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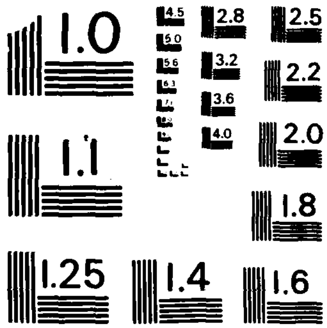

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AD-A169 753

CALCULATION OF WAVE ELEVATIONS IN SHIP WAKES BY USING THE SWIM FREE-SURFACE (SWIMFS) CODE

by

John G. Telste

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COMPUTATION, MATHEMATICS, AND LOGISTICS DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

June 1986

DTNSRDC-86/030

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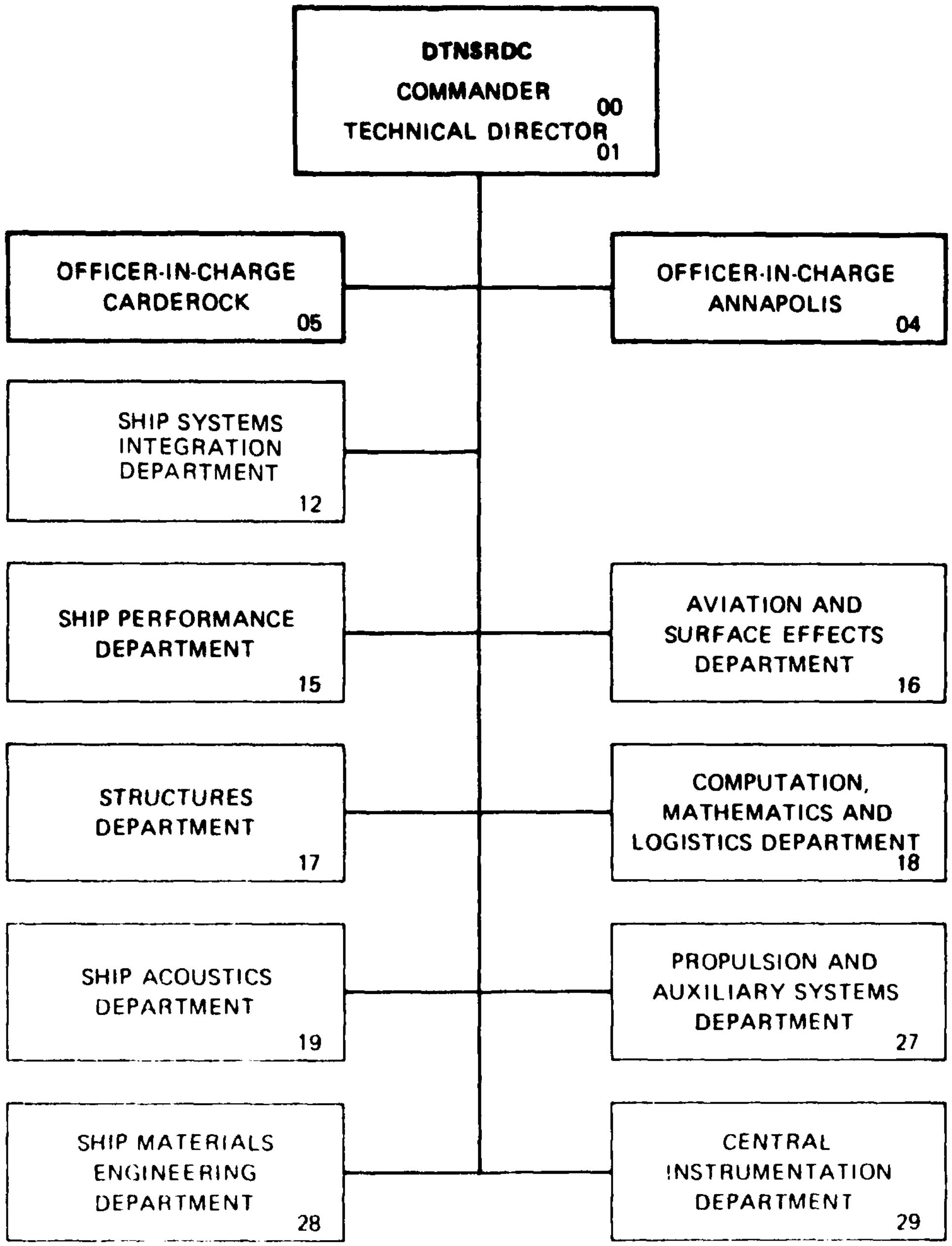
MAJOR DTNSRDC ORGANIZATIONAL COMPONENTS



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SWIMFS, a linearized free-surface potential flow program, has been developed and used to compute and analyze the near- and far-field wave elevations in the wakes of ships moving in calm water. Wake contours and three-dimensional perspective plots are presented for two ships using computer graphics. The contour plots of the near-field results have been compared with those obtained by the XYZFS computer program. Additional comparisons of the two codes have been made by plotting longitudinal cuts of the wave heights. The results show that--in spite of numerical noise in the computations of SWIMFS--the computed wave patterns behind ships are qualitatively correct, and the computed bow-wave elevations are comparable with those calculated using XYZFS.

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BIE - Boundary integral equation

SAR - Synthetic-aperture radar

Fr - Froude Number

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ABSTRACT

SWIMFS, a linearized free-surface potential flow program, has been developed and used to compute and analyze the near- and far-field wave elevations in the wakes of ships moving in calm water. Wake contours and three-dimensional perspective plots are presented for two ships using computer graphics. The contour plots of the near-field results have been compared with those obtained by the XYZFS computer program. Additional comparisons of the two codes have been made by plotting longitudinal cuts of the wave heights. The results show that--in spite of numerical noise in the computations of SWIMFS--the computed wave patterns behind ships are qualitatively correct, and the computed bow-wave elevations are comparable with those calculated using XYZFS.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

There is much interest in the remote sensing of the ocean surface. In 1978, SEASAT was the first satellite designed for that purpose.[1,2*] Two special issues of the Journal of Geophysical Research were later devoted to that mission. Particular interest in remotely-sensed surface-ship wake detection has been generated as a result of the SEASAT synthetic-aperture radar (SAR) detections of hundreds of ship wakes; additionally, many questions were raised by the SAR images. One of these questions was whether SAR images could be explained as due to the complex interaction of radar electromagnetic waves with short ocean-surface waves that had been perturbed by longer waves in a ship's wave system. To answer such questions, the study of the near- and far-field wake of a ship moving on the ocean's surface must be made.

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*A complete listing of references is given on page 25.

As a first step in this study, a knowledge of Kelvin wave amplitudes and wave slopes created by a ship moving at constant speed on the ocean's surface is required. A computer code able to calculate ocean wave elevations and ship wake patterns would be a valuable tool for the study of ship waves. However, few computer codes are available for such computational tasks. In fact, this author knows of only one computer code, other than the one described herein, for far-field calculations. That computer code, known as KELVIN[3], is proprietary. It can compute wave elevations only at distances greater than one ship length from the ship.

