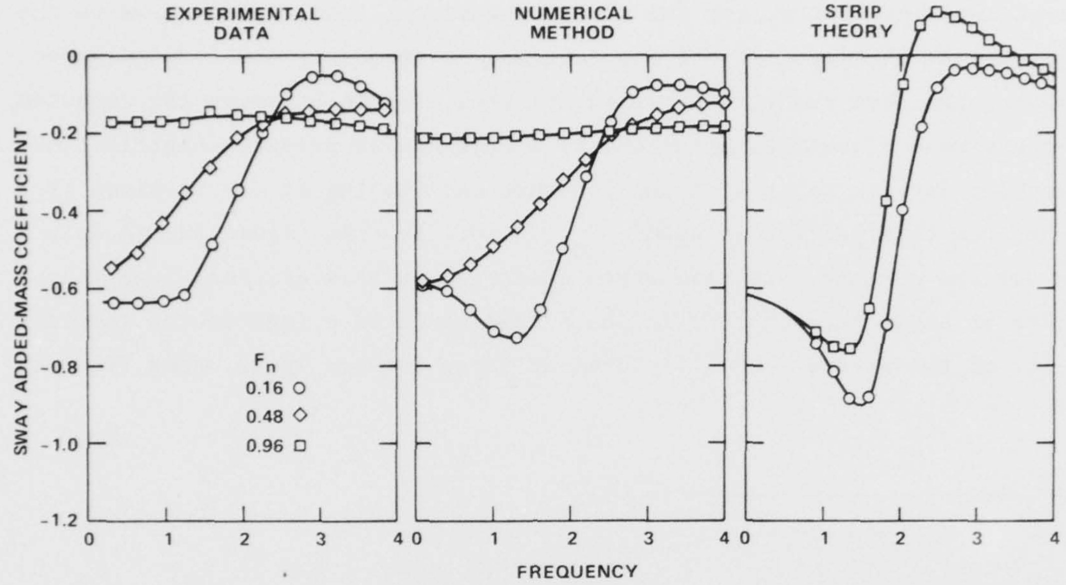


Figure 7 - Flat Plate Sway Added-Mass Coefficients (Chapman, NP 1975)

results with less computational effort. In some cases it may be even more accurate than Chang's (NP 1977) method because Chapman's method accounts for some nonlinear free-surface effects.

Most computational methods for predicting the free-surface hydrodynamics of air-cushion vehicles (ACV) treat only the case of a constant pressure distribution moving over the water. However, the ambient wave field and resulting vehicle motions cause the cushion pressure of an ACV to vary with time. Therefore, Haussling and Van Eseltine (NP 1978) developed a new method for computing the three-dimensional flow for a moving time-dependent pressure distribution. This method exploits another numerical technique in which Fourier series are used to represent the flow field. Haussling and Van Eseltine have found that this method may be applied successfully to a large variety of unsteady free-surface pressure problems. For the two-dimensional case, it has been shown analytically that there exists a critical combination of cushion oscillation frequency and forward speed for which the resistance becomes infinite. Haussling and Van Eseltine showed numerically that for the three-dimensional case, upstream waves are generated at similar critical combinations of frequency and forward speed; however, the wave resistance remains finite. Figure 8a shows the computed in-phase wave elevations generated by a rectangular pressure distribution advancing in calm water with the pressure oscillating at the critical frequency for this particular speed, $F_n = 0.40$. In this figure one clearly can see the computed upstream waves generated at this critical frequency. Figure 8b shows the computed in-phase resistance as a function of the frequency of the pressure oscillations for three forward speed cases (Froude number, $F_n = 0.4$, 0.5, and 1.0). It can be seen in Figure 8b that at the critical frequency depicted in Figure 8a ($\omega = 0.625$ and $F_n = 0.40$) the resistance is large but finite. An important part of the finding of Haussling and Van Eseltine is that the increased resistance at the critical frequency

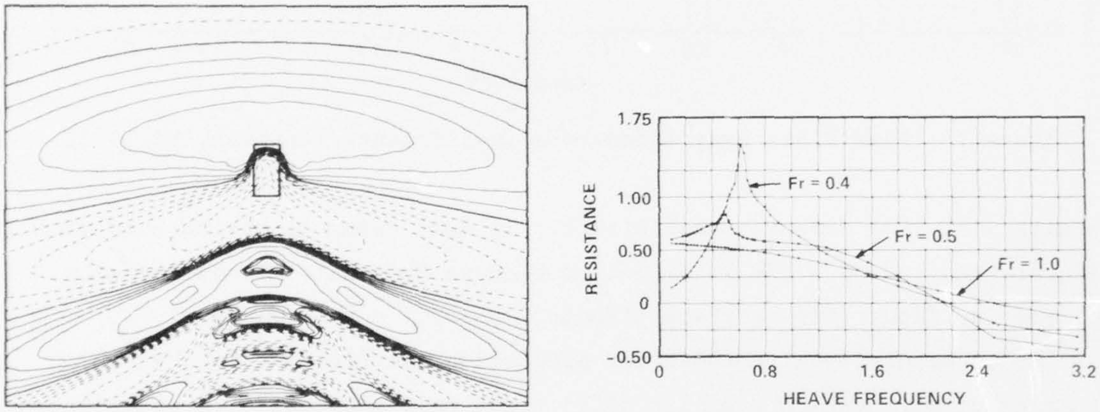


Figure 8a - In-Phase Wave Elevations for $\omega = 0.625$ and $F_n = 0.40$

Figure 8b - In-Phase Resistance for Three Froude Numbers

Figure 8 - In-Phase Wave Elevations and Resistance for Oscillating Pressure Distribution (Haussling and Van Eseltine, NP 1978)

diminishes with increasing Froude numbers. Therefore, for high-speed ACV, this critical frequency problem is not as important as may have been believed previously.

There are many practical problems of the motion of a body in or near the free surface for which the added-mass and damping coefficients may be approximated by their zero-frequency values. For example, ocean platforms and buoys usually have extremely low natural response frequencies in both heave and pitch. For such problems Bai (NP 1977b) extended his finite-element method (Bai, 1972) to predict zero-frequency motion coefficients of axisymmetric bodies piercing the free surface. Figure 9 shows computed results for prolate spheroids. In Figure 9a a schematic diagram of the finite-element mesh can be seen and in Figure 9b the zero-frequency pitch added-mass coefficients are shown as a function of the prolate spheroid's length-to-width ratio, b/a. Results obtained by the finite-element method and by strip theory are given in Figure 9b and it can be seen that for

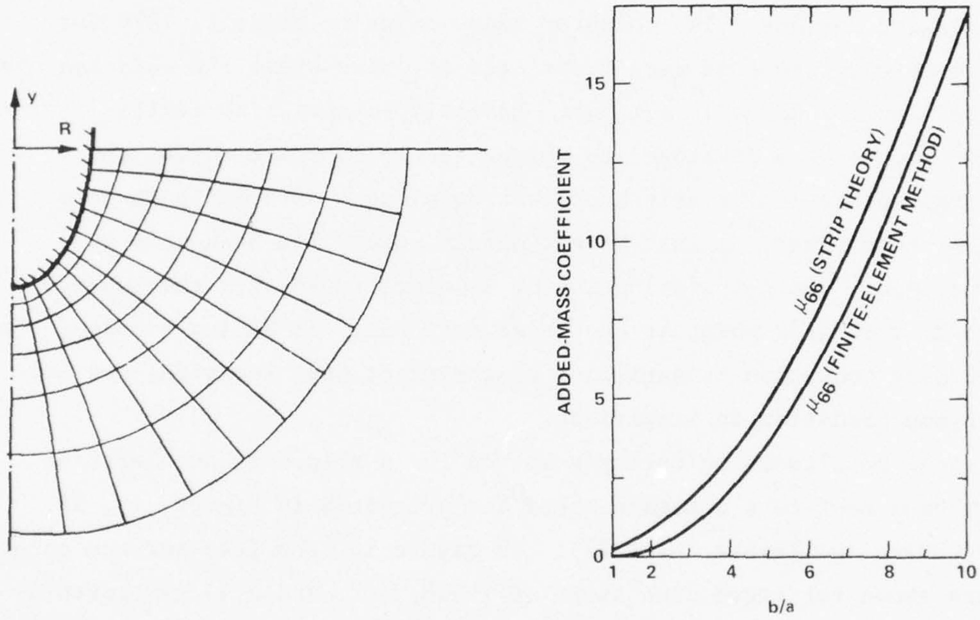


Figure 9a - Schematic Diagram of Finite-Element Meshes

Figure 9b - Zero-Frequency Added-Mass Coefficients

Figure 9 - Added-Mass Coefficients for Prolate Spheroids (Bai, NP 1977b)

small values of b/a, there is a considerable difference between the added-mass coefficients predicted by the two methods.

Further applications of Bai's finite-element method are the calculation of the added-mass and damping coefficients and the exciting forces as a function of frequency of four axisymmetric ocean platforms (Bai, NP 1976), and the investigation of the effect of finite depth on the zero- and infinite-frequency added-mass coefficient of bodies oscillating near tank boundaries (Bai, NP 1977c).

