THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
Department of Naval Architecture and Marine Engineering

# RESEARCH IN RESISTANCE AND PROPULSION

## Part I. A Program for Long-Range Research on Ship Resistance and Propulsion

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# ACKNOWLEDGMENTS

Although the name of the author of this report is given as that of the undersigned, several contributions were made by others, notably Dr. L. Landweber who wrote Appendix III, "Wave Resistance of Ships" and Appendix IV, "Ship Resistance in Rectangular Channels." In addition he also worked on some parts of Section E "Improvements of Ship Model Test Procedures" and outlined several of the proposed research projects.

Appendix I, "Personnel and Facility Needs" was written when the author visited the Institut fur Schiffbau in Hamburg, Germany. His views on these topics are probably greatly influenced by what he saw and learned during the summer of 1962 when he spent some time at various laboratories in Europe. It is no mere coincidence, however, that the manuscript was outlined at a place which today is so much a monument to Dr. Ing Georg P. Weinblum's world leadership in the field of Ship Hydrodynamics.

Through discussions and conversations Dr. Weinblum conveyed to the author his great insight into the research problems that must be solved in the future and the urgent need for preparing ourselves to the task of doing so by providing for the training of personnel and making available to it proper laboratory equipment.

Much of the material presented in this report is also the formalization of informal discussions between myself and my colleqgues, notably Dr. T. Takahei, Hun Chol Kim, James L. Moss, and Nils Salvesen. Their contributions are greatly appreciated. In addition the author cannot see how he could possibly avoid including many ideas on administration of research and education brought so strongly to his attention by Professor Harry Benford, who has been deeply concerned with this problem for some time. Finally, Robert Taylor of the Maritime Administration deserves special recognition for his helpful suggestions and efforts in trying to make this report a guide for the detailed planning of future research projects.

# PREFACE

The primary objective of this report is to outline a five-year program of research in the field of ship resistance and propulsion, with emphasis on developments of importance to U. S. merchant shipping. A second objective is to suggest what additional facilities should be planned for if the University conducted research in these fields is to become of importance on a long range basis. These recommendations are presented in partial fulfillment of The University of Michigan's obligations under The Maritime Administration's university program.

Maritime's university program was established in response to recommendations of the Maritime Research Advisory Committee. That group's final report(22) asked the Maritime Administration to encourage education through emphasis on contract research in those universities having particular interest in the marine field. The University of Michigan was one of the four selected and was asked to work in the area of ship resistance and propulsion.

The original intent of this report was to limit its objective to the outline of a research program which could be implemented for approximately $50,000 a year. It soon became apparent to the author, however, that this objective imposed a very serious restriction on the context of the report. Although the field of resistance and propulsion represents the oldest and for quite some time about the sole significant area of ship hydrodynamic research it has by no means been exhausted and depleted of new topics for fruitful investigation. Very recent developments have, furthermore, given renewed impetus to the profession's continuous efforts to produce faster and more economical ships. So much so in fact that it may now be the proper time to take a very careful and critical look at our well established techniques of model testing and interpretation of test data. The result of these new developments will undoubtedly lead to intensified experimental work requiring much in the way of new facilities and personnel. We have therefore felt compelled to outline in this report research efforts much more ambitious than can possibly be expected to be conducted under the current allotments of the Maritime Administration's university program. Furthermore, it should be said that in this initial phase of the university program it should be our responsibility to make a fairly complete analysis and survey of current research objectives.

We are pleased to have this responsibility but would emphasize at this point that many of our recommendations relative to research projects, personnel, or facilities are made <u>without respect to location</u>. There is no point in denying our natural desire to see the bulk of these research projects carried out at Michigan insofar as present or possible future facilities will permit; but, since we can make no claim to objectivity in this matter, it must be left to the Maritime Administration to reach its own conclusions. We would, however, strongly recommend that the nation's universities be given particular consideration in decisions affecting the assignment of this work. Our reasons for this are well expressed by the following quotation.(23)

> The vigor and well-being of our universities is essential for the continued leadership of U. S. science. Opportunities for development of effective careers in research and in the production of superior young scientists must be made so attractive that the majority of our best scientists will desire university careers. The principal talent of the nation flows through the universities and it is here that students can be most readily attracted to fields of marine science through close association with professors engaged both in research and teaching. In our society there are no other posts where so small a nucleus of talent can produce such great improvements in succeeding generations. Appropriate research facilities must be avilable at the universities and under their control.

and, since the Maritime Administration's research budget is too small to finance even all the worthwhile proposals that come its way, we should like to recall two of the principal recommendations of the Maritime Research Advisory Committee:(22)

> About 15 percent of the Maritime Administration research budget should be devoted to basic research in such maritime related areas as hydrodynamics, atmosphere - ocean interactions, structures and materials.
>
> The Maritime Administration should promote maritime related education through:
>
> a. Emphasis on university research
>
> b. Fellowships for advanced study
>
> c. Assistance in the construction of university laboratories.

The text of this report contains what we believe to be strong evidence in support of the above recommendations as well as a carefully considered program of related projects in the field of ship resistance and propulsion.

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# CHAPTER I

# PROPOSED PROGRAM

## A. Introduction

In his recent paper dealing with the problems of research in the field of sea transportation, Professor E. V. Lewis(1) gave this breakdown of the steps involved in carrying out research with the ultimate goal of providing better and more complete information to the design engineer:

1. Identify, define and clarify the problems.
2. Evaluate present status of knowledge and identify significant gaps therein.
3. Plan and carry out exploratory projects aimed at possible new solutions to problems or filling in the gaps.
4. Follow up with more detailed studies to broaden and generalize results and make information and design techniques available to industry.

We believe this outline to be an excellent one and have kept it in mind in developing our recommendations relative to long term research needs in the field of ship resistance and propulsion. In the proposed research programs that follow, we have tried to define the problems (Step 1), to evaluate present levels of knowledge (Step 2), and to provide plans for initial investigations (first part of Step 3). Thus, we believe we have carefully prepared for the final, important steps leading to the eventual determination and dissemination of practical knowledge. We are particularly anxious to stress the necessity of carrying each particular project all the way through the fourth step, making the results of research available to design engineers in a form that is readily understandable.

A fairly large part of our proposals is concerned with research directed towards improvement of model test technique and analysis. We believe this work is particularly important at this time because recent theoretical developments place us at the threshold of important breakthroughs in our understanding of ship and model hydrodynamic relationships.

## B. Hull Form Research

The realization of a so-called "waveless ship form," by the introduction of large bulbs, is the most stimulating event in many years in the field of ship hydrodynamics. Most fundamental mathematical studies of the concept are the product of Dr. Inui and his assistants at the University of Tokyo. This group has also performed an impressive amount of experimental testing with basic hull forms. The test results, in general, verify theoretical predictions.

During the past year, the staff at The University of Michigan has translated several of the more important Japanese publications relating to the Inui bulb.(27) It has also built and tested two 12-ft. models of forms previously tested to a smaller scale in Japan. In addition, bulbs for conventional ship forms have been designed and tested.

This work has provided basic knowledge of the mechanism of wave cancellation and of the details of computational work involved, a knowledge that will be of great value to the continued research on the problem of reducing the wave-making resistance of ships. Most of this work was carried out under the direction of Professor Tetsuo Takahei of Ibaraki University. Professor Takahei was Dr. Inui's collaborator in the development of the Inui bulb; he was brought to Michigan for two years, his principal support being furnished by The University of Michigan.

A separate research proposal has recently been submitted to the Maritime Administration covering some immediate tasks that The University of Michigan wishes to undertake in further pursuit of minimizing wave-making resistance of conventional ship forms by means of large bow bulbs. It should be pointed out that results of the proposed investigations are not expected to be final. Dr. Inui's paper(11) is an indication of the extensive amount of research that will be needed to answer all the questions on the relationships among hull geometry, wave patterns and resistance, and it must be expected that continuing research will be needed over a period of years. We feel it unwise to prepare a detailed description of such future activities at this time, however, since substantial progress can be assured only if efforts are based on a careful study of results as they are obtained from both domestic and foreign sources. To provide for continuity of research, the Maritime Administration should therefore earmark funds on a long term basis for the study of the hull form relationship to wave making resistance.