For near-field calculations, various computer codes exist. But, because they have been designed to compute quantities such as wave resistance in addition to wave elevations, many of them would be computationally expensive if they were used to compute wave elevations over large areas of the ocean's surface. XYZFS[4] and SWIM[5] are two examples of near-field codes. XYZFS, like many computer codes for near-field calculations, cannot be used directly to compute far-field wave elevations. Thus there is a need to develop a computer program that can be used for the computation of both near- and far-field free-surface elevations for a ship moving forward at constant speed.

The task of modifying SWIM was undertaken to produce a code that can compute wave elevations anywhere around a ship. As developed by Dr. Ming Chang at DTNSRDC, SWIM is based on a steady-state, linearized, free-surface potential flow theory for a ship traveling forward in calm water at constant speed. To calculate the potential flow about a ship, it uses the boundary integral equation (BIE) method in which the velocity potential and its gradient are expressed as integrals over a surface representing the hull of the ship. Whether the velocity potential and its gradient are sought on, near, or far from the ship's hull, both are expressed as integrals whose integrands do not vary in form when the point at which they are sought is changed. The integrands are comprised of a Green function and also its gradient, both multiplied by a function called the source strength. Since SWIM computes the velocity potential and its gradient on the surface representing the hull in terms of these integrals, a modification of SWIM can be made to arrive at a computer code that can compute the velocity potential or its gradient anywhere in the fluid domain. Moreover, if the gradient of the velocity potential is known at the mean-free-surface level, then the wave elevation is also known. The task of modifying SWIM led to the computer code SWIMFS.

This report describes an initial effort to validate the new computer code SWIMFS. The results are presented in the form of both contour and three-dimensional perspective plots using SWIMFS to compute wave elevations. This is done near and far from the two ships moving forward in calm water at constant speed. Additionally, computed near-field wave elevations for the two ships are compared with the near-field free-surface elevations calculated by the free-surface potential flow program XYZFS.

DESCRIPTION OF SWIMFS

SWIM uses the BIE method to represent the velocity potential and its gradient about a steadily moving ship in terms of a surface distribution of Kelvin sources on the hull. (The frame of reference has been fixed to the ship so that the hull appears to be held fixed in a uniform stream; a right-handed (x,y,z) Cartesian coordinate system, in which the x axis points in the direction of ship motion and the z axis points vertically upward, is used.) A Kelvin source is a Green function represented by the sum of the velocity potential due to a Rankine source and a harmonic function designed so that the Green function satisfies linearized free-surface boundary conditions at the mean sea level and the so-called radiation boundary condition. The source density is determined so that the hull boundary condition is satisfied; in other words, the normal component of the velocity of the hull must equal the normal component of the velocity of the fluid at every point on the hull. In this method the velocity potential and its gradient at any "field point" in the fluid below the mean sea level are represented as hull-surface integrals. The integrands consist of the source density multiplied by the Green function and its gradient, whose forms do not vary as the position of the field point varies.

The mathematical boundary-value problem just described is inconsistent. The inconsistency arises because the free-surface boundary conditions are linearized and applied at the mean-free-surface level, while the hull boundary condition is applied directly on the hull of a ship. Thus, the free-surface boundary conditions and the hull boundary condition are approximated to different degrees of accuracy. It is hoped that this more accurate treatment of the hull boundary condition will lead to flow simulations which more closely approximate the solutions of the fully nonlinear mathematical boundary-value problem than does a fully linearized treatment.

In the BIE method, the integrals representing the velocity potential and its gradient must be approximated by forms suitable for numerical computation. To do so, the surface representing a hull is first divided into a number of rectangular-shaped regions called quadrilaterals or panels. The velocity potential and its gradient about the hull are expressed as sums of contributions from all the panels on the hull. The Kelvin source density on each panel is assumed to be constant, and thus SWIM expresses the velocity potential and its gradient due to a distribution of Kelvin sources on a single panel as double integrals, over the panel, of a constant multiplied by the Green function and its gradient. To make the integrals over a single panel more amenable to computation, certain assumptions about each panel are made: (a) the longitudinal dimension (parallel to the mean sea level) is much greater than the other dimension of the panel, and (b) the unit outward normal at each point on the panel is approximated by the normal at the centroid of the panel. Then the mean-value theorem is applied in the vertical direction to reduce the double integrals over a panel to integrals over the line segment running the length of the panel parallel to the mean sea level and passing through the centroid of the panel.

Formulas for the Green function can be found in many papers in the literature. For example, the first equation in a paper by Noblesse[6] gives a formula which is closely related to the formulas used in SWIM. (Noblesse credits Shen and Farell[7] with having obtained that version of the Green function.) The Green function is a velocity potential which is due to a Rankine source submerged beneath the mean sea level in a uniform stream and which satisfies the linearized free-surface boundary conditions. It is expressed as the sum of the velocity potential from the Rankine source, the velocity potential from a point source at the image position in the mean sea level, an integral of the exponential integral, and another integral often called the wave integral. To arrive at the formulas for the velocity potential and its gradient at a "field point" due to a distribution of Kelvin sources over a panel, the last two terms involving integrals are integrated analytically along the line segment through the centroid of the panel. The other two terms, representing point-source distributions, are integrated numerically along the same line segment. Up to ten subintervals are used in the numerical integration.

The user of SWIM must provide the Froude number, various integration parameters, and a representation of the hull in terms of a finite number of quadrilaterals in a data file. The paneling is specified by listing the four corners of each quadrilateral. A system of linear equations is set up in SWIM and solved to determine the Kelvin source densities of the panels in such a way that the hull boundary condition is satisfied. This computational process requires that the normal derivative of the velocity potential, or, equivalently, its gradient at the centroid of each panel, be expressed in terms of the Kelvin source densities. The velocity potential at the centroid of each panel on the hull is also computed so that quantities related to wave resistance can be obtained. Thus, when the computer code is finished with its computation, it has at its disposal a Kelvin source density for each panel on the hull, the velocity potential on the hull, and a means to compute the gradient of the velocity potential on the hull.

Since the velocity potential and its gradient at a point are expressed in terms of integrals of the same form, whether or not the point is on the hull, a modification of SWIM can be made so that the velocity potential and its gradient can be computed at points off the hull. SWIMFS is such a modification, designed specifically for computing the wave elevations about a ship as it moves forward at a constant speed in calm water. Most of the modification has occurred in three areas.

First, since SWIMFS computes only free-surface elevations from linearized free-surface potential flow theory, the only required computations are those needed for the x component of the gradient of the velocity potential wherever the free-surface elevation is to be computed. The x component of the gradient at a "field point" is expressed as a sum (over the panels) of integrals of the x component of the gradient of the Green function multiplied by the Kelvin source density. Thus the Green function, and the y and z components of its gradient, are not computed in SWIMFS.

Second, a major part of the computation in SWIM is consumed in the computation of the coefficients in the linear system of equations to solve for the Kelvin source densities. SWIMFS assumes that these densities have been obtained previously from SWIM itself, or perhaps from slender-ship theory. Landweber and Macagno[8] and Noblesse[9] discuss the use of Kelvin source distributions based on slender-ship theory. Another alternative is to panel the centerplane of a hull and put a distribution of Kelvin sources calculated from thin-ship theory on each panel.

Finally, the exponential integral, required for the Green function and its gradient, is computed in SWIMFS from subroutine GRN2D developed by Newman.* This new subroutine is more accurate than that which exists in SWIM, which uses power series, interpolation, and rational approximation to compute the exponential integral. In summary, some computations in SWIM have been eliminated from SWIMFS, and some computations in SWIM are done more accurately in SWIMFS. A more detailed description of SWIM and SWIMFS must await further documentation.