Transient Ship-Wave Solutions

Prior to the start of the Numerical Program no computational methods existed for predicting the free-surface flow about a ship undergoing unsteady forward motions. The computer codes existing prior to 1974 for solving ship-wave problems were restricted to cases where the ship has constant speed and/or harmonic motions. Recently, a numerical finite-difference scheme was developed by Ohring (NP 1975) which solves the hydrodynamic problem of a ship accelerating along a straight path in a channel of calm water. A fast direct matrix solver has been used by Ohring to reduce the computational time involved in solving the Laplace equation at each grid point at each time interval. In Ohring's method the body boundary condition is satisfied at the exact body location, and the free-surface condition is linearized.

Typical results using Ohring's method for a ship hull accelerating abruptly from rest to a constant speed are presented in Figures 10, 11, and 12 (Ohring and Telste, NP 1977). In Figure 10, the free-surface contours are shown for three time steps (t = 0.6, 1.2, and 2.4) generated by a Wigley parabolic ship hull accelerating from rest at t = 0 to a constant forward speed of $F_n = 0.503$. At time t = 2.4 the flow in the immediate neighborhood of the ship hull has almost reached steady-state conditions. Figure 11 shows, for two different cases, the wave resistance coefficient C_R as a function of time for the Wigley hull abruptly accelerating in the first case from rest to constant speed $F_n = 0.32$ and in the second case, from rest to constant speed $F_n = 0.45$. At the higher ship speed $F_n = 0.45$,

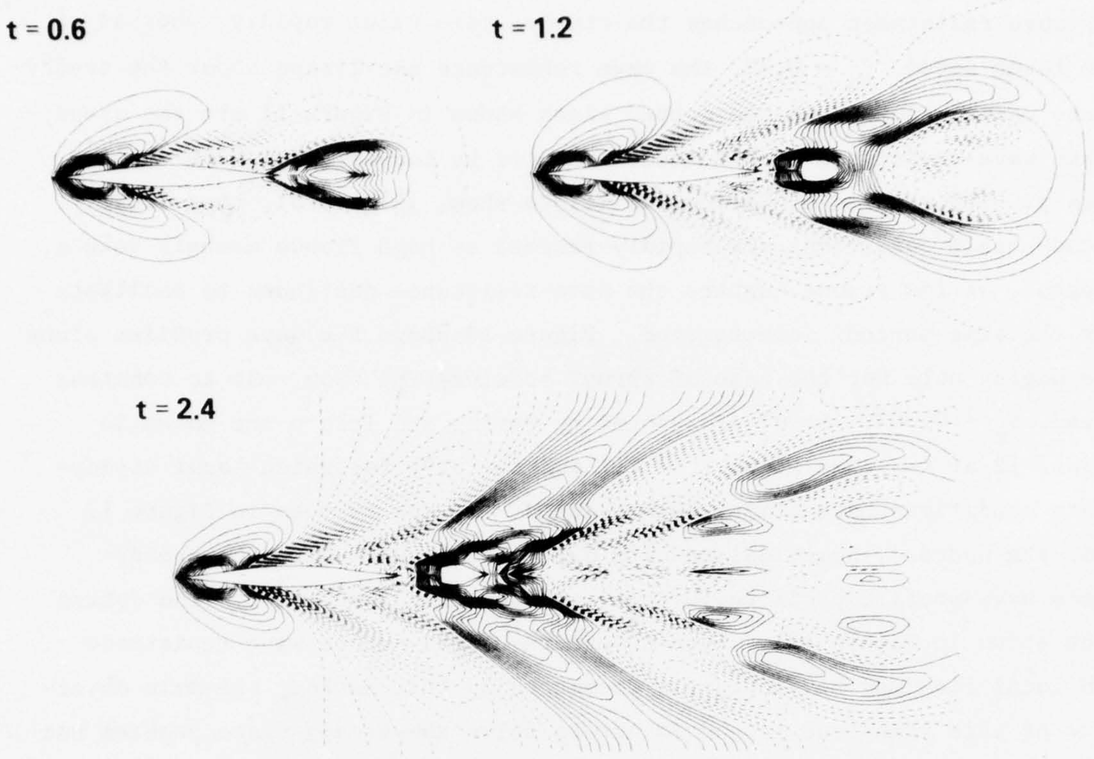
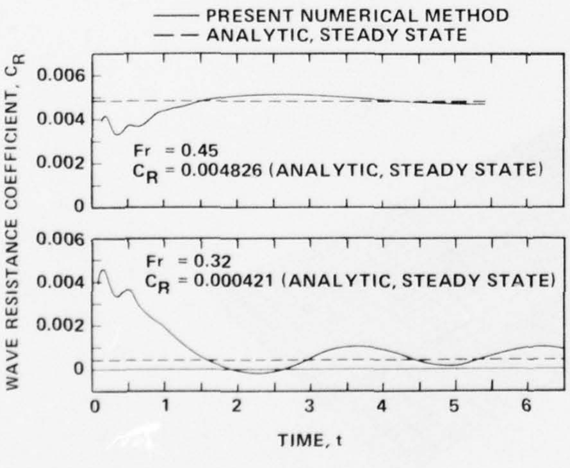


Figure 10 - Time Sequence of Free-Surface Contours for Wigley Parabolic Hull (Ohring and Telste, NP 1977)



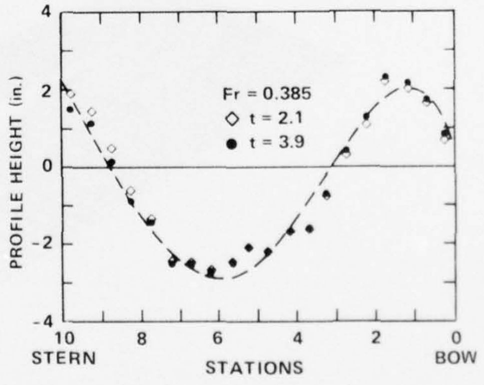


Figure 11 - Wave Resistance of Wigley Parabolic Hull versus Time for Two Froude Numbers (Ohring and Telste, NP 1977)

Figure 12 - Comparison of Numerical and Analytical Wave Profiles for Wigley Parabolic Hull (Ohring and Telste, NP 1977)

the wave resistance approaches the steady-state value rapidly, whereas at the lower speed, $F_n = 0.32$, the wave resistance oscillates about the steady-state value. Note that the dotted lines shown in Figure 11 are the steady-state wave-resistance coefficients computed by conventional thin-ship theory. The results of Ohring and Telste show, in general, that local steady-state conditions are rapidly reached at high Froude numbers values, whereas, at low Froude numbers the wave-resistance continues to oscillate for the time periods investigated. Figure 12 shows the wave profiles along the Wigley hull for the case of abrupt acceleration from rest to constant speed, $F_n = 0.385$. Results computed by Ohring and Telste are shown in Figure 12 at two time steps (t = 2.1 and t = 3.9) for which local steady-state conditions have almost been reached. It can be seen in Figure 12 that the unsteady numerical results agree fairly well with the steady-state wave-profile predicted by conventional thin-ship theory (the dotted line shown in Figure 12). Even though the steady-state wave resistance and local flow may be accurately predicted by this method, the main objective of this transient method is not to solve the steady-state problem but to solve the more general unsteady problems.

Figure 13 shows another interesting problem solved by Ohring's method: a surface effect ship (SES) accelerating from rest. The SES is represented

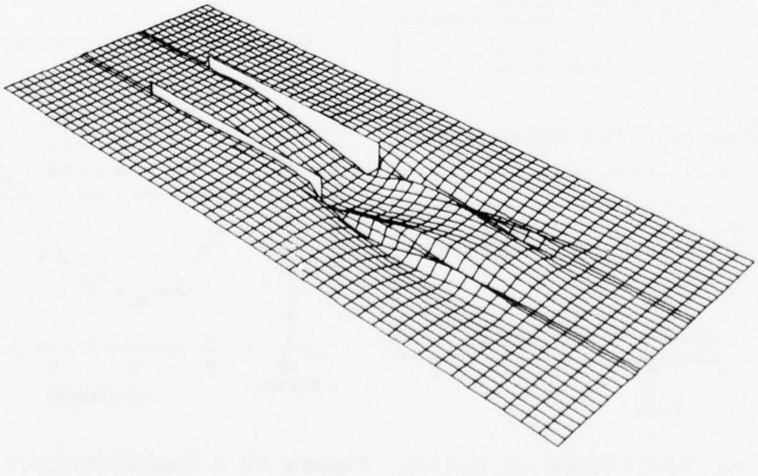


Figure 13 - Free-Surface Elevations for Accelerating Surface Effect Ship (Unpublished)

by a pressure distribution between two thin plates. This result seems to indicate that the flow is nearly two-dimensional between the two plates and that three-dimensional effects dominate the free-surface disturbance only behind the body. Since these are preliminary results for only one particular case, no general conclusion should be drawn from this initial investigation with regard to the free-surface flow past an SES. But these results do show the power of these new numerical methods in obtaining solutions of hydrodynamic problems which were beyond the capability of conventional methods of analysis.