The number of investigators actively engaged in research in the field of theoretical wave resistance is rather small. Cooperation and communication is complicated by the fact that these individuals are widely scattered geographically. Thus, there has been a real need for an international seminar on the topic of theoretical wave resistance. The purpose of the seminar should be an evaluation of recent advances and the discussion of guide lines for future research. Such a seminar was held in Ann Arbor during August 1963. Expenses were shared by The University of Michigan, the Office of Naval Research, and the National Science Foundation. The knowledge gained will undoubtedly be of great value to the Maritime Administration's research program.

We are currently working on a limited study on the effect of variations of section shapes of Series-60 hull forms with regard to resistance and propulsion. This preliminary study has been undertaken by a separate Maritime Administration Task. Results have been reported elsewhere.(31) Moderate V-shaped sections may lead to improved overall performance. It may become evident however that the sectional area curves should be different from those of the Series-60 parent forms. This point ought to be investigated, possibly with the aid of theoretical wave-resistance theory.

The original Series-60 family of hull forms covered a range of block coefficients up to and including $C_B = 0.80$. Many of the large tankers and ore-carriers being built today have block coefficients of considerably higher value. There is a definite lack of information on resistance characteristics of these ships in the literature. It is therefore proposed that a limited family of full hull forms be developed and tested for both E.H.P. and S.H.P. versus speed. The parent form could possibly be developed from the Series-60 lines, but this should not be a requirement. Careful studies of the flow conditions around the aft body of the models must be undertaken as part of the investigation of full hull forms.

In a recent paper D. J. Doust(28) describes the development of trawler hull forms based on statistical methods of analysis of the N.P.L. resistance and propulsion data. The resistance qualities of these forms have been expressed in equational terms, dependent on certain non-dimensional parameters of their hull shape and dimensions. By minimizing this equation, new combinations of parameters have been derived which give superior performance relative to all previous results. Predictions of optimum hull forms have apparently been verified by full scale results. It is noteworthy that the evolution of the trawler form based on experience did not lead to an optimum choice of design parameters, in spite of extensive model testing. This leads one to wonder whether in the past new designs have not been based too heavily on existing ships.

The regression equations used by Doust are not necessarily the only equations of this type suitable for the analysis of ship performance. Several similar methods are already available at The University of Michigan Computing Center. These have already proven to be very successful in the analysis of complex engineering problems, and it is therefore proposed that the Maritime Administration sponsor a computer project for the purpose of the statistical determination of optimum hull form parameters of commercial ship forms.

## C. Ship Propulsion Research

Although it has always been recognized that an interplay exists between the flow to a ship's propeller and the flow around the ship itself, it has been customary to more or less separate the field of ship propulsion from that of ship resistance. In the case of slow speed cargo ships such a separation is probably not too serious, since it is often sufficient to obtain a nominal wake at the propeller disc from the resistance test model, and then design, from propeller charts or by more refined methods (such as the circulation theory) an optimum propeller to suit this wake. Frequently, an average wake obtained from a windmilling propeller is all that the designers have been willing to pay for, and in many cases not that much. The development of highspeed ships has changed such simple design procedures, however, and it has become more common to provide the propeller designer with a complete wake survey, determining the wake condition at all points on the propeller disc.

To measure velocities in the wake, a five-hole pitot tube was developed at DTMB several years ago. With this instrument, pressures in the flow are measured by means of U-tube manometers. The dynamic response of such an instrument is so low that one reading, at the most, is obtained from a single run down the basin. More than one run per reading is often necessary in order to reach equilibrium conditions in the U-tube. Owing to modern electronics technology, major improvements can be made in the design of the five-hole pitot tube. In an instrument, now under construction at The University of Michigan, it is planned to use electronic pressure transducers instead of U-tube manometers. The response of these transducers is sufficiently high that it will enable the wake survey to be made around a complete circle, of constant radius from the shaft line, during one towing tank run. By digitizing the transducer outputs directly onto magnetic tape and developing a computer program a harmonic analysis can be made with great facility. The purpose of the instrument is to provide a simple technique whereby the wake survey becomes a matter of routine. In the future it should therefore be included as part of the testing of new model forms. The construction of the five-hole pitot tube is already partially supported by the Maritime Administration. It is proposed that this support be extended to cover electronic components and programming of calculations.

In the discussion above, only the steady state values of wake velocity components are considered. Except in cases of unusual forms, the opinion is generally held that the wake is essentially steady. From recent measurements it appears that a revision of this opinion is in order. These measurements have indicated that predominant time-dependent wake variations may exist around a frequency of approximately 20 cycles per second. Two distinctly different causes may give rise to such variations. Several flow studies have shown the formation of large vortices around the aft body of models, originating at about the aft shoulders. These vortices are undoubtedly unstable and will therefore produce a time-variable flow at the propeller. It is interesting to note that Dr. Hogben and Dr. Gadd(10) mention that such vortices may always be present, and that they may, indeed, partially account for the discrepency between experimental and theoretical values of energy transfer of ship waves.

Although vortices of the type described cause variations in the wake flow, it is difficult to believe that the predominant frequency of these variations will be as high as 20 cycles/second. It is therefore reasonable to suspect that the principal cause of non-steadiness of the wake flow is to be found in instability flow phenomena of the boundary layer. Measurements recently performed elsewhere point to what may be called, for lack of a better name, a ragged edge of the boundary layer. In a particular case, this raggedness appears to be located at about eight-tenths of the radius of the propeller, resulting in significant thrust and torque variations at that location.

Sufficient evidence is not available at this time to make it possible to predict the occurrence and nature of this type of boundary layer instability. Detailed studies of the flow around the aft body of the models should therefore be undertaken as soon as possible.

A complete description of the wake flow will be of immense value to the propeller designer. Non-steady propeller theory has not as yet advanced to a point where it can accurately predict the magnitude of alternating torque, thrust, and transverse forces. Application of quasi-steady techniques in some cases produce calculated values close to those measured, but there is serious doubt that such methods are fully reliable, especially where the wake has sharp peaks smaller in width than the propeller blades. It is, in fact, even doubtful that Sears' non-steady airfoil theory applies to this type of flow condition. Professor Frank M. Lewis is now installing, in the MIT towing tank, a special water tunnel designed for the study of forces on a foil subjected to a sudden gust.

Pictures of flow around the foil may reveal whether the Kutta conditions are being satisfied at the trailing edge. A similar study is presently being carried out in air at The University of Michigan. These programs should produce some valuable information on two-dimensional non-steady foil theory. After the two-dimensional theory has been formulated, there remains the extension to three-dimensional cases such as the ship propeller.

Since 1960, DTMB has been using a stern section separated from the rest of the hull as a means of investigating propeller-induced forces on the hull.(18) Although the magnitude of the forces acting on the stern section reveals the overall effects of the propeller, little information is provided about the distribution of pressure forces on the hull. The magnitudes of pressure forces and their distribution has a great effect on the elastic response of a ship, and it is important that more information be produced in this area of propulsion research. A few years ago attempts were made at DTMB to measure propeller induced pressures.(29) The tests did not produce reliable results and were, in general, discouraging. Although modern pressure transducers are far superior to those used then, more immediate demands have prevented a renewed attack on the problem at DTMB. The recent theoretical developments by Dr. Breslin(19) and others serve to give impetus to further research on this subject. We recommend that the Maritime Administration sponsor additional tests in this area, at DTMB or elsewhere. It is interesting to note that pressure measurements on a full-scale destroyer have been made in Japan.(30)

## D. Research On The Effects Of Ship Motion On Resistance And Propulsion

St. Denis and Pierson's 1953 paper(20) provided such a stimulus to the study of ship motions that the subject has gained more study and attention since that date than during the entire previous history of naval architecture. The introduction of the concepts of statistical mathematics made it possible for the first time to describe rationally typical sea states and the resulting motion of a ship. The deleterious effects of slamming, extreme rolling, or the shipping of green seas are well known. It is therefore not surprising that these new tools were applied principally to the problems of extreme ship motion. The question of maximum loading of the hull girder also received new attention.