A user of SWIMFS must prepare a data file identical to the one required for SWIM. This is because the Froude number, integration parameters, and ship paneling are essential information for SWIMFS. Additional data must be supplied for SWIMFS. In particular, since the modified computer code no longer computes the Kelvin source strengths on the panels of the ship hull, these must be calculated beforehand and stored in a data file. The off-body points at which the free-surface elevation is to be computed must also be provided. The additional data for SWIMFS and the SWIM-type data are read from two separate data files by SWIMFS.

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*J.N. Newman, "Note on the Computation of the Two-Dimensional Green Function," (unpublished manuscript, 1984).

RESULTS

Wave elevations in the wake of two ships have been computed using the computer code SWIMFS. Ship A has been paneled with 216 panels; it is traveling forward in calm water at a speed corresponding to a Froude number (based on hull length) of 0.185. Ship B has been paneled with 296 panels; it is traveling forward in calm water at a speed corresponding to Froude number 0.252. More panels were used for ship B than ship A because of the presence of a bulbous bow on ship B. With this paneling of the ships, the original computer code SWIM was used to compute the Kelvin source strengths on each of the hulls traveling at the appropriate speed. These source strengths were then used as input to SWIMFS for the wave computations.

In performing the calculations for the ships discussed here, it was discovered that the wave integral was computed too inaccurately in SWIM and in the initial version of SWIMFS to produce any semblance of the theoretical 19-1/2° angle within which most of the waves in the wake of a ship are contained. As a temporary measure, the subintervals used to numerically integrate the wave integral between $-\pi/2$ and $\pi/2$ have been decreased in size in SWIMFS. (The wave integral is actually a multiple integral over the length of a panel and over the range of numbers in the interval from $-\pi/2$ to $\pi/2$. As was mentioned previously, the integration over the length of the panel is handled analytically.) Much better looking wakes, which are the ones presented in this report, were calculated. Unfortunately, the inaccuracy was not discovered until after SWIM had been used to compute the Kelvin source strengths. Because of the expense involved in using SWIM, it was decided not to recompute the Kelvin source densities. Thus the discussion of results will be confined to qualitative remarks.

Figure 1 shows a contour plot of the computed wave elevations behind ship A traveling with speed corresponding to Froude number 0.185 (based on hull length).

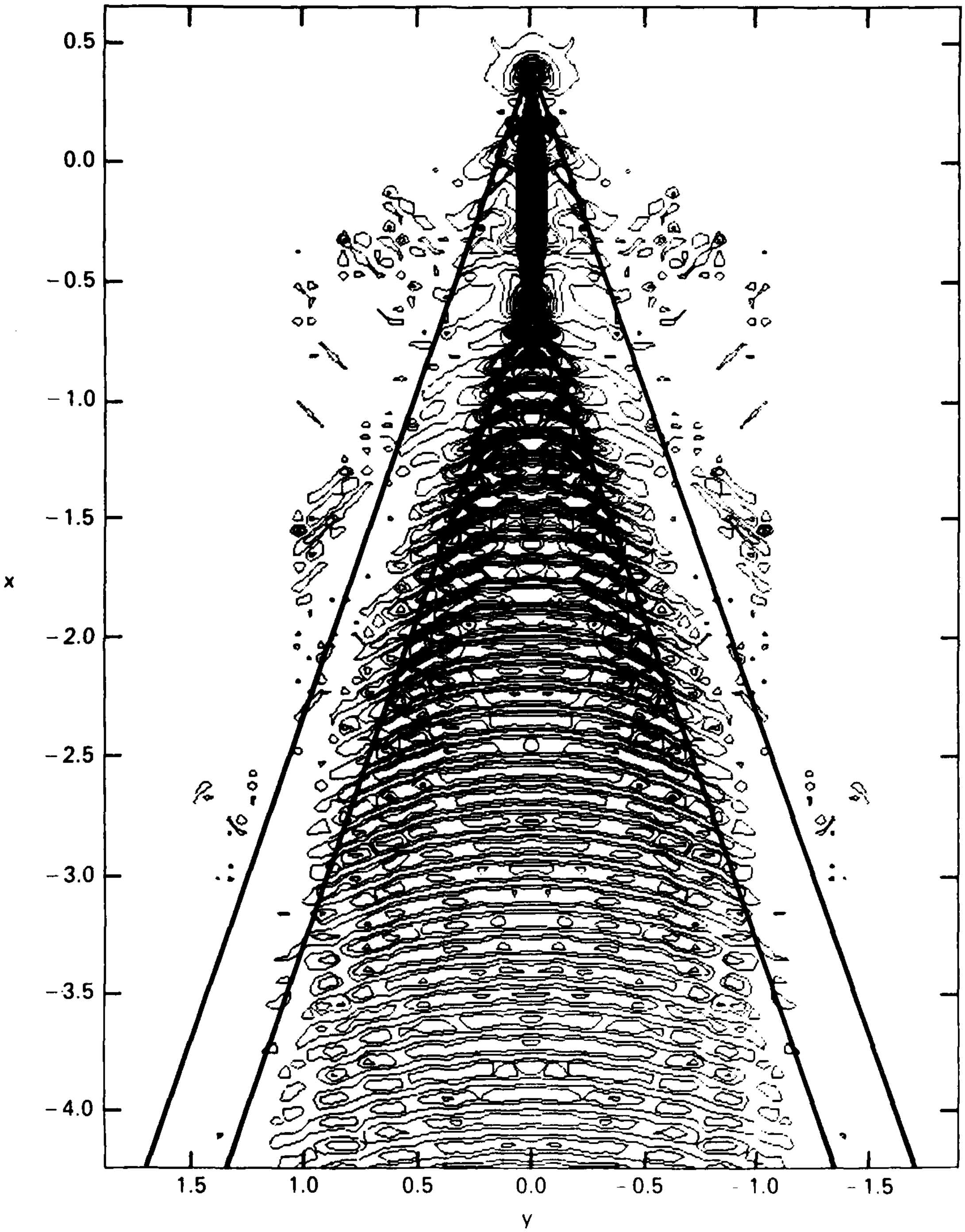


Figure 1 - SWIMFS-Computed Contour Plot of Wave Elevations Behind Ship A at Froude Number 0.185

Contours have been plotted for free-surface elevations (above the mean sea level) equal to 0.00025, 0.0005, 0.00075, . . . , 0.0050 times the length of the hull, and for free-surface elevations (below the mean sea level) equal to -0.00025, -0.0005, -0.00075, . . . , -0.0050 times the length of the hull. The greatest deviation from the mean-free-surface level is clearly contained within the theoretical 19-1/2° angles emanating from the bow and from the stern. (See Figure 2 for a definition of the angles.) These theoretical angles have been