Ship Maneuvering

At the present time, ship maneuvering characteristics cannot be predicted by any purely computational method. The time-domain computer simulation methods now in use at the DTNSRDC for estimating ship maneuvering characteristics utilize several experimentally obtained coefficients. Therefore, one objective of the Numerical Program has been to develop not only purely computational methods for predicting ship maneuvering characteristics, but also to develop numerical methods for predicting the hydrodynamic coefficients needed for the time-domain simulation of ship maneuvering.

Haussling and Van Eseltine (NP 1976a) have developed a method for analyzing the local flow field and the hydrodynamic forces and moments on an ACV performing any prescribed maneuver in calm water or in some given sea condition. In this method, the ACV is represented by a specified pressure distribution which may be a function of time. The potential flow problem is solved in a completely confined fluid domain so that Fourier series representation of the potential can be used. The final results include the wave resistance, side force, yawing moment, total power, wave elevations, and local flow field.

Sample results obtained by the method of Haussling and Van Eseltine are presented in Figures 14 and 15. Figure 14 shows the wave contours for an ACV performing a turn in otherwise calm water, whereas Figure 15 shows the yawing moment exerted on the ACV and the power expended by the ACV as

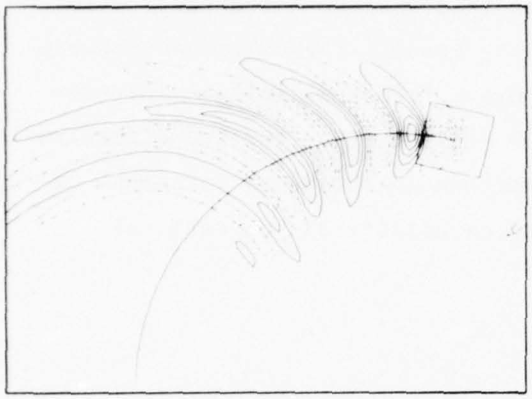


Figure 14 - Wave Elevations Generated by an Air Cushion Vehicle Moving over Calm Water (Haussling and Van Eseltine, NP 1976a)

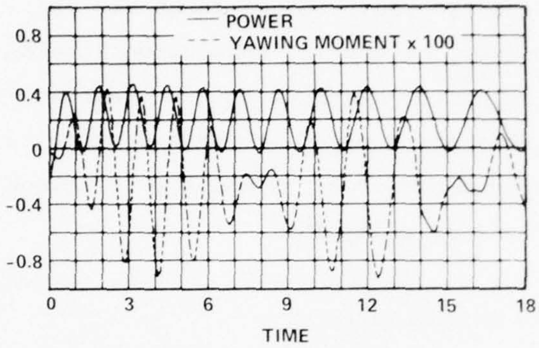


Figure 15 - Yawing Moment and Power versus Time for an Air Cushion Vehicle Moving over a Disturbed Sea (Haussling and Van Eseltine, NP 1976a)

functions of time for the case of an ACV moving over a disturbed sea. It is anticipated that this numerical method will have many useful applications since it treats the very general case of an ACV moving with arbitrary trajectories in a specified sea condition.

The lateral stability characteristics of a body depend primarily on its outline, so that a vertical flat plate is a useful model of a maneuvering monohull, strut, or surface effect ship. For this reason Chapman (NP 1976a) has developed a method for predicting the flow past vertical yawed surface piercing plates advancing at constant speed. Figure 16 shows the computed free-surface disturbance generated by a yawed plate. The three-dimensional problem is solved by applying the same slender-body approximations as discussed for Chapman's (NP 1975) ship-motion work and solving the resulting two-dimensional initial-value problem by a finite-difference method. Chapman (NP 1976a) developed separate numerical methods for linear, second-order, and nonlinear free-surface conditions. Results for the side-force coefficient are shown in Figure 17 where, in the upper right corner, the grid system for the nonlinear method is shown.

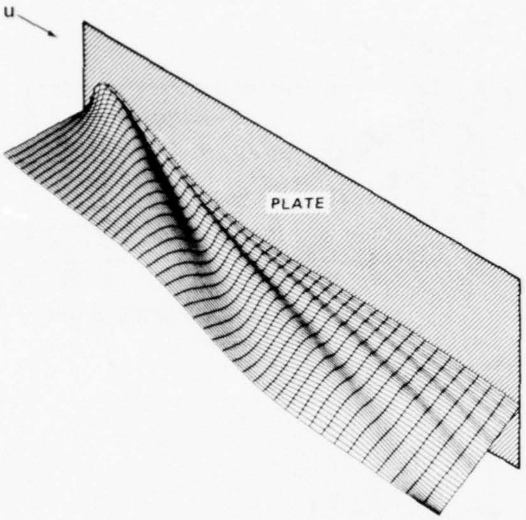


Figure 16 - View of Free Surface for Plate Yawed to Starboard (Chapman, NP 1976a)

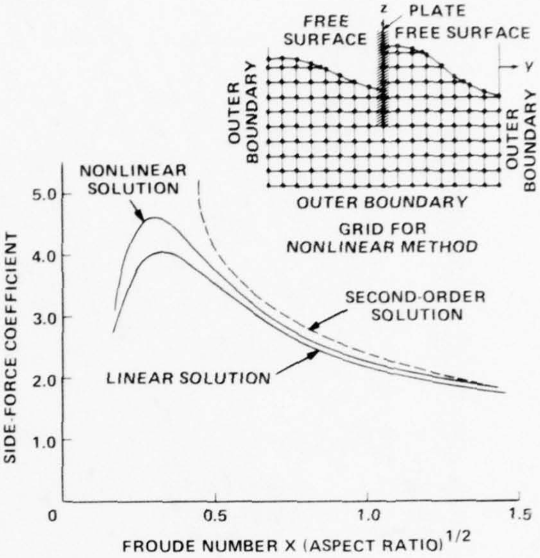


Figure 17 - Linear, Second-Order, and Nonlinear Solutions for Side-Force Coefficients for Yawed Plate (Chapman, NP 1976a)

Chapman (1977) also conducted experiments in order to evaluate the accuracy of this method. Figure 18a shows experimental free-surface elevation contours for a flat plate with a 5-degree angle of attack advancing at 6 knots. These free-surface contours were measured by stereographic photogrammetry. A comparison between experimental and theoretical results for a longitudinal wave cut is presented in Figure 18b, where it can be seen that the agreement is good. Chapman's results show that the measured values of side force, yaw moment, and roll moment also agree well with results obtained by his numerical method.

Large-Amplitude Ship Motions

In linear ship-motion theories, it is assumed not only that the free-surface conditions can be linearized, but also that the ship displacements

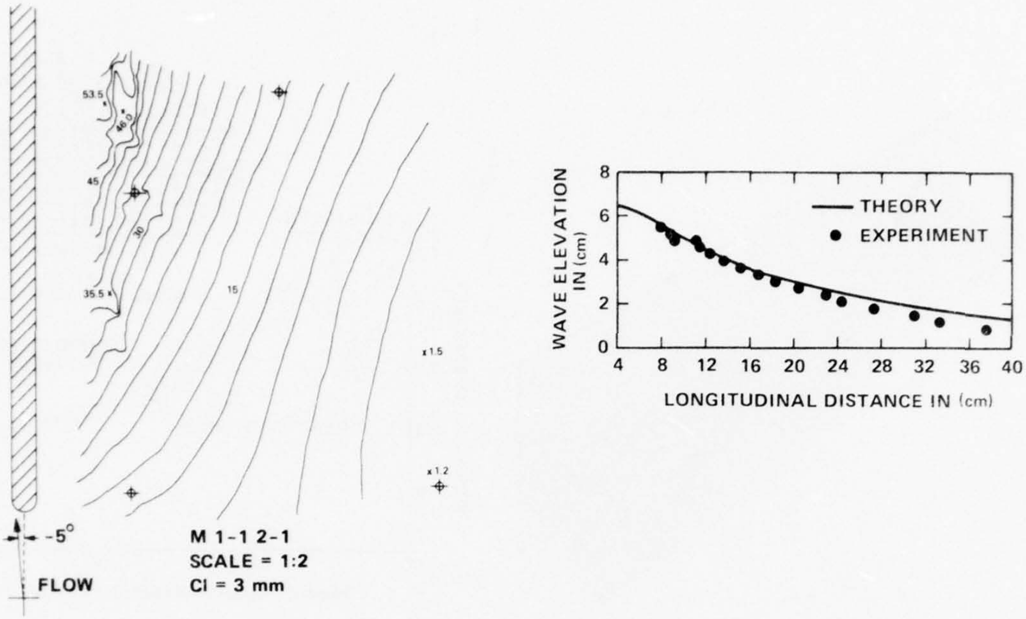


Figure 18a - Experimental Free-Surface Contours for Flat Plate with 5-Degree Angle of Attack and Advancing at 6 Knots

Figure 18b - Comparison between Experimental and Theoretical Longitudinal Wave Cut 23 Centimeters from Plate

Figure 18 - Free-Surface Elevations for Yawed Plate (Chapman, 1977)

are small relative to the ship dimensions. The exact body-boundary condition then can be approximated by satisfying it at the mean position of the hull. However, ship motions cannot always be assumed to be small. In fact, they can be on the order of magnitude of the ship dimensions even in typically moderate sea conditions.