Although the above mentioned developments have been beneficial, we believe that one economically important area has been badly neglected. We refer to the determination of the influence of sea state on ship's speed within the range of conditions where full power can be maintained. Ship operators are interested in using electronic computers in optimizing the routing of their ships. Clearly, any realistic computer program will demand more information than the stillwater speed and power relationships. The importance of further work in this area is also underscored by Benford's recent report(26) in which he concludes that the lack of quantitative data on sea speed is the missing link in the use of economics to optimize ship design.

The problem of providing speed and power relationships for various headings, wave lengths, and wave heights may appear overwhelming. However, there is reasonable evidence(21) that a ship's response is a linear function of wave amplitude, or nearly so, for the greater part of the region wherein it is practical to maintain full power. It would therefore probably be sufficient to test models of standard size in waves of standard height. This would facilitate direct comparison of results.

In view of the above, we recommend that the Maritime Administration sponsor comprehensive self-propelled model tests in head-sea conditions. Subsequently the program should be expanded to cover the complete range of ship headings with respect to the waves. In addition to measuring average values of propeller torques and thrusts, we hope that time variations of torque and thrust can also be evaluated experimentally.

It is often stated that ship motion studies do not require large models, and that it therefore would be less expensive to build a large model for SHP tests and a smaller one for ship motion tests, rather than using the large model for the whole program. In view of the high costs of models in general, it is doubtful that the two-model procedure will prove to be less expensive in all cases. If self-propulsion in waves is considered, only a large model can be used if scale effects are to be avoided. The large models impose requirements on the tank width, however, since it is known that ship motion is quite susceptible to tank wall effects. A further need in the area of ship motion is the study of the damping effect of the large Inui bulbs. Information on this aspect is of great importance in the overall evaluation of these bulbs.

### E. Improvement of Ship Model Test Procedures

With a single stroke of genius, William Froude laid the foundation of the theory of model testing when he assumed that the total resistance $R_t$ of model or ship could be divided into two parts, i.e.,

$$R_t = R_f + R_r,$$

and furthermore, that the frictional resistance $R_f$ is a function of the Reynold's number only, whereas the residual resistance $R_r$ is assumed, in addition, to be the sum of the wavemaking resistance and the eddy resistance. We have long realized that this simple relationship between the forces acting on a ship's hull, even when moving at constant speed on a straight course in smooth water, ignores possible interaction effects. If the forces are expressed in terms of non-dimensional coefficients, it would probably be more correct to write

$$C_t = C_w + C_f + C_e + C_{wf} + C_{we} + C_{ef}$$

where the terms $C_{wf}$, $C_{we}$ and $C_{ef}$ represent the interaction effects of waves and boundary layer, waves and eddies, and eddies and boundary layer respectively. Research in the field of ship resistance in the past has indeed shown that these secondary interference effects are appreciable. It has, however, been incapable of producing accurate methods by which they can be evaluated. The standardization of model sizes used in individual tanks, together with the prediction of performance of ships of standard lengths, and the introduction of correlation coefficients, such as $\triangle C_f = .0004$, may very well have blindly compensated for a great deal of the interference effects in most cases, thus providing satisfactory estimates of full-scale performance based on model test results. It has taken a great many years and an immense number of model tests to get this far, the main reason being that -- because of differences in size, technique, or instrumentation -- almost every tank must determine its own correlation factors. Even today, we find it desirable to test one and the same model in the various testing tanks of the world so as to assure a continuation of comparable results.

One may logically ask for the reason why interference effects are not well known. The answer is not hard to find; it can, in fact, be stated in two words: analytical complexity. In the past, the problems of treating both the wavemaking and the frictional resistance components on a purely theoretical basis have been dealt with quite intensively. These contributions to our knowledge of the fundamentals of ship resistance have been significant indeed. The application of theories to quantitative evaluation of resistance components in the case of practical ship forms, however, has not been too successful. We believe the main reason for this may be the limitations imposed on theories by the assumptions made in their derivations. In the case of frictional resistance, for instance, we are still applying flat plate theories to the three-dimensional ship's surface. As far as wave making is concerned, the theory is restricted by the linearization of boundary conditions and by the fact that even these are not satisfied at the true boundary surfaces.

Introducing limitations so as to avoid mathematical complexities is a feature that is certainly not confined to ship theories alone. In many non-ship cases it has been found possible to evaluate these limitations by means of carefully planned and executed laboratory tests. Until recently, however, it has been impossible to do so in the field of ship resistance. The only quantity that the ship model tester has been able to measure is that of total resistance, and he has not been well equipped with analytical tools to deduce from this measurement the magnitude of individual force components and their interplay. How, then, could the mathematical wave-resistance theory be evaluated when it was not even agreed what part of the total resistance of a model was due to the generation of waves? Within the past year, investigators have undertaken to measure the magnitudes of the separate forces contributing to the resistance of a model. The methods proposed by these investigators offer an opportunity to determine the validity of the basic Froude assumptions of ship-model resistance testing, and possibly to develop improved procedures.

One way of analyzing the resistance of a ship is to express it as the sum of the frictional and pressure drags. The latter, which can be obtained from measurements of the pressure distribution over a hull, has been obtained for a few ship models in the past, and has been measured recently by Townsin at King's College(2) for a Victory ship model. The significant result of all these tests is that the frictional resistance, derived by subtracting the pressure drag from the total, is considerably greater than the flat plate or the extrapolator values usually assumed in the analysis of ship-model data.

An alternative analysis expresses ship-model resistance as the sum of the viscous and wavemaking drags. The former, obtained by Wu(3) from a wake survey conducted at The University of Iowa, has yielded a value, for the viscous drag of a Series-60 ship model, about 4 percent greater than the frictional resistance computed from Schoenherr's formula for the resistance of a flat plate. Since the viscous drag is the sum of the frictional resistance and the viscous pressure drag, and 4 percent is probably too small a value to allow for the latter, it follows that a ship model must have a lower frictional resistance than a flat plate. This result contradicts those obtained from the hull-pressure surveys, noted above, but is in agreement with some measurements of Wieghardt(4) on the frictional resistance of cylinders of non-circular sections.

The wavemaking part of resistance has been measured by Ward at Webb Institute of Naval Architecture(5) employing a method, based on theory, requiring the measurement of surface-wave profiles. His values for the wavemaking resistance of the ATTC Standard Model are about two-thirds of those calculated by Wigley(6) from the Michell ship-wave-resistance integral, with corrections for viscosity. They are also about two-thirds of those obtained by Nevitt(7) who subtracts an assumed value for the frictional resistance from the total. In analyzing his measurements, Ward assumes that the flow is potential, so that his results may be subject to an undetermined error owing to the failure of this hypothesis in the wake region. Assuming that this error is small in comparison to the magnitude of the aforementioned discrepancies, his results would indicate that linearized gravity-wave theory seriously over-estimates the wave-making resistance and that the viscous drag, at a Froude number $v/\sqrt{Lg} = 0.28$, is 11 percent greater than the frictional resistance given by Schoenherr's flat plate resistance formula.

Eggers(8) presented a paper in which he proposed to evaluate the wave resistance of the model from two wave profiles located behind the ship, an arbitrary distance apart along sections perpendicular to the direction of motion. During the summer of 1962 this principle was used by Sharma, of the Institut für Schiffbau, in the evaluation of the wave resistance of a mathematical form derived from a linearly varying source distribution. Some of Mr. Sharma's tests were observed by the author who also had the opportunity to discuss results and many of the questions left open for evaluation in the future. At a Froude number of 0.121, calculations indicate that the wave-resistance obtained from wave profiles was only about 60 percent of that arrived at in the usual manner (subtracting the frictional drag -- as given by Dr. Hughes formula -- together with a form factor K, from the total drag measured). Obviously, such a surprising result led to a series of questions about the validity of theory, accuracy of measurements, magnitude of viscous forces, etc. As far as theoretical formulation is concerned, Eggers' method is probably better suited than Ward's for model testing, since it does not require a wide tank with respect to model size. In Ward's case there is also the question of selecting the point of origin of the coordinate system, a limitation that is removed in Eggers' work. Mr. Sharma has taken profiles along six sections and, by pairing any two of these, he has been able to obtain several independent values of the wave resistance -- from which an average can be taken. Furthermore, he obtains in this way a good evaluation of the accuracy of numerical calculations. It should be mentioned that two independent methods were used in obtaining the wave profiles: stereo photographs and a sonic surface-wave transducer of the type developed at St. Anthony Falls Laboratories, University of Minnesota.(9) Both methods gave comparable results, and since the echo sounder gives the profile directly and is easier to handle, it will probably be preferred for this type of work in the future. A sample wave profile obtained with the echo sounder is shown in Figure 1.