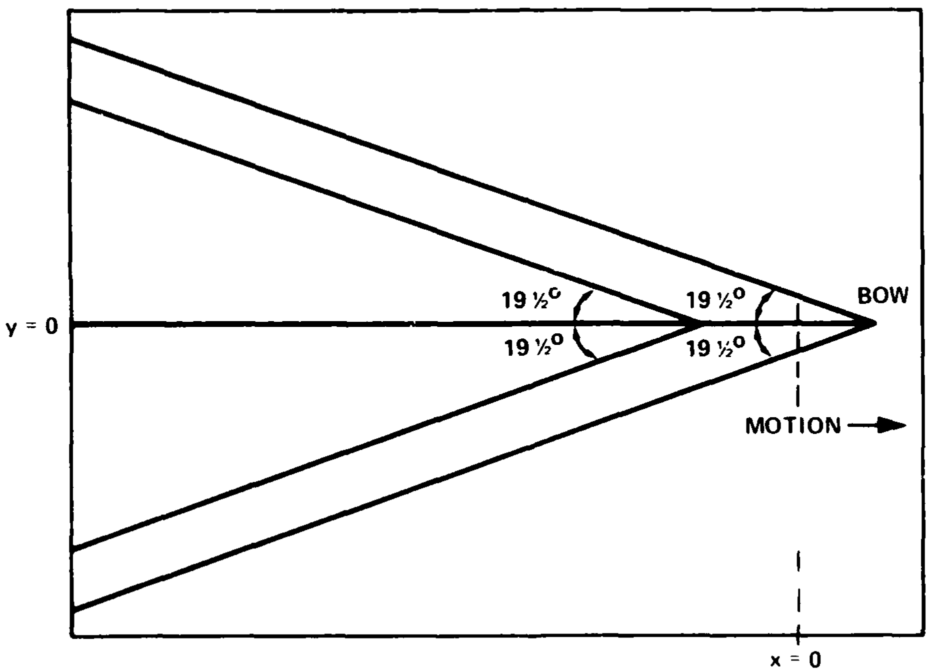


Figure 2 - Theoretical 19-1/2° Bow and Stern Angles Within Which Most of the Waves Generated by the Forward Motion of a Ship are Contained

depicted on the contour plots as solid lines. What appears to be noise outside these angles is due to numerically inaccurate computation of the wave integral. A test case with only one panel and with the use of an adaptive integrator has confirmed that a very accurate computation of the wave integral will remove the noise. However, because of the increased computing expense, adaptive integrators cannot be used for problems with many panels on the hull and with many off-body points at which to compute the wave elevation.

Figure 3 shows a plot of the computed wave elevations for ship B at Froude number 0.252 (based on hull length). As is to be expected, the wavelength is longer for ship B than for ship A. In fact, with lengths scaled so that the ships have the nondimensional length one, the longest theoretical nondimensional linear wavelengths are $2\pi Fr^2$. Thus the wavelength of the waves behind ship A should be about 0.215 times the length of hull A, and the wavelength of the waves behind ship B should be about 0.40 times the length of hull B. The computed waves have wavelengths approximately equal to these values. The 19-1/2° angles are seen more clearly in this case. Numerical noise is also present in the data here.

Figures 4 and 5 show three-dimensional perspective plots of a portion of the same free-surface elevations near the ships. Although there is less information available in these plots than in the contour plots, it is easier to visualize the waves in these perspective plots.

Figure 6a presents a contour plot of wave elevations for ship A calculated from the free-surface potential flow program XYZFS. These elevations can be compared with the SWIMFS-calculated elevations in Figure 6b. Contour values have been selected as in Figure 1. The low-level contours plotted at the top and bottom of Figure 6b, and absent from Figure 6a, represent numerical "noise" resulting from the numerical approximation of the wave integral using SWIMFS. The XYZFS-computed bow wave plotted in Figure 6a is higher than that computed by SWIMFS. However, since questions remain about how accurately SWIM calculates the Kelvin source densities on the hull, and since no experimental data has

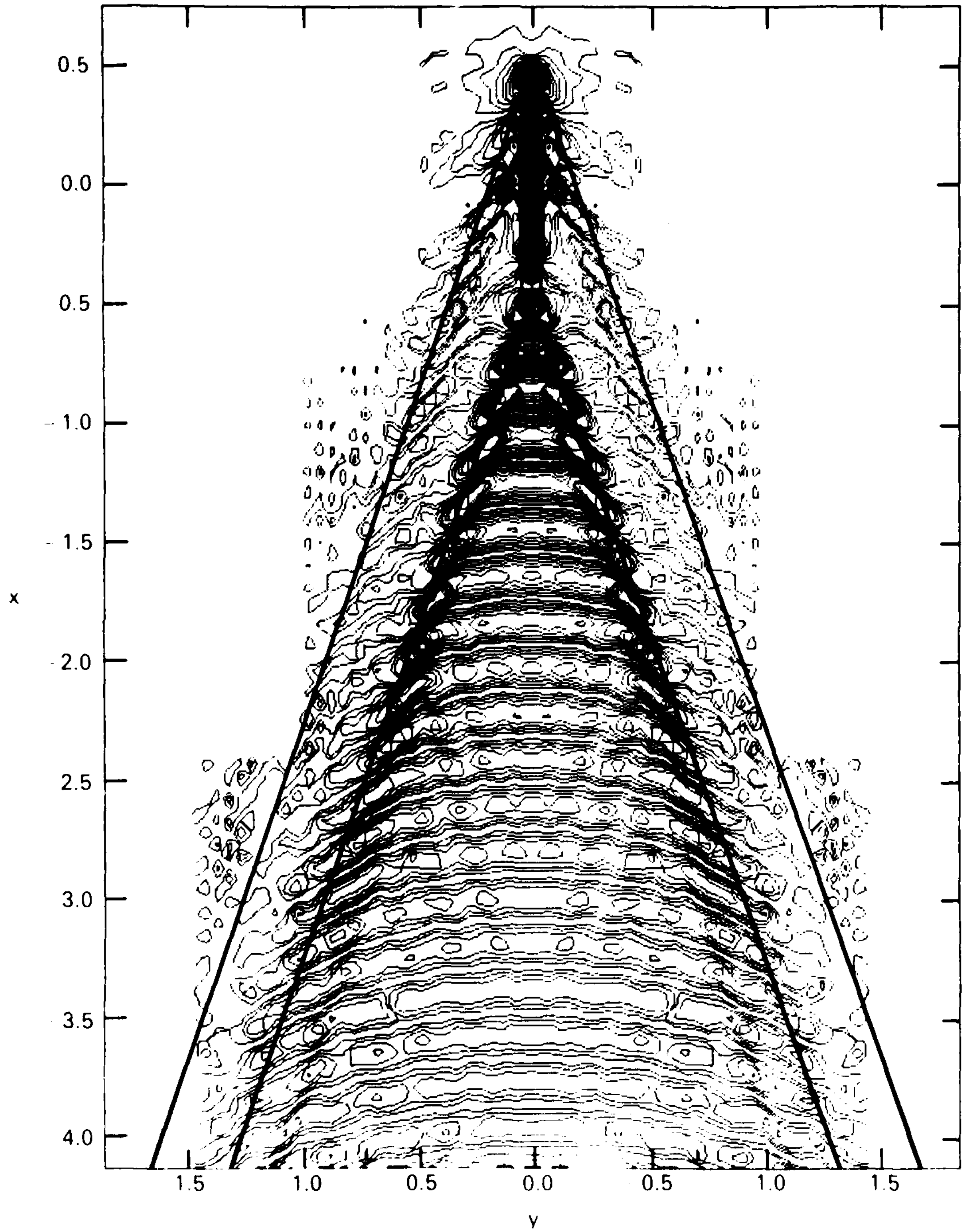


Figure 3 - SWIMFS-Computed Contour Plot of Wave Elevations Behind Ship B at Froude Number 0.252