Figure 19 shows computed bow motions of a destroyer hull in head waves (Salvesen, NP 1978). These results indicate that the bow displacement is nearly equal to the ship draft for waves with a height-to-length ratio H/λ of only 0.013. Since the maximum value of H/λ for nonbreaking waves is almost ten times this value (Salvesen and von Kerczek, NP 1976a), one may expect that the assumption of small bow displacements is violated during a large portion of the ship's operating life.

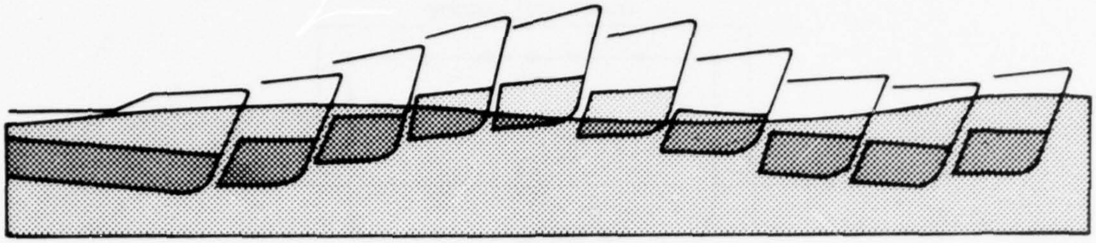


Figure 19 - Bow Motion of Destroyer Hull in Sinusoidal Wave with Wavelength, λ = 1.20L, Wave Height, H/λ = 0.13, and Froude Number, F_n = 0.35 (Salvesen, NP 1978)

Therefore, another goal of the Numerical Program is to develop new numerical methods which can predict large amplitude ship motions. This is a very complicated nonlinear problem where linearization cannot, in general, be applied to the boundary conditions at the hull or at the free surface. However, if it is assumed that the frequency of the ship motions is sufficiently small,* and that the slope of the incident waves is fairly small, then it may be valid to linearize the free-surface conditions even for large body displacements. One must realize though that this low-frequency assumption will greatly restrict the class of practical ship-motion problems which can be solved by such methods. But there are many important ship-motion problems in which the oscillation frequency is low. Examples are the ship motions in following and quartering seas, roll motions in beam seas, and pitch and heave in long head waves.

As a start on developing such a low-frequency ship-motion theory, Chapman (NP 1979) has developed a two-dimensional, large-amplitude, time-domain method with a linearized free-surface condition. A spectral representation of the wave field combined with a source distribution over the entire body, as shown in Figure 20, is used. The wave field is represented by two series which are both harmonic in space and time. The coefficients

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*Note that when the frequency is small, the slope of the body-generated waves will also be small.

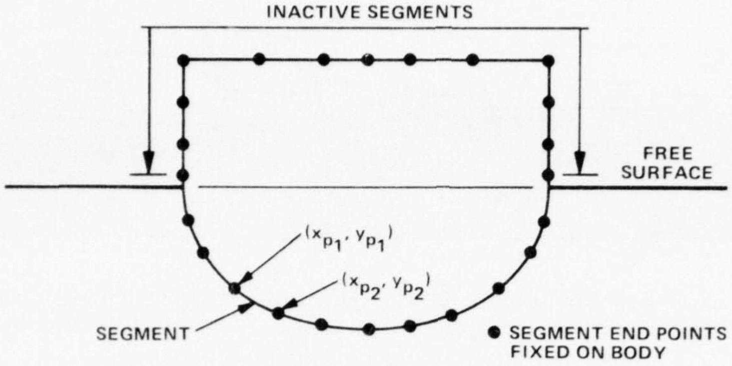

Figure 20 - Body Segments for Large-Amplitude Body-Displacement Computations (Chapman, NP 1979)

of these series and the strengths of the submerged source segments on the body are updated at each time step. There are no restrictions with regard to the body displacement other than that the motions must be so slow that they only result in small free-surface disturbances. For example, the upper part of the body (the deck) may become completely submerged. An application of this method is the analysis of capsizing problems.

Figures 21 and 22 show results computed by Chapman for the wedge-entry problem. In Figure 21, the computed pressure distributions on the wetted surface of two wedges with ψ = 5- and 15-degree apex angles, respectively, are shown at one time step. Theoretical results for the wedge with ψ = 0 degree are shown for comparison. Figure 21 shows the effect of wedge angle on the pressure. The larger the wedge angle, the higher the pressure along the side of the wedge. The free-surface elevations at three time steps are shown in Figure 22 for a wedge with half angle, ψ = 15 degrees.

NONLINEAR TWO-DIMENSIONAL SOLUTIONS

A major difficulty in solving ship-wave problems is that the free-surface boundary conditions are not only nonlinear, but they must be

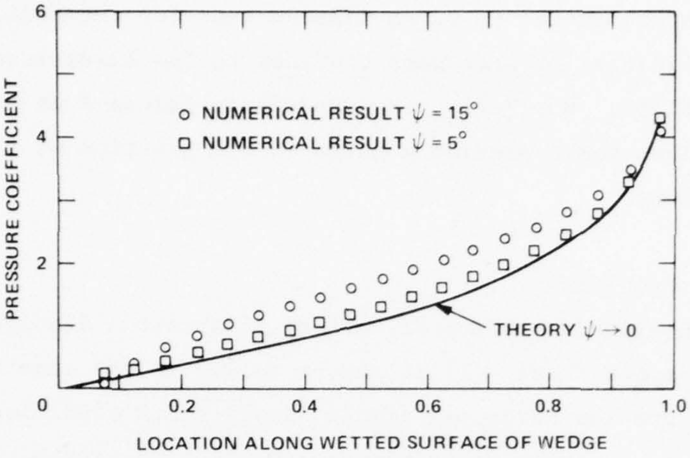

Figure 21 - Pressure Distribution on Wetted Surface of Wedge Entering Free Surface (Chapman, NP 1978)

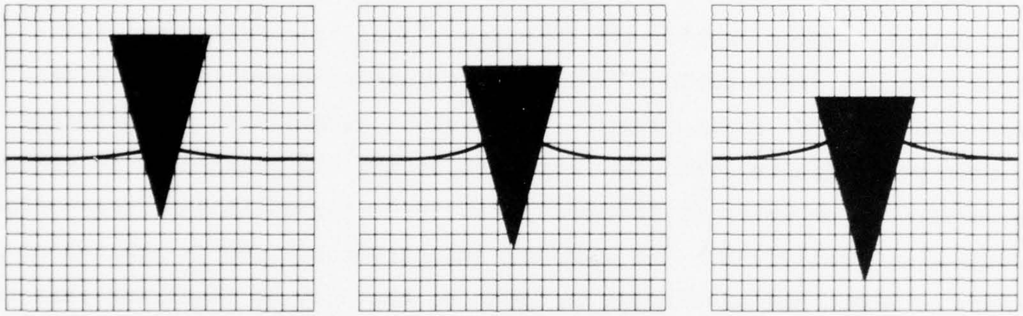
t = 0.4 t = 0.6 t = 0.8

Figure 22 - Free-Surface Elevations for Wedge Entry, Half-Angle, ψ = 15° (Chapman, NP 1979)

satisfied at the actual location of the free surface which is a priori unknown and must be found as part of the solution. Classical analytical techniques attempt to overcome this problem by building up perturbation solutions about a known free surface (the uniform stream). Such techniques are described by Salvesen (1969).

Part of the effort in the Numerical Program was devoted to research on numerical methods in which the nonlinear implicit equations are solved directly. This was considered to be an immense task for three-dimensional problems so that initial efforts were confined to two-dimensional nonlinear free-surface problems. Hopefully, the experience gained from the two-dimensional problems would provide a guide to the solution of the three-dimensional problems.

Steady Body-Wave Problems

The steady nonlinear problem of uniform flow past a disturbance may be solved by two approaches: (1) it may be solved in the time domain as an initial-value problem advancing toward steady-state conditions, and (2) it may be solved as a steady-state problem in which an assumed free-surface shape is iterated until the free-surface conditions are satisfied. In this section we shall discuss first the steady-state iteration approach. The initial-value approach will be discussed in the next section on unsteady problems.

A numerical method has been developed which solves the exact nonlinear potential-flow problem for two-dimensional hydrofoils, and free-surface pressure distributions advancing at uniform speed in otherwise undisturbed water of finite depth. The Laplace equation is approximated by a five-point finite difference equation in a field bounded by an assumed free-surface shape which is systematically corrected until the free-surface conditions are satisfied. The upstream infinity condition is applied at a distance of about one wavelength in front of the body by requiring that the flow be uniform and have a horizontal free surface there. Because the problem is steady and because the upstream boundary condition does not admit waves propagating upstream, the downstream closure condition is satisfied by simply assuming the proper mass flux out of the region at a finite distance downstream of the disturbance. This downstream closure condition has been shown to work well and it has been found to affect the accuracy of the computations up to a distance of less than half a wavelength in front of the section where it is applied. Computations have shown that the downstream condition can be applied as close as only one and one-half wavelengths behind the body with no discernable effect on the computed forces. Von Kerczek and Salvesen (NP 1974) demonstrated that this iteration scheme converges to a steady solution with periodic waves downstream of the disturbance. Comparisons between the nonlinear numerical results and second-order perturbation theory show reasonable agreement. The finite difference grid system and the location of the submerged vortex, which was used to simulate a hydrofoil in this case, is schematically shown in Figure 23. In this first investigation, the results, which were only for moderately steep waves, showed encouraging trends and that the method is effective.