In the higher speed ranges, Sharma finds that the discrepency between theory and test varies. The best agreement was reached at a Froude number of 0.34. This corresponds to a speed at which the linear wave-resistance theory generally checks most closely with experimental results. To eliminate the question of the correctness of the frictional resistance formula used in the calculations, some wake measurements were made with pressure probes. Calculations of frictional drag, using the Betz formula, indicate good correlation with Hughes. It is therefore our opinion that the low value of wave resistance predicted by Eggers' method could not be explained by a possible insufficient magnitude of the frictional resistance. One would expect that a constant discrepency would exist over the speed range if this were the case, or -- at the most -- that the difference would be monotonically increasing or decreasing. It appears, however, that the variation between results is an oscillating function of Froude number. The mathematical formulation of Dr. Eggers' work is given in Appendix II.

What is known at present is that the flux of energy, owing to free waves, as evaluated by means of a linear theory, is in apparent disagreement with the value arrived at from the towrope pull. This disagreement is not the same as that which exists between the linear Michell theory and the measured resistance. Perhaps the linear theory of free waves is not sufficiently accurate in portraying free surface conditions. Any improvement in this regard, however, could hardly be expected to make up for the total difference of results. Is it then possible that some mechanism of exchange of energy exists between waves and boundary layer? Dr. Inui, in his work, introduces a correction factor to account for the attenuation of bow wave amplitude owing to the presence of a boundary layer. He also adds a shelving correction factor that accounts for the fact that the ship runs on top of its own bow wave. Both these factors serve to bring the linear theory into better agreement with experiments. Considering the energy in the free waves, however, one is forced to look for further corrections. We want to point out that a mathematical theory based on potential flow, even accounting for nonlinear boundary conditions, assumes that the ship is 100 percent efficient in generating waves. It is reasonable to expect that this is not true. If the ship is less than fully efficient in producing waves,

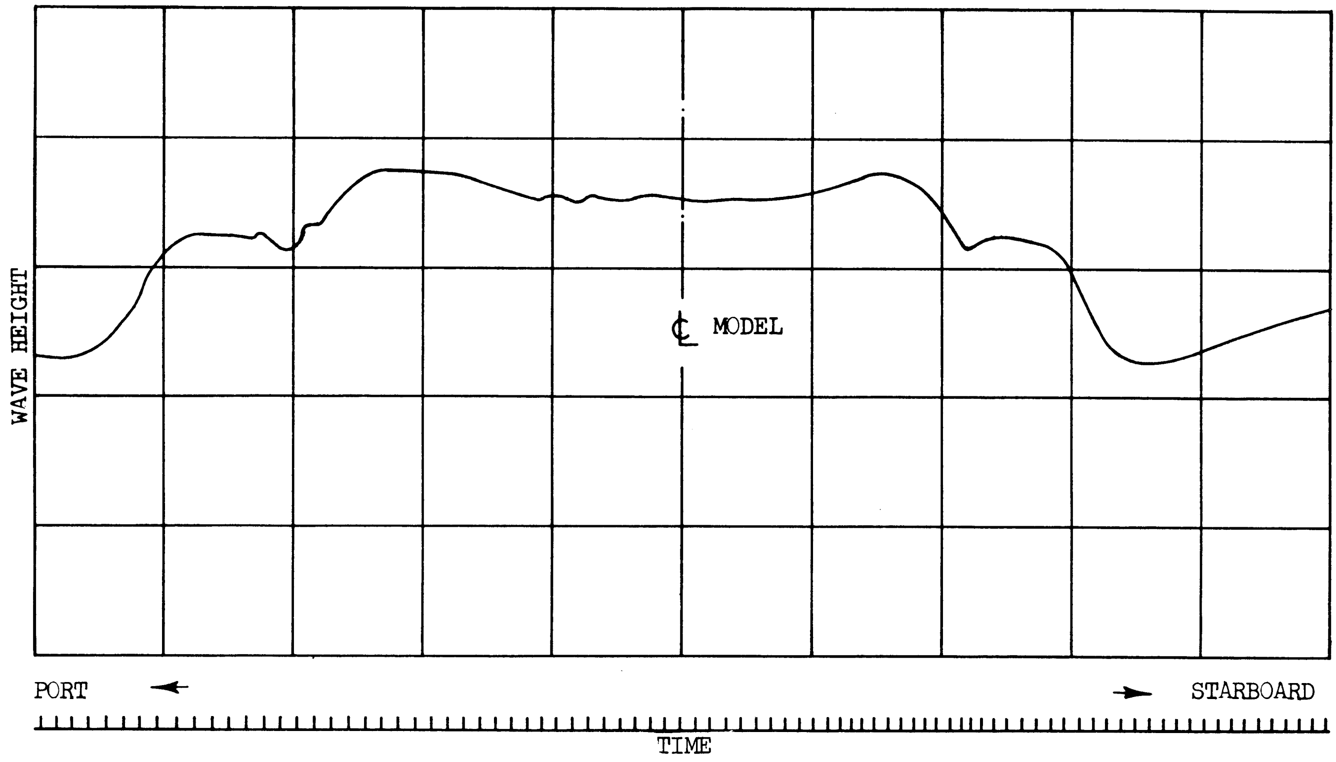

Figure 1. Typical Wave Profile Obtained 12 Ft. behind the Model in the HSVA Model Basin.

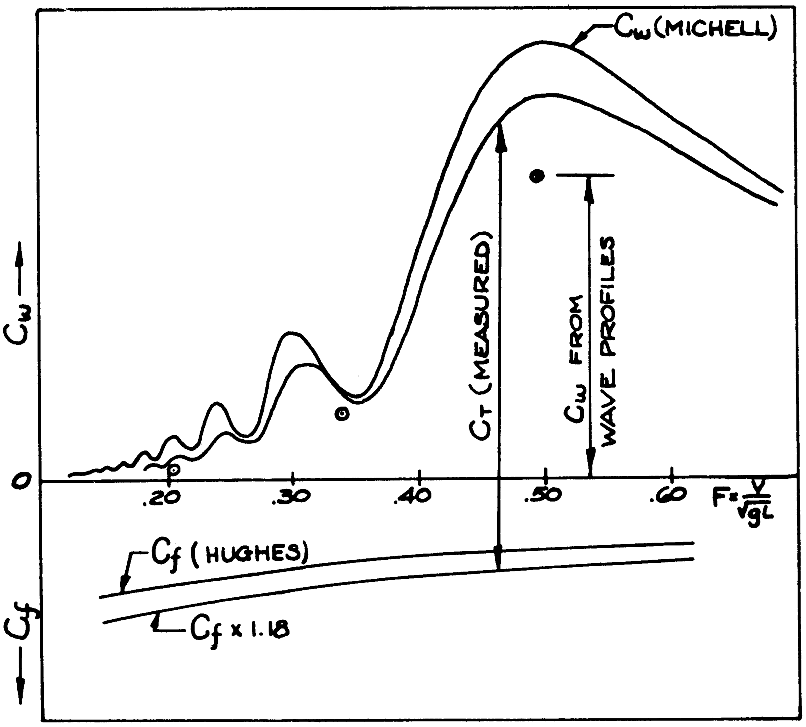

Figure 2. Relationships Between Measured and Calculated Drag Coefficients.

it simply means that part of the wavemaking resistance will not appear in the form of free waves. This idea is quite distinct from that of Dr. Inui since we are considering here a reduction in wave amplitude even before the waves have been in contact with much or any boundary layer, or have been affected by rigid boundary surfaces. After witnessing the manner in which bow waves are normally generated by a full size ship, it is not difficult to imagine how some wave energy may be dissipated in the breaking crests.