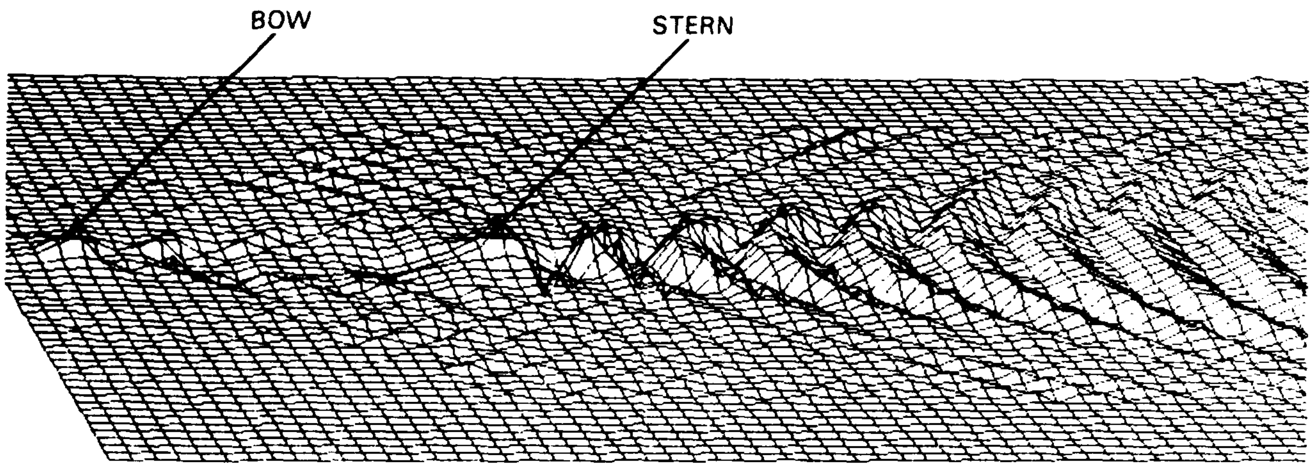


Figure 4 - SWIMFS-Computed Three-Dimensional Perspective Plot of Wave Elevations Behind Ship A at Froude Number 0.185

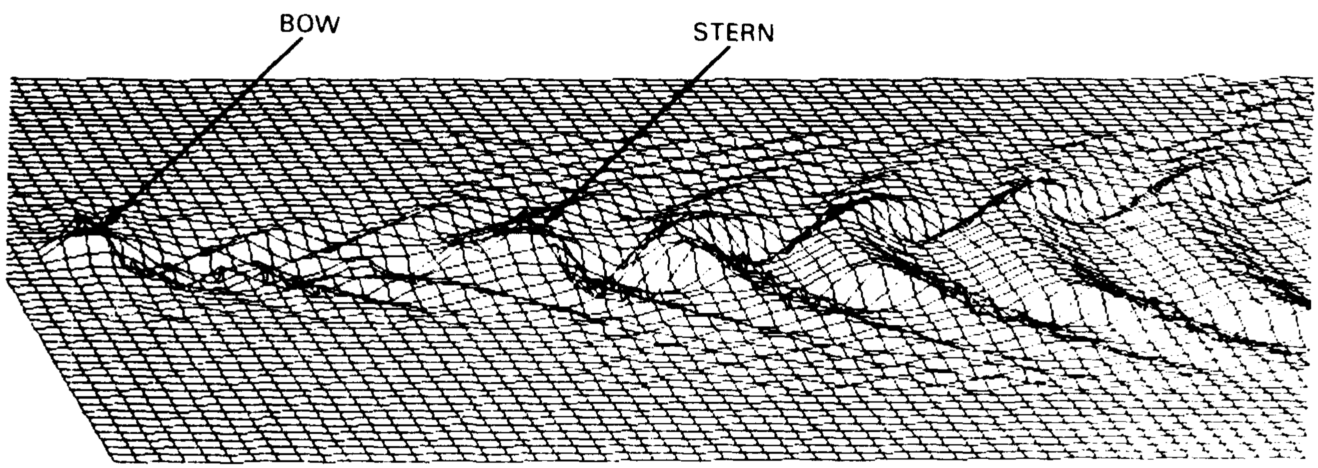
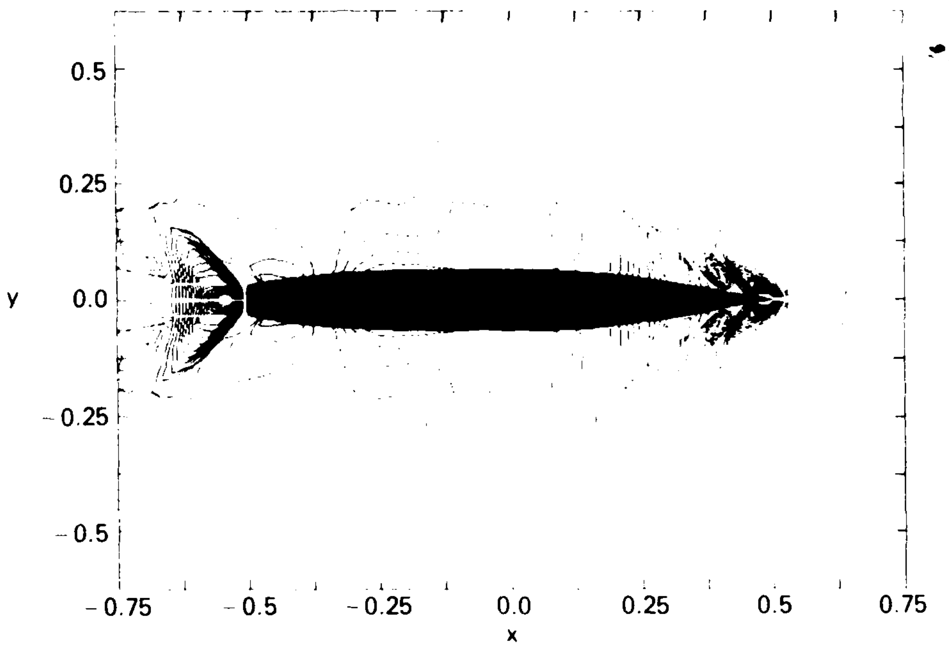
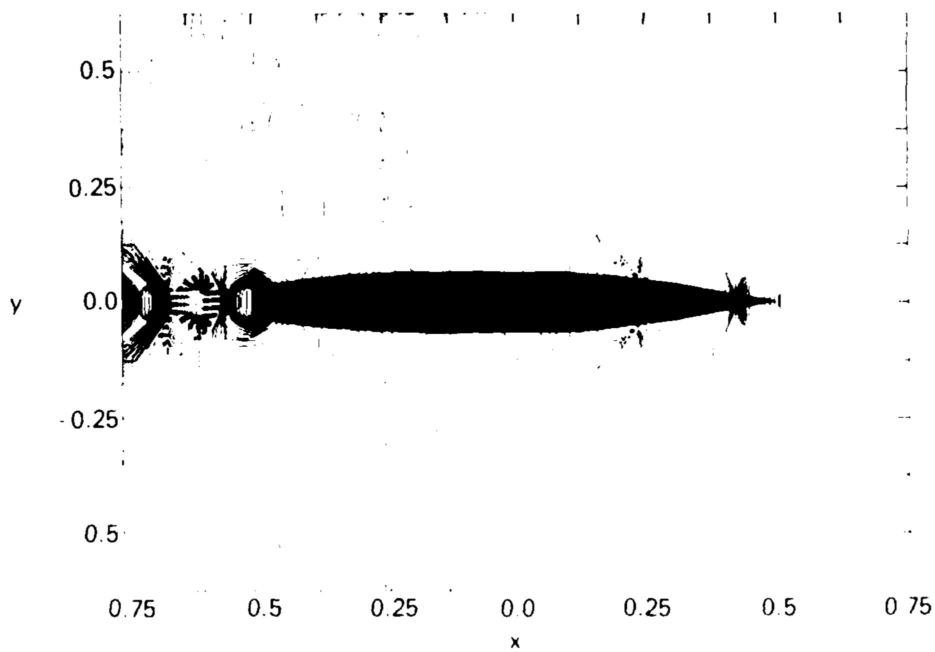