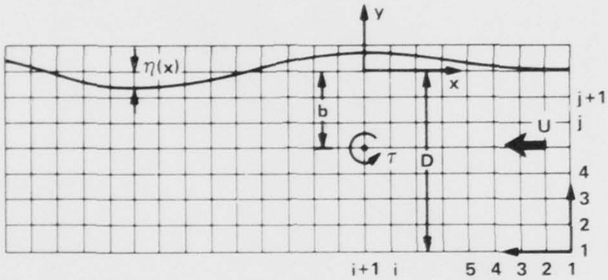

Figure 23 - Finite Difference Grid for Submerged Vortex Case
(Salvesen and von Kerczek, NP 1976a)

Von Kerczek and Salvesen have used this finite-difference method in the investigation of several important nonlinear aspects of free-surface flow past two-dimensional disturbances. They have demonstrated that the method can solve problems which are highly nonlinear and with wave steepnesses near that for which waves are observed to break. For most of the cases investigated, they have found good agreement between the numerical results obtained by solving the complete nonlinear problem and third-order perturbation theory results. Furthermore, these investigations have shown that for subcritical shallow-water flow some of the nonlinear free-surface effects are very sensitive to depth. In the following paragraphs some sample results obtained by von Kerczek and Salvesen will be discussed.

Figure 24 shows the wave resistance as a function of vortex circulation predicted both by the numerical finite-difference method and by first-, second-, and third-order perturbation theory (Salvesen and von Kerczek, NP 1976a). The agreement between third-order theory and numerical results is remarkable even for the larger vortex strengths where the steepnesses of the generated waves are close to the breaking limit. The results presented in Figure 24 are for positive vortex circulation. For negative circulation strengths, Salvesen and von Kerczek found that the perturbation theory did not agree well with their numerical results. A considerable amount of experimentation with the numerical method and the perturbation theory, and

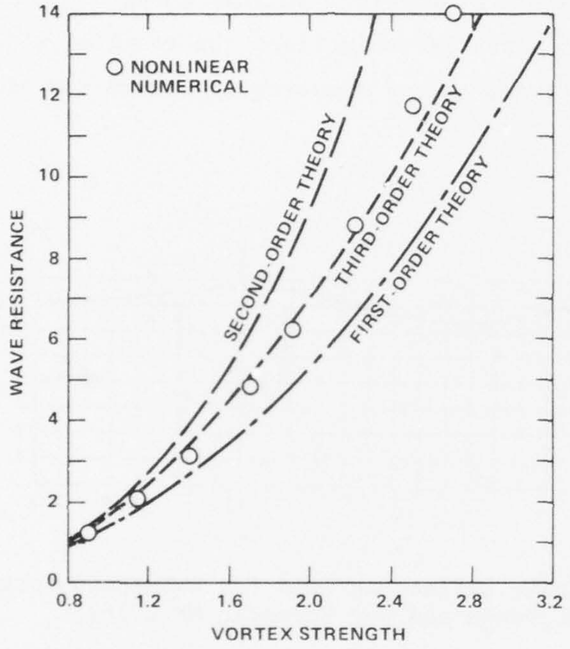

Figure 24 - Wave Resistance as a Function of the Strength of Submerged Vortex Advancing at Constant Speed (Salvesen and von Kerczek, NP 1976a)

also evidence obtained from calculations obtained by other investigators using perturbation theory, led Salvesen and von Kerczek to conclude that numerical results are correct and that the accuracy of perturbation theory is not only a function of wave steepness but also depends on the type of disturbance.

Salvesen and von Kerczek (NP 1975) have demonstrated that their numerical iteration method predicts with good accuracy the wave resistance and the waves generated by a hydrofoil moving at a fixed submergence with uniform speed. Figure 25 shows the shape of the foil that was used as a test case and the finite-difference grid system that was used in their calculations. A series of experiments in a towing tank was conducted with this hydrofoil and Figure 26 shows a photograph of one test result. The free-surface elevations predicted by linear theory and the numerical method, and those obtained experimentally are compared in Figure 27. It is seen that the numerical results obtained by solving the complete nonlinear problem agree well with the experimental results whereas there are larger

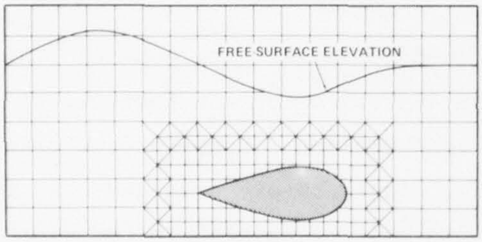

Figure 25 - Finite Difference Grid System for Submerged Foil (Salvesen and von Kerczek, NP 1975)

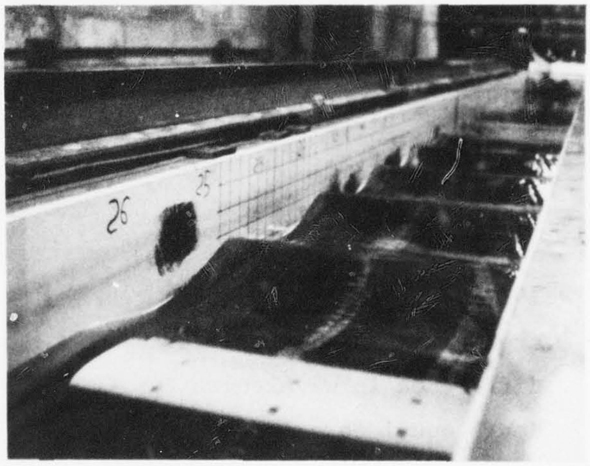

Figure 26 - Experiment for Foil Advancing at U = 3.38 ft/sec (Salvesen and von Kerczek, NP 1975)

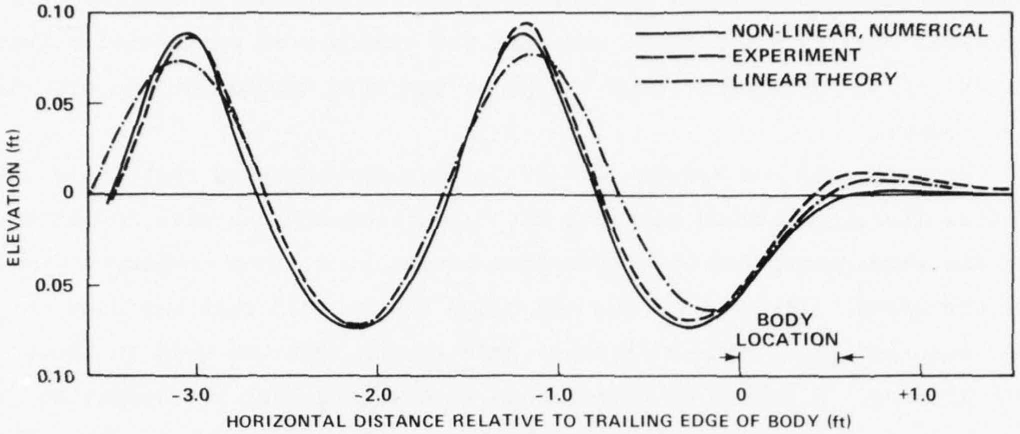

Figure 27 - Comparison of Experimental, Theoretical, and Numerical Free-Surface Elevations for Submerged Foil Advancing at U = 3.18 ft/sec (Salvesen and von Kerczek, NP 1975)

discrepancies between the linear theory predictions and the experimental results. Linear theory underpredicts the wave amplitudes and overpredicts the wavelengths.

The same numerical method has been used to investigate some nonlinear aspects of subcritical shallow-water flow (Salvesen and von Kerczek, NP 1978). This investigation reveals that some nonlinear free-surface effects are very sensitive to depth. For example, linear theory predicts that the difference in wavelength for infinite depth and the wavelength for finite depth equal to half the infinite-depth wavelength is less than one-half of a percent. However, the fifth-order perturbation results and the results of von Kerczek and Salvesen's numerical method given in Figure 28 show that due to nonlinear effects, this difference in wavelength can be as large as 5 percent if the waves have a wave-height-to-wavelength ratio $H/\lambda = 0.10$. This is an important result since nonlinear numerical computations for finite depth are often evaluated by comparing them with infinite-depth perturbation results.