The result of Sharma's work is outlined in Figure 2. He is currently continuing his work in this field. The method of analyzing the wave resistance from wave profiles behind the ship opens up a great many possibilities in regard to the evaluation of the effects of design parameters and testing conditions and we hope that some investigations, parallel to Sharma's, can soon be started in this country. One fundamental question that immediately presents itself is that of scale effect. If the efficiency of the model as a wave-maker is less than 100 percent, there is a definite possibility that a new scale effect would exist in relation to wave making. This scale effect would be distinct from that already known to exist because of the difference in the thicknesses of the boundary layers.

Dr. Hogben of NPL has also formulated a method for obtaining the wave resistance from wave profiles. It is of interest to note that one of his measurements gave a calculated value of the wave resistance in the order of one-half of the value obtained from the towrope pull. This led Dr. Gadd, also of NPL, to perform some simple experiments in a small flow channel. Assuming that the boundary layer was the cause of the difference between wave profile and towrope wave resistance values, he wished to introduce a boundary layer in a two dimensional wave train without creating a new wave. To accomplish this he used an essentially flat plate strut. The general experimental setup is shown in Figure 3.

Dr. Gadd observed that, when the trailing edge coincided with a trough, the wave behind the strut was essentially undiminished; whereas when the trailing edge was at the crest, the wave downstream from the strut was reduced to about one-half its original amplitude. An adverse pressure gradient existed in the second case, which may be of some significance. The results are startling, and this case of fluid flow should be more fully investigated. In a report on their work, Dr. Hogben and Dr. Gadd(10) attempt to ascribe the lack of energy transfer of the free waves to energy transfer of eddies.

A fourth procedure for obtaining the wave energy of a ship from its wave pattern is presented by Mr. Wisashi Kajitani in his discussion of Dr. Inui's recent paper on "waveless" hull forms.(11) In this, the path of integration is chosen along crest lines, and a fairly complete picture of the wave field is therefore required. We note that a good correlation between calculated wave-resistance values obtained from wave patterns and those evaluated from towrope pull has been obtained in Japan. This fact only serves to emphasize the need for more detailed investigations.

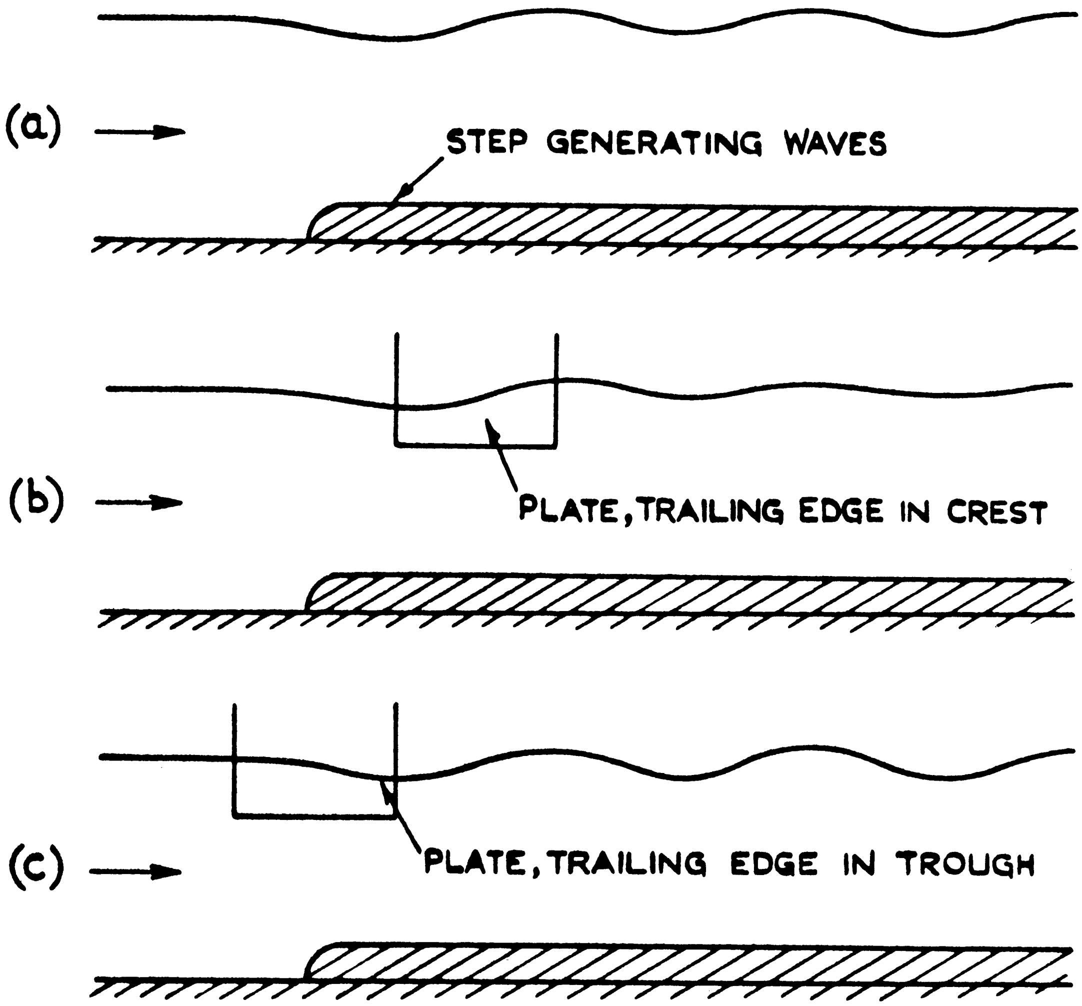

Figure 3. Flume Experiments on Interactions Between a Wave System and a Boundary Layer.

A clear and consistent view of the magnitudes of the various kinds of resistance force components is not yet available from the experiments described above. What is significant is that they indicate the availability of means for measuring these individual components, thus leading to a fuller understanding of their interdependence. The new developments in the field of ship resistance theory have provided us with several independent methods by which resistance forces can be measured. This redundancy should be used to reveal characteristics of the flow around ships and to provide data by which their effects can be evaluated.

This suggests the following research projects:

1. Select a ship form for which the wavemaking resistance is readily calculable by potential theory. Calculate the wave resistance versus Froude number not only from the Michell integral but also in accordance with Appendix II "Wave Resistance of Ships," which introduces non-linear corrections to the Michell solution and a more accurate determination of the source distribution on the center plane as the solution of an integral equation. It is a well established fact that the Michell theory, in addition to exaggerating the humps and hollows, overestimates the wave resistance of ships of finite beam. The introduction of non-linear boundary conditions is expected to bring theory and experiments into better overall agreement, although correction factors and an efficiency concept, as mentioned before, may be necessary to explain the apparent lack of wave interference effects.

It is possible to include the theoretical effects of changes in sinkage and trim in the calculations of the non-linear case. This would greatly complicate the analysis, however, so we propose to assume no change in the ship's attitude. Calculations based on the linear theory have shown that correlation with theory is improved if the model is left free to adjust its own sinkage, but is restrained from trimming. If sinkage is restrained, the displacement of the model would also change. It is proposed that a similar procedure be used initially in any experimental verification of the non-linear theory.

2. Determine the viscous drag versus Froude number by means of a wake survey in one transverse plane. Analyze the data in accordance with the most accurate of the viscous drag formulas discussed in a recent report by Landweber and Wu.(12) Also measure total resistance.

The determination of frictional resistance may seem to run into the fundamental question of the degree of turbulence stimulation. But this is really not the case here since the purpose of this investigation is to determine accurately what the total frictional force is in a given case, regardless of what type of turbulence stimulation is used. One may say that stimulation will be necessary only in so far as it stabilizes the flow and improves the consistency of the measurements. The values of the residuary resistance versus Froude number, obtained as the difference between the total and viscous drag, should be compared with the values of wavemaking resistance obtained from non-linear potential theory and from wave profile analysis in accordance with Eggers and others.