Figure 5 - SWIMFS-Computed Three-Dimensional Perspective Plot of Wave Elevations Behind Ship B at Froude Number 0.252



(a) XYZFS



(b) SWIMFS

Figure 6 - Comparison of XYZFS- and SWIMFS-Calculated Contour Plots of Wave Elevations Near Ship A at Froude Number 0.185

been made available, one should concentrate on the qualitative differences in the two figures rather than the quantitative differences. It is felt that the bow-wave contours in Figure 6b are too circular, while those in Figure 6a display a more realistic "swept-back" appearance. The two jags in the lowest-level bow-wave contour of Figure 6b probably come from numerical "noise" in the results from SWIMFS. A more noticeable difference between Figures 6a and 6b is that the results from SWIMFS lack almost all of the free-surface depression near the hull immediately behind the bow wave. The depression calculated by XYZFS is judged to be more realistic. The computed contours alongside the hull in Figure 6b may be exhibiting the presence of numerical noise in the results from SWIMFS; the results from XYZFS, shown in Figure 6a, do not display these finer structures near the middle of the ship. The wave contours in the vicinity of the stern are also different. XYZFS, which employs a paneling of the free surface near the ship hull, is usually used to obtain accurate results near the ship hull. To save time, the standard XYZFS hull paneling was used to obtain these results, rather than going to a refined configuration. The standard paneling contained an insufficient number of panels (four per wavelength for this Froude number) behind the stern for accurate prediction of the waves in that area. The low contour levels near the stern in Figure 6b should be "swept back" more than they are. The computations depicted near the stern may not be realistic since the wave elevations attain a peak very close to the stern. However, this might be result of the low speed. XYZFS appears to have produced somewhat better free-surface elevations near the bow, and SWIMFS appears to have produced better results behind the stern. No judgment can be made about which results are better near the middle of the ship.

Figure 7a presents a contour plot of wave elevations for ship B from the free-surface potential flow program XYZFS. These are to be compared with the elevations calculated by SWIMFS in Figure 7b. The contours for ship B are more "swept-back" than those for ship A because ship B is traveling faster than ship A. There is less numerical noise in the calculations by SWIMFS for the faster ship B, Figure 7b, than for ship A, Figure 6b. As before, the bow-wave contours computed by SWIMFS (Figure 7b) are more circular and less realistic than the bow-wave results from XYZFS (Figure 7a). Of course, as for the case of ship A, the predictions from XYZFS behind the stern cannot be expected to be realistic because of the choice of paneling. The blank area behind the stern in Figure 7a is due to the presence of computed wave elevations higher than the highest contour level plotted. (The same contour levels have been plotted as in Figure 1.) In the midship region there is not enough information to judge whether SWIMFS or XYZFS is more accurate. Thus, just as in the case of ship A, XYZFS appears to have produced better free-surface elevations near the bow, SWIMFS appears to have produced better results behind the stern, but no judgment can be made about which results are better from the middle to the stern of the ship.

Another comparison of computations from the two computer codes is depicted as wave cut data in Figures 8 and 9. Each figure shows computed free-surface elevations from the two computer codes as a function of x (distance parallel to the path of each ship) at a fixed distance y from the centerplane of each hull. The vertical axis in each figure measures wave height. All measurements are given in terms of a fractional part of a ship length, e.g., a height of 1 would correspond to a wave amplitude equal to the length of a ship.

Figure 8a shows how the results of the two codes compare at a distance $y = 0.075$ ship lengths from the centerplane of hull A. Figure 8b shows the comparison for hull A when the distance from the centerplane is $y = 0.175$.