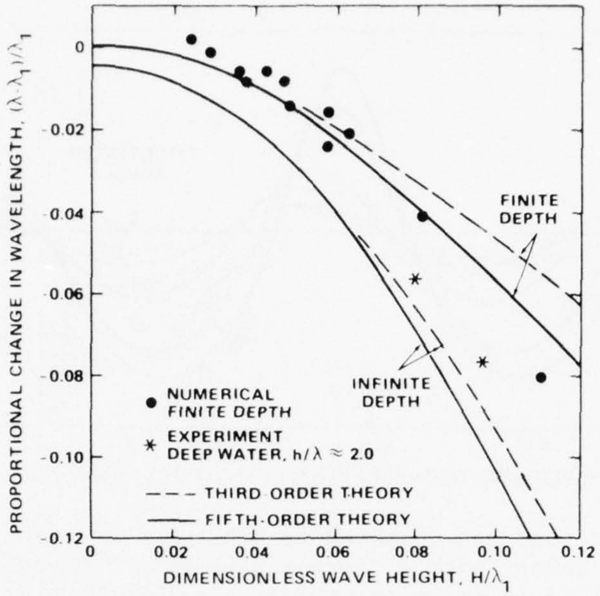

Figure 28 - Nonlinear Change in Wavelength as a Function of Wave Height H for Depth-to-Wavelength Ratio 0.50 (Salvesen and von Kerczek, NP 1978)

Figure 29 shows some other important nonlinear finite-depth effects which were clarified using the numerical method of von Kerczek and Salvesen. In this figure, free-surface elevations computed by Salvesen and von Kerczek (NP 1978) are presented for steady flow past a vortex with four different circulation strengths. The depth-to-wavelength ratio is 0.160 and corresponds to shallow but subcritical flow. The upstream rise in the free-surface level due to nonlinear blockage effect is clearly noticeable. The lowering of the mean depth of the downstream waves can also be seen. Experimental results obtained by Salvesen and von Kerczek (NP 1978) seem to verify that this raising and lowering of the free-surface level can be predicted to within 15-percent accuracy by Benjamin's (1970) second-order theory. For the particular case presented in Figure 29, we note that the wavelength increases with increasing disturbance strength. This is opposite to the deep-water case where the wavelength always decreases with

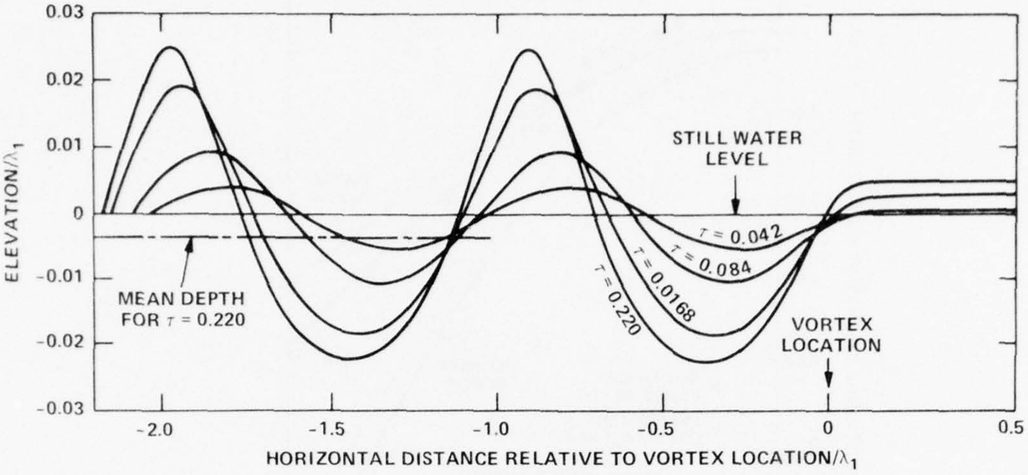

Figure 29 - Wave Elevations Computed by Nonlinear Numerical Method for Submerged Vortex with Different Strengths τ Advancing at Constant Speed in Undisturbed Finite-Depth Water (Salvesen and von Kerczek, NP 1978)

increasing disturbance strength. These results provide further useful information concerning the nature of free-surface flow that will be important to efforts in the numerical modeling of the ship-wave problem.

In a study of the nonlinear effects for free-surface pressure disturbances advancing with constant speed on the free surface (i.e., a model of the ACV), von Kerczek and Salvesen (NP 1977) show the interesting result that "the main effects of nonlinearities of the (pressure) problem are due to changes in the phasing (increase of the distance) between the front and rear portion of the local free-surface deflection." This can clearly be seen in Figure 30 where free-surface elevations are shown for two values of the pressure coefficient $C_p = 0.80$ and $C_p = 1.60$. Here, $C_p = 100\ p/\rho gL$. Note that in this particular case the nonlinear effects are so dominating that the doubling of the pressure coefficients from $C_p = 0.8$ to $C_p = 1.6$ results in only a very slight increase of the wave height (and hence wave-resistance) although the amplitude of the local disturbance is almost exactly doubled.

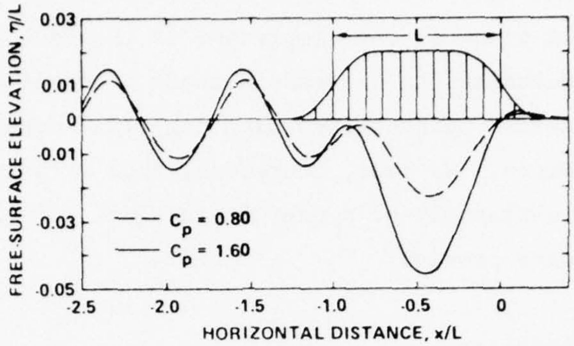

Figure 30 - Free-Surface Elevations for Pressure Disturbance with C_p = 0.80 and C_p = 1.60 and Advancing at $F = U/\sqrt{gL} = 0.357$ with Depth D/L = 0.43 (von Kerczek and Salvesen, NP 1977)

Probably one of the most important findings of the above cited studies of two-dimensional nonlinear waves generated by a traveling obstacle is the fact that third-order perturbation theory agrees fairly well in most cases with numerical results. In only one case--negative vortex circulation (Salvesen and von Kerczek, NP 1976a)--is the discrepancy substantial between third-order theory and the numerical results. In all of the other cases investigated, the agreement between the numerical and third-order predictions is good even for waves with steepness close to the steepness for which waves are observed to break. Furthermore, in a recent paper, Doctors and Dagan (1979) have compared results obtained by their new third-order finite-depth perturbation method as well as three other perturbation methods with the numerical results of von Kerczek and Salvesen (NP 1977). For flow past two-dimensional free-surface pressure distributions the third-order perturbation and one of the other perturbation theories give satisfactory agreement with the von Kerczek-Salvesen numerical results. This is very encouraging since the success of perturbation theory for two-dimensional problems is an indication that a perturbation theory may also predict accurately the nonlinear aspects of the complete three-dimensional ship-wave problem. Perturbation methods have many advantages over completely numerical schemes which satisfy the exact free-surface boundary conditions. One advantage of the perturbation methods is the much shorter computation time, but probably more important is the fact that all of the numerical methods including the unsteady methods we shall discuss in the next section, have severe difficulties with numerical convergence in the case of very steep waves. We feel, therefore, that a third-order perturbation approach may ultimately be a useful practical solution method for the nonlinear ship-wave problem.

Unsteady Body-Wave Problems

A considerable effort has been concentrated on numerical solutions of the initial-value problem of a two-dimensional body starting from rest with arbitrary motion. Ideal fluid is assumed and the exact free-surface conditions are satisfied. In the initial-value unsteady problem method one can obtain solutions for both the transient phase of the body motion and the steady phase by letting the time advance to appropriate values. Haussling, Van Eseltine, and Coleman have developed some efficient numerical methods for solving several interesting unsteady nonlinear free-surface problems. We shall briefly discuss these encouraging results.

The first successful numerical method developed by Haussling and Van Eseltine (NP 1974) solves the problem of a pressure distribution moving with unsteady motion over the free surface. A finite-difference method is used to advance the solution in time while simultaneously solving the Laplace field equations by a spectral (Fourier series) method. The results of their method are encouraging and clearly show that the waves have the character of nonlinear Stokes waves with a shortening of the wavelength as predicted by third-order theory. However, to improve the versatility of the method, Haussling and Van Eseltine (NP 1975) changed to a finite-difference method of solving the Laplace equation. With this method they obtained good agreement with the spectral method.

In a further development of the Haussling-Van Eseltine finite-difference method of solving unsteady problems, Haussling and Coleman (NP 1977) developed a finite-difference technique with boundary-fitted coordinates. This method can be applied to problems of the unsteady motion of cylinders on or beneath the free surface and possibly may also be extended to three-dimensional bodies. For the case of a submerged circular cylinder, the time-dependent physical region shown in Figure 31 is transformed into an H-shaped computation region. Since the geometry of the flow region is not known in advance, but is part of the solution, the transformation must be computed simultaneously with the flow field at each time step. Some numerical instability difficulties were encountered with this method, but they were overcome by a numerical filtering procedure.

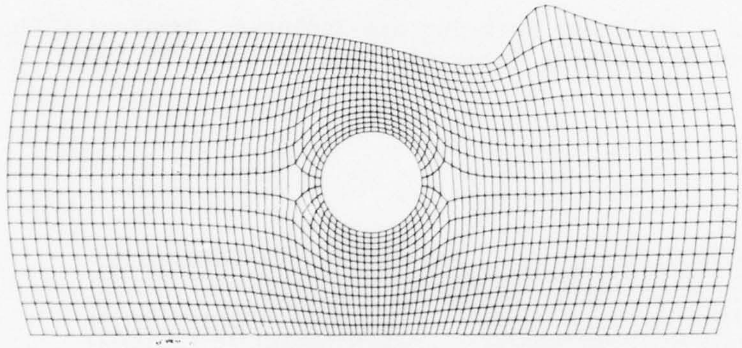

Figure 31 - The Boundary-Fitted Coordinate System for the Translating Cylinder (Haussling and Coleman, NP 1979)

As an example of some results that can be obtained by the Haussling-Coleman method, Figure 32 shows some free-surface elevations behind a submerged circular cylinder started from rest at three values of time after the start of the motions. The results of solving both the nonlinear and linear problems with the Haussling-Coleman method are given in the figure which show that the nonlinear free-surface effects may be significant for this case. As another interesting example of the power of this method we show an application of this boundary-fitted coordinate-system method to the problem of a submerged cylinder in sway motion in Figure 33.