3. The new theories advanced by Landweber, Wu, and Eggers should make it possible to determine the total resistance of a ship model from the flow conditions at some arbitrary location behind the model. The wave profile analysis should therefore be put to full use in conjunction with the analysis of wake survey.

Naturally, we hope that the total resistance obtained by means of the theories mentioned above will be the same as the towrope pull. Sharma's failure to achieve this in the few tests made to date indicates, however, that a great deal of detailed experimental work and analysis remain to be done. The ultimate reward from such research should be improved methods for the determination of the hydrodynamic forces acting on a ship's hull.

4. The wake analysis advanced by Landweber and Wu provides a method by which the change in frictional resistance can be determined directly. Since the thickness of the boundary layer will influence both frictional and wavemaking resistance, it is not sufficient or satisfactory merely to evaluate the frictional drag from the towrope pull. Therefore, it is proposed that the problem of boundary layer stimulation be studied in greater detail, using various types of devices, and measuring simultaneously both the wake and wave profiles. This study should also include some investigations of scale effects. It is proposed that this be done by means of performing identical test series with geometrically similar models of different sizes.

Wavemaking resistance for this series of models should also be computed from theory and compared with wave profile evaluations.

Although it may become possible to determine with certainty what the frictional resistance of a given model is, one does not escape the question of turbulence stimulation. Since the degree of turbulence in the boundary layer has a direct influence on the separation of flow around three-dimensional ships, it is important that the flow around models be turbulent. In spite of the large amount of research done to date in the field of turbulence stimulation, no final conclusion has been reached in regard to type and amount of stimulation required. Some towing tanks use one trip wire, others use two. Studs of various shapes and location have also been fitted to models. From this fact alone it should be obvious that a standard roughness correction of $\Delta C_f = 0.0004$ is at best a guess. The name "correlation factor" used by many investigators is probably a better choice than "roughness correction." The opinion held by several reseachers today, among them Dr. Hughes, is that it is preferable to introduce complete turbulence stimulation to the flow around models by mechanical means, such as studs. These devices must, however, be of such design that their own drag can be easily estimated.

5. Three dimensional boundary layer theory has been developed(14) to a point where efforts should be made to calculate the viscous drag of ship forms. The known viscous drag of the model could be used to suggest correction factors for these calculations. The theory may also indicate the nature of the laws of variation of the viscous drag with hull shape and Reynolds number.

6. During the past year, a successful semi-empirical formula was derived and tested, allowing very good estimates of the blockage effect in The University of Michigan towing basin. We are still not sure that it does not also take into account some scale effects and we therefore suggest that the blockage effect on the wave resistance be studied from a theoretical point of view as indicated in Appendix III, and that the contribution to the frictional resistance, owing to the presence of tank boundaries, be determined from wake surveys.

The problem of predicting the resistance of the full scale ship remains. Undoubtedly, the wavemaking resistance depends primarily upon the Froude number and can be obtained approximately from the values for the model. It is important, however, to investigate the effect of Reynolds number of the wavemaking resistance coefficient. The following additional tasks are therefore proposed.

7. If wave resistance calculations based on potential flow with corrections for viscous effects are found to be in good agreement, repeat the calculations, taking into account viscous effects at the Reynolds number of the ship, assuming a smooth hull.

8. We believe that the Maritime Administration should also sponsor full scale measurement of wavemaking resistance on an existing hull. Thus, the lines selected for model tests should be that of an existing vessel. Selection of a form on the basis of ease of theoretical wavemaking calculations

would then have to be sacrificed. The full size surface wave profiles could be measured by means of stereoaerial photographs. Measuring the ship's total resistance would also be desirable. Since the wave-making would be disturbed by the usual propeller drive, we suggest that some form of air thrust propulsion be employed. Further, we suggest that this full-scale trial be carried out both with a clean, freshly-painted hull and also after the ship has been out of dock for a considerable time.

A practical procedure for the above might be first to conduct tests with the ship as is, then to dock it to examine the nature of the roughness, and then to clean and paint. These full-scale results should yield an evaluation of the degree of validity of the Froude law of comparison and of the success of theoretical methods for computing wave-making resistance. If the effect of Reynolds number on wave-making is found to be significant, the theory might be applied to compute a correction factor -- presumably differing only slightly from unity -- for the extrapolation from model to ship.

# CHAPTER II

## FIVE YEAR RESEARCH PROGRAM SUMMARY

In the preceding sections we have described and elaborated on areas of research on ship resistance and propulsion which we believe require immediate attention, to be followed by continuous research efforts for several years to come. It is realized that in so doing we have been discussing much research which cannot be conducted with the present facilities at The University of Michigan. In this section we will therefore outline specific tasks which we can perform without any capital expenditures for new major facilities. It is expected, however, that funds will have to be provided for certain instrumentation which will be needed for the specific investigations proposed.

Rather than arranging the separate tasks described below in the order of priority, they have been listed in accordance with the sequence in which they are discussed in this report.

A. Hull Form Research

a) A study of the relationship between hull form and wave-making characteristics. Both mathematical and conventional hull forms are to be investigated. The work on large bulbs now underway should be continued.

b) Systematic evaluation of the effect of changes of section shape on resistance and propulsion, primarily as applied to the Series-60 forms. As an extension, an investigation of the effect of changes of the sectional area curve will be undertaken, based on the linear wave-resistance theory and on model tests.

c) The study of a family of hull forms of fullness greater than $C_B = .80$ to determine resistance and propulsion characteristics of present day large slow speed commercial ships in a systematic manner.

d) Application of regression equations to existing tank test data for the purpose of a statistical determination of optimum hull form parameters for commercial ships.

B. Ship Propulsion Research

a) The complete development of the five-hole pitot tube fitted with electronic pressure transducers and mechanical drive for the survey of the wake field in the plane of the propeller. The introduction of electronic recorders and analyzers to provide a harmonic analysis of the wake flow, and the application of this instrumentation to the determination of flow conditions behind the hull forms tested under project Ab above.

b) A detailed study of time variable flow conditions in the wake field of various ship forms to determine parameters governing this phenomena.

c) Experimental determination of propeller induced pressures acting on the hull. Results to be checked against prediction of existing theories.

C. Research on the Effects of Ship Motion on Resistance and Propulsion

a) Self-propulsion tests of models in moderate head seas to determine average changes of propulsion characteristics.

b) Measurements of time variations of thrust and torque of self-propelled models in waves. Such measurements will be correlated with ship motion date to determine relationships between variations of propeller forces and motion amplitudes at the stern.

c) Testing of models fitted with large bulbs in head seas to study effect of these bulbs on ship motion and resistance. Self-propulsion tests will be included.

D. Research to Improve Ship Model Testing Procedure

a) The development of higher order corrections to the linear wave-making resistance theory. Evaluation of simple mathematical ship forms in an attempt to bring theory into better agreement with experimental results.

b) Determine the viscous drag by means of wake survey in one transverse plane. Analysis of data in accordance with a recent paper by Landweber and Wu. Mathematical hull forms, for which the wave-making resistance can be readily evaluated, should be used primarily.

c) Evaluation of wave-making resistance from wave profile measurements by means of several methods recently proposed by Eggers, Ward and others. Investigation of second order corrections necessary to bring theory and experiments into better agreement. The effect of the boundary layer and eddies on the wave-making resistance should be studied very closely, and also the possibility of a scale effect on the generation of ship waves.

d) Investigation of boundary layer stimulation by means of wake surveys accompanied by calculation of viscous drags. In addition hot film anemometers should be used to determine laminar flow regions and flow separation at the stern. Models of different sizes need to be tested to provide data for evaluation of scale effects.

e) Application of three-dimensional boundary layer theory to ship hull forms. Comparison with wake survey measurements.

f) Blockage effect study incorporating theoretical evaluation of increase in wave-resistance of a ship moving in a channel and the evaluation of the change of frictional resistance due to blockage from wake surveys.

g) On the basis of information obtained on the dependence of wave-making resistance upon the Reynolds number and scale effects, an attempt will be made to calculate the wave-resistance of a full size ship from available theories.

h) Planning of full scale trials to verify predictions derived from projects D: a, b, c, d and e.