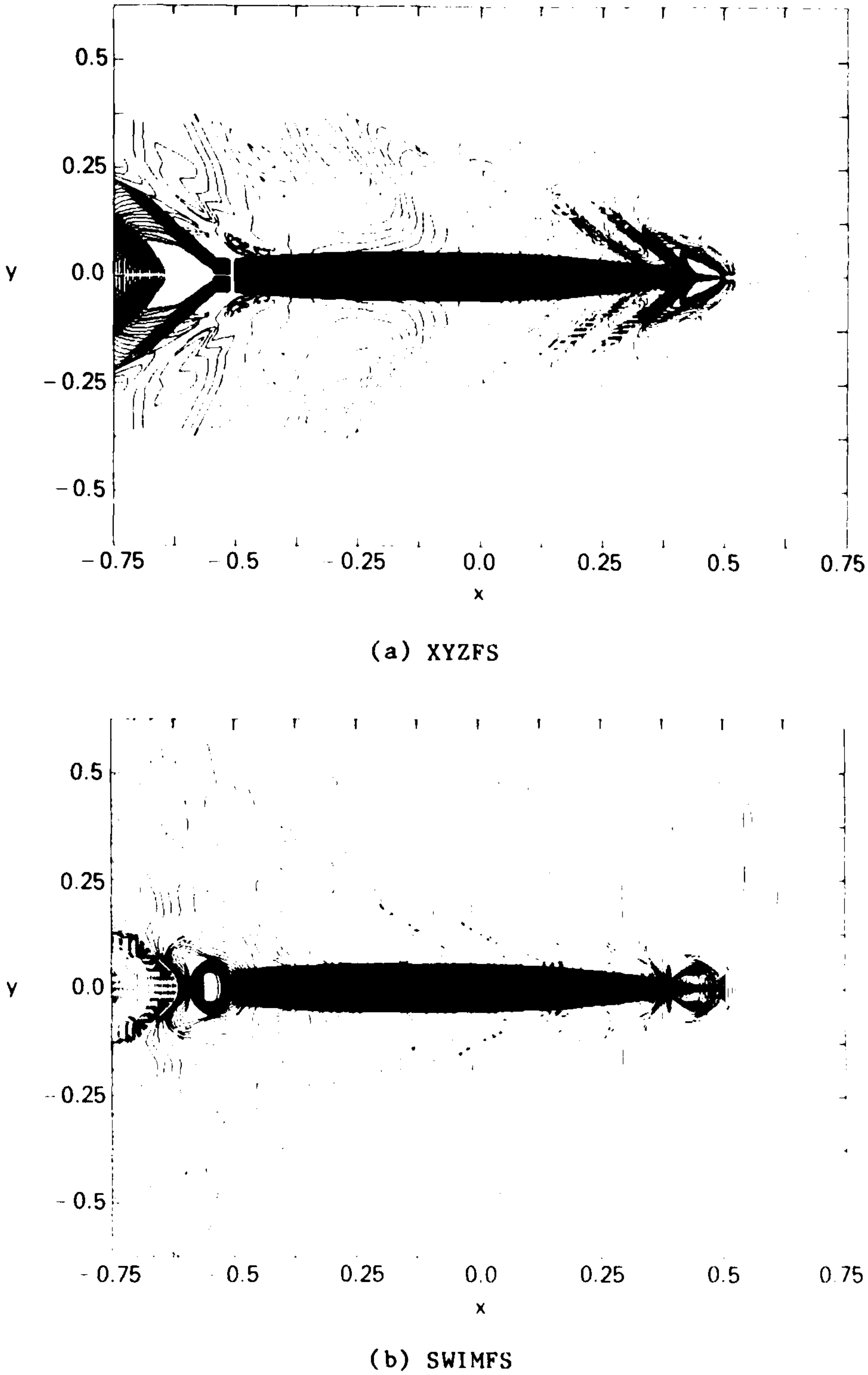
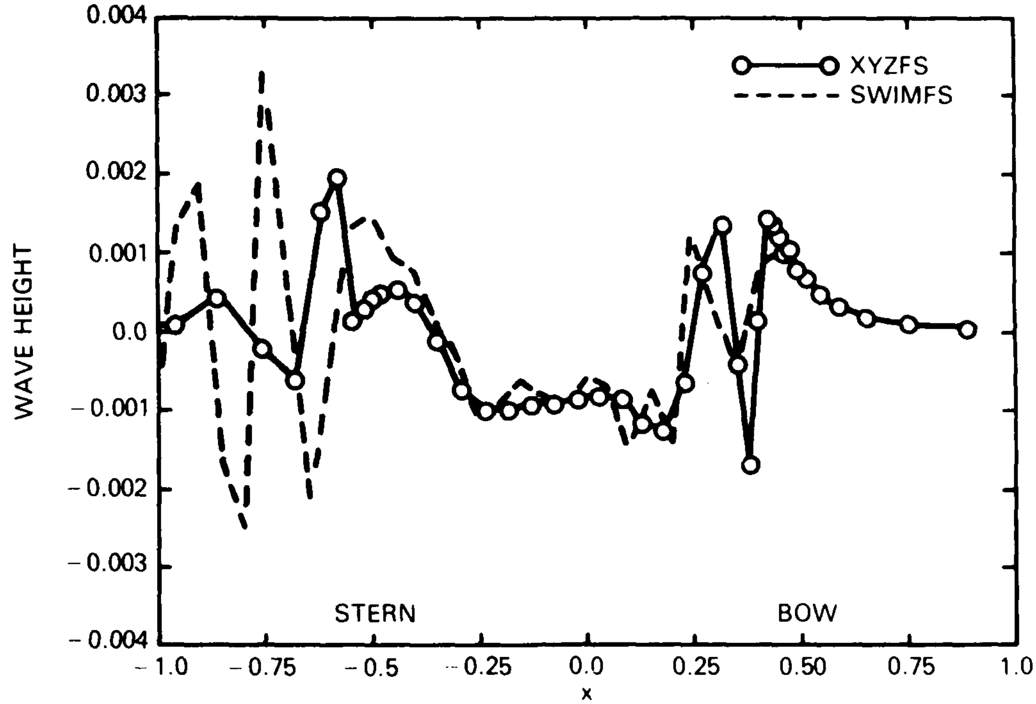
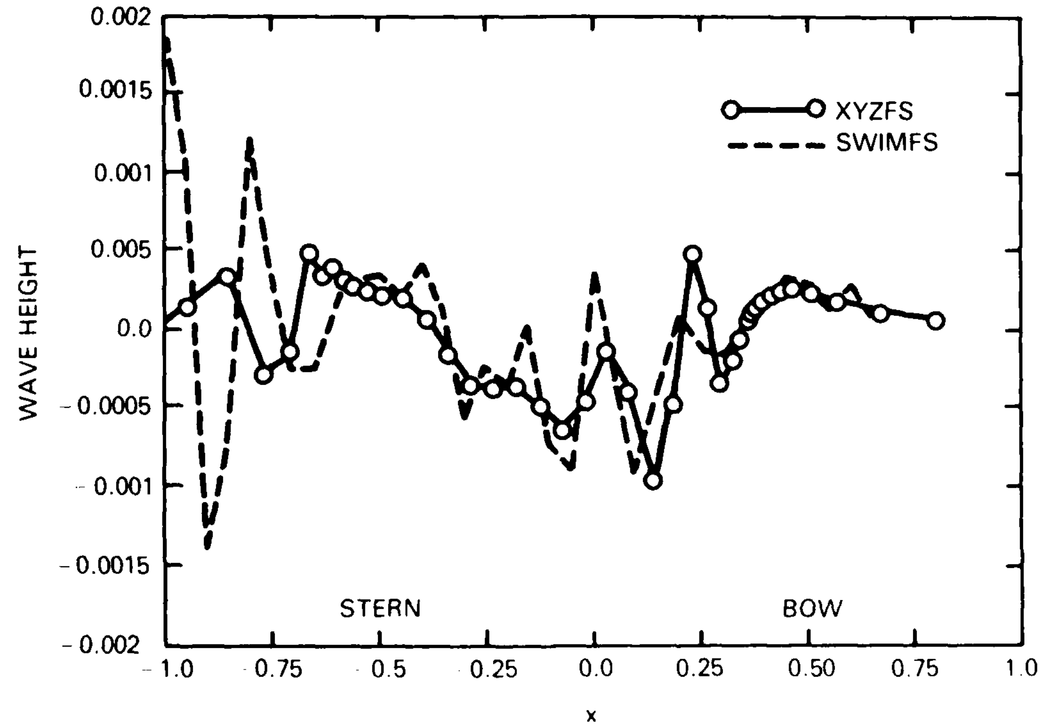


Figure 7 - Comparison of XYZFS- and SWIMFS-Calculated Contour Plots of Wave Elevations Near Ship B at Froude Number 0.252



(a) y = 0.075



(b) y = 0.175

Figure 8 - Comparison of XYZFS- and SWIMFS-Computed Wave Elevations Along the Lines y = 0.075 and y = 0.175 for Ship A at Froude Number 0.185

(All measurements are in terms of a fractional part of a ship's length.)

Figure 9a shows how the results of the two computer codes for ship B compare at the distance of y = 0.075 ship lengths from the centerplane of hull B. Figure 9b shows the comparison for hull B when the distance from the centerplane of the hull is y = 0.175.