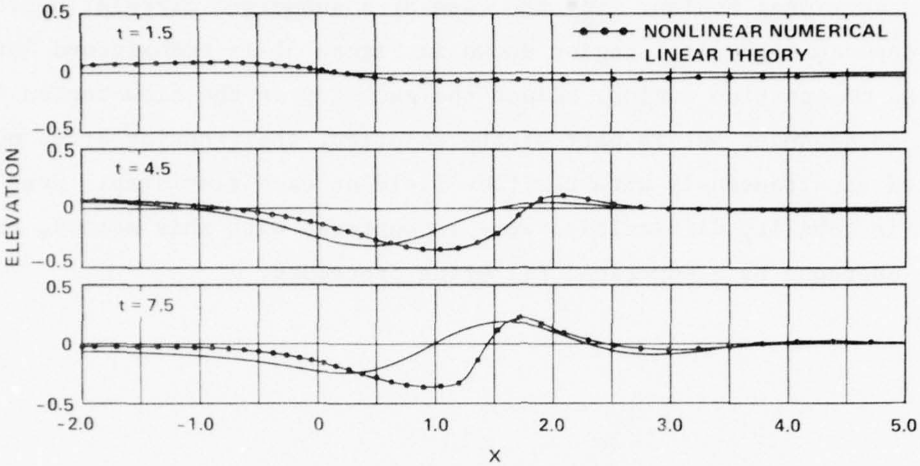

Figure 32 - Nonlinear Free-Surface Evolution Compared with Linear Development (Haussling and Coleman, NP 1979)

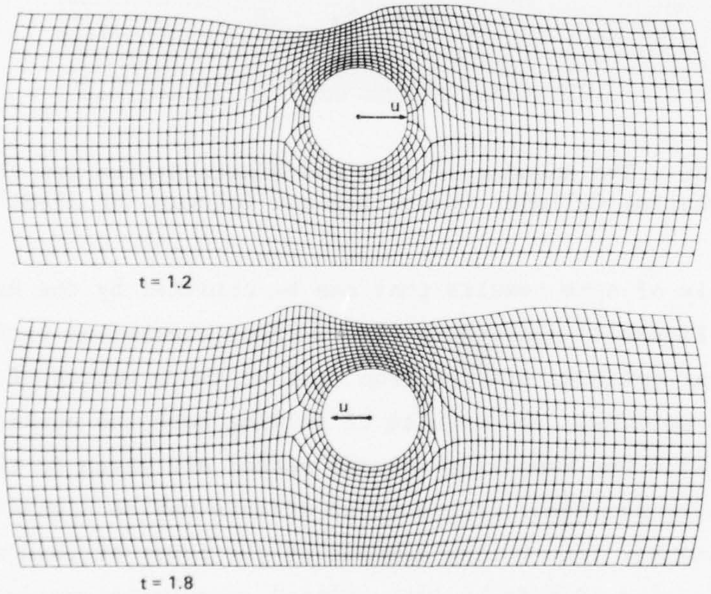

Figure 33 - Time-Dependent Boundary-Fitted Coordinates for Swaying Cylinder (Haussling and Coleman, NP 1977)

Haussling and Van Eseltine (NP 1976b) have also developed a finite-difference method for solving two-dimensional unsteady planing-body problems. The shape and location of the body are specified and the time-dependent wetted length is computed. The method has been applied successfully to planing bodies with both sharp and smooth trailing edges. The evolution of the free-surface for a translating body with a smooth trailing edge is shown in Figure 34. In these computations, the free-surface conditions are linearized; however, the method has been extended (Haussling, NP 1979) and used in a study of the nonlinear effects of two-dimensional stern waves as shown in Figure 35. From this study Haussling concludes that "for draft-based Froude numbers (F_n) less than three the nonlinear effects can be significant." Presently a code for solving the three-dimensional transom-stern wave problem is being prepared. We expect that this study will reveal some of the unknown aspects of the flow past transom sterns. It is very important in solving the wave-resistance problem for

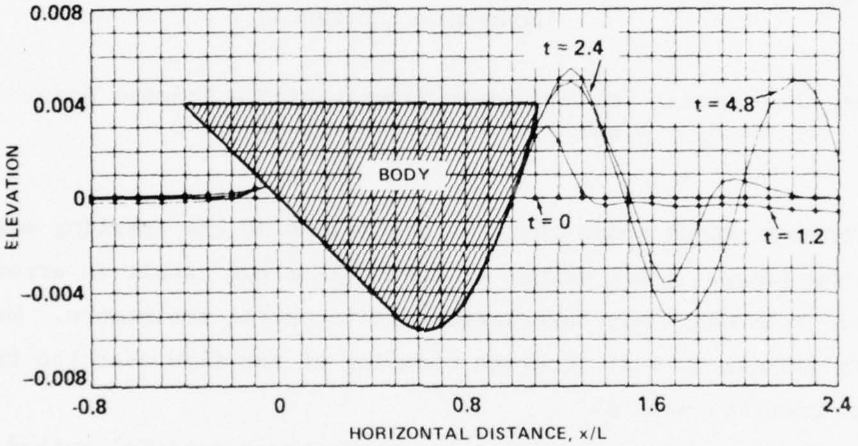

Figure 34 - Evolution of Free Surface for Planing Body with Smooth Trailing Edge (Haussling and Van Eseltine, NP 1976b)

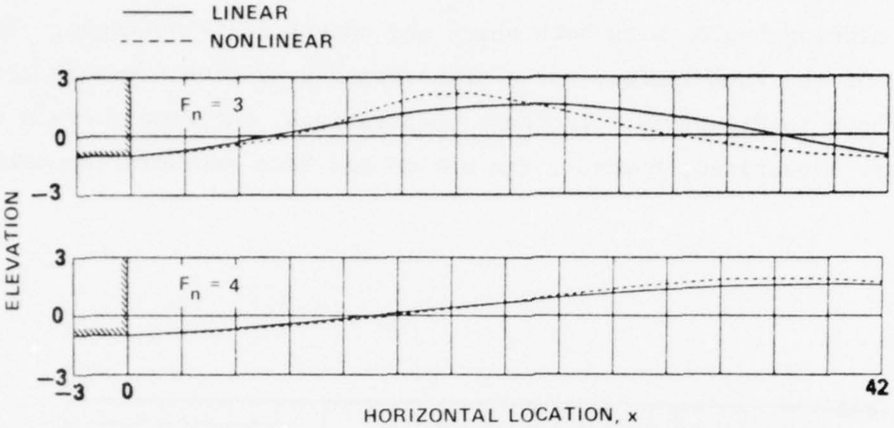

Figure 35 - Linear and Nonlinear Waves behind a Transom Stern at $F_n = 3$ and $F_n = 4$ (Haussling, NP 1979)

high-speed transom-stern ships that the conditions at the trailing edge be satisfied accurately. Small errors at the transom can result in error in the predicted trim which may have large effects on the resistance. We believe that one can achieve accurate modeling of the flow near the transom stern using numerical methods.

As already stated, the initial-value approach is a useful method for solving steady-state nonlinear ship-wave problems. However, most investigators using the initial-value approach have encountered difficulties in obtaining steady-state conditions with steep nonbreaking waves. Haussling and Coleman (NP 1977) have obtained steady-state conditions with wave steepnesses approximately 80 percent of the steepness at which waves are observed to break. For steeper waves, their method encounters difficulties with regard to numerical stability at such an early time step that a wave train has not yet been developed behind the first wave crest aft of the body. Figure 36 shows the wave profile obtained by linear theory and the

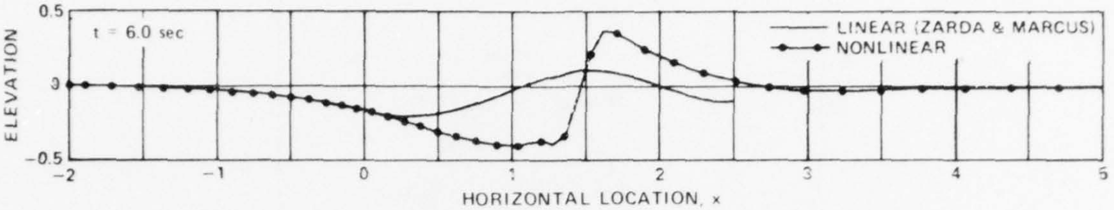

Figure 36 - Nonlinear Unsteady Free-Surface Elevation for
Translating Cylinder Compared with Linear Steady-State
Results (Haussling and Coleman, NP 1977)

unsteady profile obtained by the nonlinear numerical method of Haussling and Coleman at the last time step before the computations broke down due to numerical instability. Haussling and Coleman state that after this time step, "features develop which cannot be adequately handled by the numerical scheme." Whether such features have anything to do with physical reality has not yet been determined and requires much experimental and numerical study.