Progress made at The University of Michigan and elsewhere may change the picture considerably as time goes on. It is therefore important to add the following project:

> Maintain a continuing survey of world wide research activities in related fields and, when necessary, modify or augment the proposed program. Report to be submitted to the Maritime Administration yearly.

# APPENDICES

# APPENDIX I

## PERSONNEL AND FACILITY NEEDS

### A. Introduction

In the conduct of experimental research, laboratory facilities and research personnel are intimately connected. One cannot consider one of these factors without, at the same time, taking the other into account. We fear that the intimate relationship between facilities and personnel has quite often been overlooked with the result that research facilities have been built more as a symbol of stature than as a place for intensive scientific investigations. Research facilities must be considered as tools in the hands of able and competent researchers. The type and size of facilities must, therefore, bear direct relationship to the immediate projects at hand; they must also be, as much as possible, adaptable to future requirements.

Simple principles of economics dictate that the tools in the hands of the researchers be of the right type, size and of the best design. Size is of the utmost importance. One must be careful to distinguish between overall plant size and size of individual pieces of equipment. The plant size should be geared to the rate of flow of the overall production, whereas the size of the item of equipment in question should be sufficient to perform the tasks at hand properly. If it is foolish to attempt to lift a two-ton load with a one-ton crane, it is also foolish to buy a two-ton crane if loads never exceed one ton.

As a matter of expediency, this appendix treats personnel and facility needs in separate sections. In several important areas, however, the two must be considered simultaneously. Thus, the section on facilities makes frequent reference to associated personnel considerations.

## B. Personnel

Chapter I outlines a long range research program in the field of resistance and propulsion of ships. The program is ambitious, and it should be. The United States has established itself as a leader in the field of theoretical studies, but as far as follow-up investigations are concerned, it does not enjoy the position it had in the past. The number of research establishments in Europe and Japan, compared to those in this country, underlines this fact. The difference in training of our researchers is possibly the main reason for this state of affairs. Most European Maritime researchers are naval architects, whereas, in the United States they are more likely to be mathematicians or physicists and, as such, improvement of merchant shipping is likely to be anywhere but at the forefront of their minds. This is not to say that our researchers have not made significant contributions to the field of naval architecture, for indeed they have. The main problem today, however, is that pitifully few of their contributions have ever been proven out or converted into practical terms for use in shipyards and design offices. The solution of this problem will require two things:

1. Continued experimental research to verify theories and to investigate forms and parameters important in the actual design of ships, and the presentation of results suitable for use in ship design.

2. Stronger training of naval architects in the fields of mathematics, physics and applied mechanics so that they can fully appreciate potentially useful developments in theoretical aspects of hydrodynamics. Training in the field of experimental research is of equal importance. Both require increased emphasis on graduate training.

Part 2, above, has long been overlooked. As a result, the process of translating new scientific knowledge into a form suitable for the design of ships is seriously inhibited by a lack of competent personnel. Since the Maritime Administration is directly connected with the welfare of the U. S. merchant marine, it can no longer afford to overlook our country's critical shortage of naval architects with advanced university training. The original 1936 Act (Section 201-e) specifically authorized the establishment of scholarships for advanced study, and this was echoed by The Maritime Research Advisory Committee(22): "The Maritime Administration should establish a program of 20 to 30 annual unconditional fellowships for advanced study in maritime or related fields." The Maritime Research Advisory Committee also understood the important interrelationship of education and research activities as witnessed by the following recommendation:

> An important consideration in assigning research facilities should be to exploit to the maximum the potential influence of such facilities to arouse the interest of able young researchers, to provide them with opportunities for employment both before and after graduation and to develop the research interest and abilities of senior scientists in maritime fields of need.

> In placing contracts, attention should be given to furthering education in maritime related fields. Particular consideration should be given to universities, especially those with strong interest in naval architecture and marine engineering. Consideration should also be given to private non-university research or industrial organizations and to the David Taylor Model Basin for its specialized facilities and services.

The State of Michigan deserves a great deal of credit for the way in which it instituted and now voluntarily supports the national resource which is this Department of Naval Architecture and Marine Engineering, the country's largest source of trained naval architects and marine engineers. The University of Michigan will without doubt continue to support undergraduate and graduate training in the marine field, but the critical needs of a greatly expanded graduate program cannot be met without financial assistance from outside the state. Such assistance would include funding for unconditional fellowships for graduate study and -- if we are to attract topnotch young people -- there should be scholarships for undergraduates as well. We do not mean to imply that the Maritime Administration, alone, should furnish such support nor that Maritime's educational assistance should be confined to The University of Michigan. We do feel, however, that the common interests of the Maritime Administration and The University of Michigan are uncommonly strong. Therefore, educational funding, of the type suggested here, seems uniquely prudent and natural.

Personnel needs, of course, have two facets. The first -- production of better educated naval architects -- has been stressed in the preceding paragraphs. The second relates to the more immediate problem of finding properly trained researchers to assist in carrying out the research efforts now being planned under Maritime's university program. We believe the Maritime Administration could be of greatest assistance here if it would make special provisions to assure long term support to the various cooperating universities. We say this because qualified men are in short supply and we find it difficult to bring them into our employ without at least some promise for the future. Obviously, too, good researchers demand reasonably generous support for facilities. We believe our own personnel needs could be met if we had assurances of long term funding for both salaries and facilities, coupled with the ability to offer scholarships and fellowships to promising students. The other universities would presumably be in the same position. Assurances of long term support have important secondary effects in that they free the researcher from the unattractive burden of preparing large numbers of proposals. This has implications, not only in facilitating the technical work, but in making the positions attractive to topflight technical people.

In summary of this section, we would suggest that the Maritime Administration 1) confer with representatives of the interested universities to learn what might best be done to stimulate greater interest in the marine field through the provision of scholarships and fellowships; 2) following the first step, procure funds for annual allocation to the universities for their individual decisions and distribution to students;

3) grant future university contracts on long term bases (3 to 5 years).

## C. Facilities

1. Model Basin: Resistance and propulsion play the most important parts in the study of ship hydrodynamics; they were, in fact, for many years the only aspects of significance to ship model researchers. Resistance and propulsion will always be important simply because they are so closely associated with economics. During the last 10 years we have also witnessed concentrated efforts in the fields of ship motion and maneuvering. It is unfortunate that these fields are considered, by some, to be separate from that of resistance and propulsion. Such a divorce can have only detrimental effects on the overall success of ship design. Cause and effect of hydrodynamics are intimately related by the laws of physics, and all of them must be considered without prejudice in the design of a ship. In the end, any design is a compromise, and the neglect of one or more design factors can lead only to an inferior end product. It is therefore important that laboratories engaged in ship hydrodynamic research be equipped to investigate all aspects necessary to the successful design of a ship as a complete entity from the hydrodynamic point of view. If this can be accepted as a criterion for the specification of a resistance and propulsion research laboratory, it follows that there exists in the United States today only one such laboratory, namely the David Taylor Model Basin.

These facts were at the forefront of the late Admiral E. L. Cochrane's mind when, in 1959, he recommended that the Maritime Administration consider the establishment of a new model basin.(22) His views coincided with a proposal from The University of Michigan asking for Maritime Administration sponsorship of a large new ship hydrodynamics laboratory at the Michigan campus. The Maritime Administration studied the possibility and found considerable favor on the part of U.S. shipyard management. Spokesmen for DTMB and Stevens Institute, on the contrary, argued against the proposal. Any decision of the matter was thereupon indefinitely postponed.

Following the Maritime Administration's postponement of a decision relative to establishing a new model basin, The University of Michigan has done its utmost to upgrade its original (1903) model basin, which is second in this country only to DTMB in allowable model size (up to 16 feet in length). New tracks were installed, a new towing carriage was purchased, and a new wax model and propeller shop was established. Sophisticated instrumentation was bought or produced within University shops, and key personnel were retained on a full-time basis. Although the Maritime Administration encouraged this with research contracts, including funds for calibrating the new equipment, the State of Michigan furnished by far the major share of the required financial support. Recently also the University has allocated funds for the construction of a wave-maker.