In these figures, the results from XYZFS are smoother than the results from SWIMFS. This may due to the presence of numerical error in the computation of the wave integral by SWIMFS. An alternative explanation may be that the free-surface near the hull has been paneled and a finite-difference scheme has been used by XYZFS in each case. The differencing scheme may smooth what is in reality a more oscillatory longitudinal wave cut. In the absence of experimental data with which to compare the computational results, no judgment can be made as to which set of longitudinal wave cuts is more realistic. The agreement between the bow-wave results from both XYZFS and SWIMFS appears to be better than one would conclude from the contour plots. As was stated previously, too few panels were used in the input preparation for XYZFS to produce reasonable results behind the stern. This is reflected in the figures.

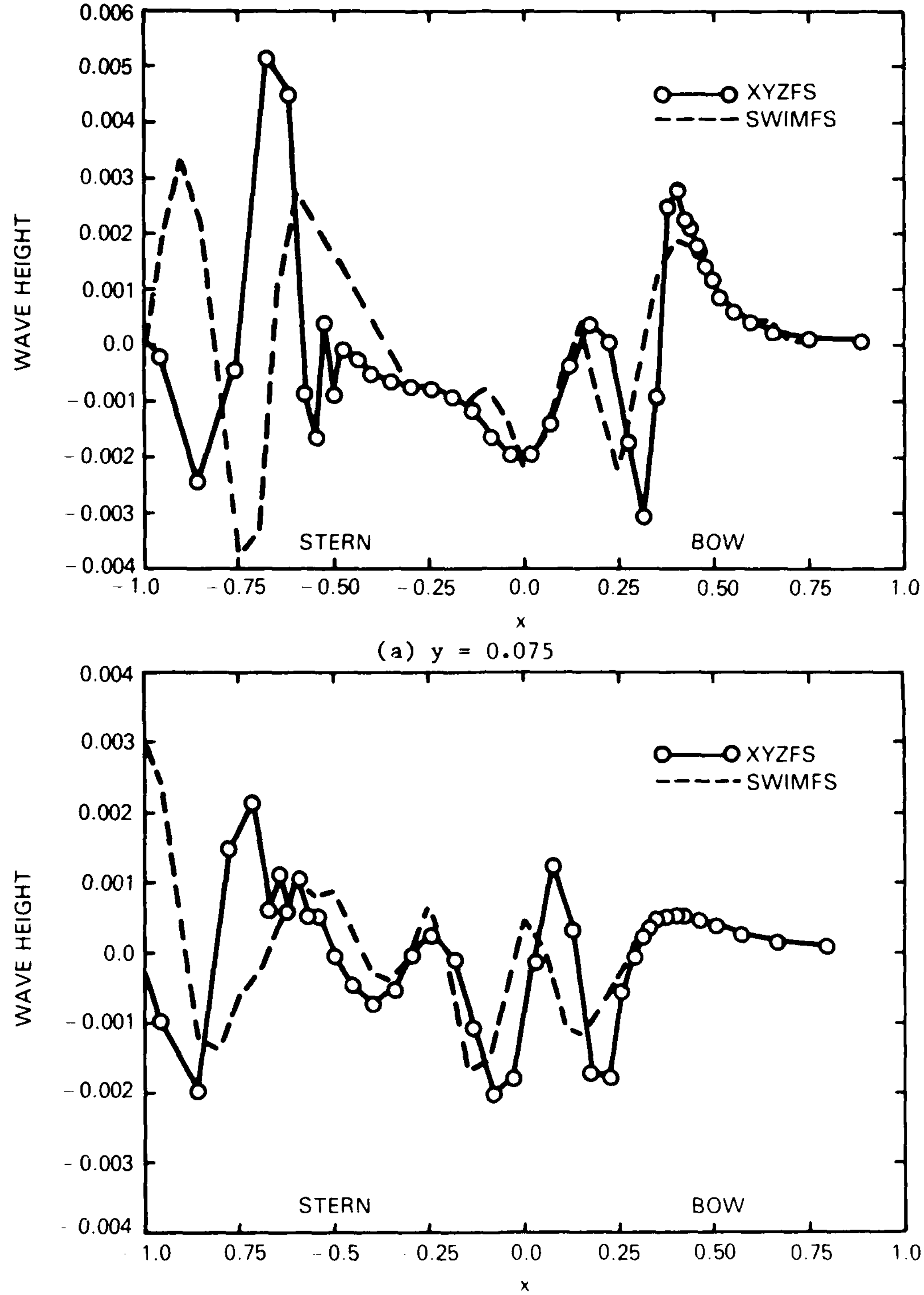


Figure 9 - Comparison of XYZFS- and SWIMFS-Computed Wave Elevations Along the Lines y = 0.075 and y = 0.175 for Ship B at Froude Number 0.252

(All measurements are in terms of a fractional part of a ship's length.)

CONCLUSIONS

The computer code SWIM has been modified so that it can compute wave elevations in the wakes of ships moving forward at constant speed in calm water. The modification has been achieved by removing some unnecessary calculations, making some computations more accurate, and extending the computation of the x component of the velocity potential to points off the ship hull. The resulting new computer code, called SWIMFS, computes the wave elevations if it is supplied with (a) a representation of the ship hull as a set of quadrilaterals, (b) the Froude number, (c) integration parameters, (d) Kelvin source densities for the quadrilaterals, and (e) the off-body points at which the wave elevations are to be computed.

The results presented in this report indicate that it is possible to predict, at least qualitatively, the wave elevations in the wake of ships. Contour plots of computed wave elevations indicate that most of the waves predicted by SWIMFS are inside the theoretical 19-1/2° angle behind a ship, and that the computed wavelengths are those which are expected in linear free-surface potential flow. A comparison of contour plots of near-field results from XYZFS and SWIMFS shows that there are differences in computations from the two computer codes. Based on the contour plots, it has been judged that, in the area of the bow, XYZFS produces qualitatively better results than does SWIMFS. This judgment, however, is not confirmed by a comparison of longitudinal wave cut data near the bow because the two computer codes have produced wave cut data near the bow that compare favorably with one another. Thus one must conclude that the results are comparable near the bow. In the absence of experimental data, it is not clear whether the results of XYZFS or SWIMFS are better from the midship area to the stern. Behind the stern the results from SWIMFS are better because the choice of using the standard paneling for XYZFS produced too few panels for accuracy in this region.

If the computer codes SWIM and SWIMFS are to be used extensively in the future, much more attention must be paid to accuracy. In the judgment of this author, many numerical approximations have been made to speed up the computation in SWIM, and hence in SWIMFS. The effect of these numerical approximations on the results is not clear in most cases. However, it has been demonstrated that one approximation of the wave integral in SWIM, carried over to SWIMFS, produced conspicuously bad free-surface elevations. For this reason, and in light of the numerical "noise" present in the contour plots, it is recommended that an effort be made to obtain a more accurate numerical model of the wave integral that will not add significantly to the computational time. This may not be an easy task since most of the computational time is spent in computing wave integrals. It is also necessary to expend more effort in validating both SWIM and SWIMFS if these codes are to be used in the future; in particular, it is necessary to compare results from the two codes with experiments and with the results from other codes. The author does not know of any such study that has been performed on SWIM.

The computations were carried out on various Apollo microcomputers and on a VAX 11/780 computer. The amount of computational time required for each ship was on the order of 20 to 40 hours on the VAX computer. Most of the computational effort went into the evaluation of the wave integral. Thus, in view of the computational expense and numerical noise present in the results, it would be beneficial to have a more efficient and more accurate algorithm for the computation of the wave integral.

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