One of the critical problems with the unsteady approach is that even if a steady-state condition with nonbreaking waves exists, an unsteady numerical method may fail because of the presence of wave breaking during the transient period. Model-tank experiments have shown that there are steady-state conditions with stable nonbreaking waves that can only be obtained by accelerating the body through intermediate conditions where wave breaking is present. Figure 37 shows the results from an experiment conducted in a 40-foot tank having a two-by-two-foot cross section (Salvesen and von Kerczek, NP 1976b). A submerged foil which spanned the width of the tank was used as the wave generator, as shown previously in Figure 26.

The shaded region in Figure 37 indicates the combined conditions of foil submergence and speed for which breaking occurred. The numbers next to each point in the figure give the maximum slopes measured at the first crest of unbroken waves. The inception of wave breaking is affected by the acceleration of the foil before breaking occurs. The left- and right-hand

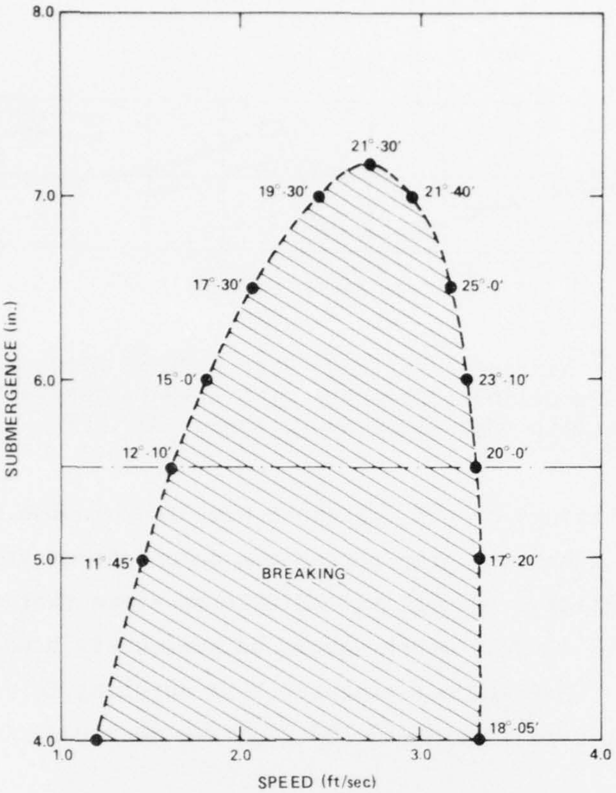

Figure 37 - Wave Breaking as a Function of Foil Submergence and Speed (Salvesen and von Kerczek, NP 1976b)

parts of the dotted lines in Figure 37, which we shall refer to as the lower and upper speed limits for nonbreaking waves, have been obtained by two different acceleration patterns. For the lower speed limits, the foil was accelerated very slowly until breaking occurred, whereas for the upper speed limits, the foil was accelerated rapidly to a speed somewhat higher than the limiting speeds; then after uniform nonbreaking waves had formed behind the foil, it was slowly decelerated until breaking occurred. Thus, the breaking conditions were always obtained by approaching them from an established stable condition. These experimental results seem to indicate that there are steady-state conditions that cannot be obtained by accelerating the body from rest without wave breaking occurring at intermediate stages and, therefore, it seems likely that any numerical scheme modeling such cases would also have to break down at some intermediate time step.

This wave-breaking problem may be avoided by use of any of the following initial-value approaches. For the two-dimensional case of a submerged body as investigated by Haussling and Coleman (NP 1977 and NP 1979), one could, for example, let the starting condition be the uniform flow past a deeply-submerged body and then slowly decrease the submergence until the desired condition is reached. One could also let the starting condition be the uniform flow past an infinitesimally thin body, and then slowly increase the thickness of the body. Such an approach would be applicable to both two- and three-dimensional bodies. However, these approaches have the disadvantage that the geometry of the problem would change with each time step. Therefore, a better approach may be to consider the body as a porous medium. One would start with uniform flow, going completely through the body and then, in the time domain, change the body-boundary condition so that less and less fluid goes through the body until it finally becomes a solid body.

We stress again the belief that initial-value approaches may have the potential for solving steady ship-wave problems with steep nonlinear waves. Presently, a study is being performed to demonstrate that the unsteady approach can advance for a sufficiently long period of time so that a uniform wave train is formed downstream of the disturbance with steepness close to the wave-breaking limit. The accuracy of the steep-wave results obtained by the unsteady approach will be evaluated by comparing them with results obtained by steady-state perturbation theory and nonlinear steady-state numerical methods.

CONCLUDING REMARKS

The research conducted under the Numerical Naval Ship Hydrodynamics Program has yielded numerical methods for solving several ship-wave problems which could not have been solved five years ago. Nor can they be solved today by the traditional nonnumerical methods. The problems for which we now have successful potential-flow solution methods can be grouped into five areas:

1. The ship-wave resistance and local flow problem with linearized free-surface conditions and exact body boundary conditions; Dawson (NP 1977), Chang (NP 1977), Bai (NP 1977d), Ohring and Telste (NP 1977).

2. The fully three-dimensional ship motion problem with linearized free-surface conditions and the hull boundary condition satisfied at the mean position; Chang (NP 1977).

3. The exact nonlinear two-dimensional steady-state body-wave problem; Salvesen and von Kerczek (NP 1978).

4. The exact nonlinear two-dimensional unsteady body-wave problem for moderately steep waves; Haussling and Coleman (NP 1979).

5. The large amplitude two-dimensional body motion problem with exact body boundary condition and linearized free-surface conditions; Chapman (NP 1979).

Significant advances have also been made on several other important problems as discussed in the main text. However, only in the above stated areas can we consider that research is, in general, complete and further refinements and validation should be transferred to the development phase.

During the first five-year phase of the Numerical Program the emphasis has been on ship-wave problems which can be solved by *potential-flow* theory. We believe that the research effort in this area should be continued and that the most important unsolved potential-flow ship-wave problems are:

1. The nonlinear three-dimensional ship-wave resistance and local flow problem.

2. The large amplitude ship-motion problem.

The experience gained from the nonlinear two-dimensional research seems to indicate that a useful and immediate solution method for the nonlinear wave-resistance problem may be obtained by a perturbation method. It is recommended that work be continued in this area and on the development of iteration methods which satisfy the exact free-surface conditions. In the latter case, one can expect severe difficulties with numerical instability for cases with relatively steep wave slopes. Furthermore, methods should be developed for analyzing cases with extreme nonlinear effects as, for example, wave breaking and spray. The energy dissipation due to such effects is an important aspect of the total resistance problem for most high-speed naval ships.

The complete nonlinear large amplitude ship-motion problem is extremely difficult and complex. In addition to the difficulties involved with satisfying the nonlinear free-surface conditions, the hull boundary conditions must be satisfied at each time step at the actual location of the wetted hull surface. For the complete nonlinear case, it is necessary first to develop successful two-dimensional methods. For the three-dimensional case, one may first attempt to solve the low-frequency case, since the free-surface conditions can be linearized when the frequency is sufficiently low. Many of the important practical ship motion problems, as for example, the roll motions and the general motions in quartering and following seas, are low-frequency problems.

A useful fact to be aware of is that most of the important nonlinear effects associated with the ship wave problem occur only in local domains near the body. The most important nonlinear effects might be solved satisfactorily by applying nonlinear methods only in local domains and then matching these solutions to the far field which may be solved by some linear solution technique.

As already stated, the Numerical Naval Ship Hydrodynamics Program has concentrated its efforts so far on ship-wave problems which can be solved by potential-flow theory. This initial phase can be considered largely complete. The Numerical Program should now expand its effort and include other problems in the following areas of ship hydrodynamics:

1. Ship wave making and viscous boundary layer interaction.
2. Ship boundary layers and large-scale separated flow, including vortex shedding.
3. Hydrodynamics of ship propulsion.

It is believed that the application of advanced numerical techniques and computers to these other important areas of naval hydrodynamics may be as rewarding as their application has been to ship-wave problems. However, for most of the unsolved problems within the three above stated areas, we do not have as well-defined mathematical models as we have for ship-wave problems. Therefore, the development of successful numerical methods for solving these problems will require theoretical and experimental research in addition to the numerical work.

In a recent paper, Tulin (1978) discusses the future role of the computer relative to model experiments with regard to the prediction of ship hydrodynamic performance characteristics. He asked several of the model tank directors the following question: "Which old (model tank) tasks will be taken over by computers?" The answer given by Dr. W. E. Cummins deserves some attention. He stated simply: "Most of them." It is not hard to agree with this view considering the technical accomplishments over the last couple of decades and what can be expected within the next one or two decades. However, we must be aware that Dr. Cummins' prediction about the future role of computers can only become a reality if adequate support is given to the implementation of the research results. The implementation is a challenging task in itself and has not been given sufficient attention in the past.

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