We have operated the upgraded model basin for a couple of years now and have determined that our facilities are suitable for a great many kinds of tests. We have found however that scale effect limitations may preclude dependable measurements in several highly important categories of research, particularly where self-propulsion is involved. Considering in addition, the large number of organizations, both public and private, that have used our tank -- coupled with the knowledge that a large percentage of private U. S. testing and research is still done abroad -- lead us again to the conclusion that this country needs another model basin capable of handling models of 20- to 24-foot length.

As regards model basin operating costs, our experience to date leads us to believe that a well managed university facility in this country could be operated at a cost level comparable to levels at European model basins. Commercial clients at the Michigan tank assure us that the cost difference between our tank and those abroad is apparently disappearing.

The proposed basin should be available for regular commercial testing as well as long range research. We believe such a combination of purposes is both necessary and desirable. We think it is necessary because it is the best way to keep overhead costs within reason. We think it is desirable because there is no hard and fast line between the two kinds of activity and also because their unnecessary separation tends to cause sterility in both.

We believe the proposed model basin should be located at a large university that has a strong interest in the marine field. From a university's point of view, such a facility would greatly strengthen its ability to attract outstanding staff and students. From the Maritime Administration's point of view, a university location would mean minimum costs as well as those extra benefits inherent in the stimulation of education (as already discussed in the Introduction). These conclusions are entirely in harmony with the following recommendation of the Maritime Research Advisory Committee:(22)

> The Maritime Administration should give favorable consideration to establishing five-year programs of sustained grants-in-aid to those universities which are particularly interested and well qualified to carry out maritime research.

In addition, we would call attention to the following advantages inherent in large universities:

a) A university is already in possession of extensive related research facilities such as general hydrodynamics laboratories, computers, wind tunnels, libraries and electronic equipment.

b) A university provides a better environment for basic research and stimulates researchers to look for solutions outside their own special field. It also provides a ready availability of expert consultants in related fields.

c) The advantages of the university town makes it easier to attract highly qualified research personnel.

d) Fixed costs such as taxes and maintenance are minimized.

e) A university provides a better atmosphere and provides better conditions for serving many interests, including that of international cooperation, than does a fully *government sponsored laboratory or a privately owned research* organization.

We believe we are safe in saying that no single government agency, educational institution, or industrial organization is willing to finance the construction of a large new model basin in this country. Many such groups, however, would benefit from the availability of such a laboratory. Therefore, we propose that the Maritime Administration establish a cooperative program involving the many interested parties. A partnership between the Maritime Administration and a large university, with supplementary support from industry, seems to be the only practical solution to the problem of initial financing. Obviously, such a large central facility should be made available to industry for commercial testing and research; it should also be available to qualified researchers from other institutions. We suggest that the Maritime Administration discuss this proposal with the interested universities in order to reach its own conclusions as to the best course of action.

The next few paragraphs present our carefully considered conclusions in regard to the size and capabilities of the proposed new hydrodynamics laboratory.

To carry out standard testing of self-propelled models, without excessive scale problems or tank wall effects, we consider the following model basin dimensions to be an absolute minimum.

| | |
|---|---|
| Length: | 600 ft. |
| Width: | 30 ft. |
| Depth: | 15 ft. |
| Max. carriage speed: | 30 ft/sec. |

A wave maker installed at one end should be capable of generating waves of 35-ft. length and 24-inch height and also of a random unidirectional sea.

Although a towing basin of dimensions as given above may prove quite satisfactory for much of the work at hand, it does not provide a good foundation for future expansion. The most serious limitation is its cross section. Much research, such as wave pattern analysis, will require wider basins and, for testing submerged bodies, a greater depth is desirable. We therefore recommend that the following dimensions be considered for the first stage in the construction of a moderately large towing basin:

| | |
|---|---|
| Length: | 800 ft. |
| Width: | 40 ft. |
| Depth: | 20 ft. |
| Max. carriage speed | 50-60 ft/sec. |

The relatively high carriage speed would provide flexibility of design so that special tests requiring high velocities could be undertaken. We realize that a length of 800 ft. is not sufficient to permit the use of the higher speeds, since it will take from 500-600 ft. to reach the 60 ft/sec. upper limit. The ultimate length should therefore be about 1200 ft. Thus, provisions must be made for a lengthening at a later date. This extension could be built as a ship motion basin of the same type as that now in use at the Netherlands Ship Model Basin.

The towing carriage should preferably be equipped for programmed acceleration. Electronic components, needed to accomplish this, are already on the market. Controlled acceleration would give researchers a much needed tool for the systematic study of transient and non-steady phenomena.

2. Water Tunnel: In a model study of propeller performance there is one major facet that cannot be investigated in the model tank, namely that of cavitation. To study cavitation one needs a water tunnel. This is one of the most important tools of the laboratory engaged in research in resistance and propulsion, because it provides a means of isolating parameters governing the performance of the propeller. One such parameter is the effect of non-uniform flow to the propeller. Many of the water tunnels in operation today can vary the velocity distribution in the plane of the propeller. To obtain a three-dimensional flow pattern, a model of the stern section of the ship can also be located in the tunnel ahead of the propeller. Nevertheless, we doubt that the flow conditions in a tunnel can ever be made to correspond fully to those behind a ship. Therefore, in regard to propeller research, the water tunnel should be used to study the effect of selected flow patterns, regardless of whether these patterns can be found behind any particular ship.

In addition to propeller research there are a great many hydrodynamics problems that can be investigated most easily in a water tunnel, among them, we would include boundary layer studies in connection with pliant coatings and other surface treatments. The test section of the proposed water tunnel should measure approximately 36" x 36".

This would permit placing dummy bodies in from of the propeller so as to simulate wake distributions and the effects of the propeller pressure field. Maximum velocity of water in the test section should be 20 ft/sec, with the pressure being variable from a high vacuum to about 15 lbs. per sq. inch measured at the pressure regulation container.

The propeller dynamometer should meet the following specifications:

| | |
|---|---|
| Maximum RPM | 4000 |
| Maximum thrust | 600 lbs. |
| Maximum torque | 75 ft. lbs. |

We anticipate that a 24" x 24" test section could be supplied in the future so that maximum water speed could be increased to 40 ft/sec., making it possible to test supercavitating propellers. In addition, it would be desirable to obtain equipment for propeller tests with inclined shafts and for counter-rotating propellers. For testing of bodies and profiles, a 6 - component balance should also be eventually included.

We expect the tunnel would be equipped with means for the adjustment of the velocity distribution at the test section.

The remaining paragraphs of this section deal with the facilities and equipment which will be needed at The University of Michigan if we are to carry out the research program described in Chapter I. The proposed new model basin and water tunnel would, of course, rank first and second in the list of desired facilities. However, the program we propose does not hinge on the availability of these facilities -- at least for the first few years. We do, however, consider them to be essential to much of the research that is forseeable beyond that proposed here. And, we might add, the sooner the new facilities become available, the greater will be their economic benefit.

3. Work Shop and Tools: Tools and space must be provided for efficient production of ship models and model propellers, and also for manufacturing special instrumentation. Many of the required machine tools are of the

standard type and are available at the University. Special model-building tools must, however, be supplied to the ship hydrodynamics laboratory.

Our wax cutting machine has served a useful purpose up until now and will probably still do so if financial conditions prevent the procurement of a new machine. It would be desirable however, to replace it with a machine designed for cutting hard wax, such as that now used and able to cut wood models as well.

At The University of Michigan, model propellers are now made almost entirely by hand. As long as the number of propellers (and their physical size) is small, this probably the cheapest method. Whenever this situation changes, however, we believe it would be of considerable advantage to purchase a propeller cutting machine.

4. Propeller Dynamometer: Until a realistic propeller theory for non-uniform, non-steady flow is brought forth, experimentation will remain the only means available for the determination of propeller performance in time-varying types of flow. And even when an analytical method becomes available, experimentation would hardly become superfluous. In a broad sense, the performance of a propeller includes much more than the efficiency. Considerations of thrust and torque variations, together with transverse forces and moments, are often of the greatest importance in the design of propellers for modern highspeed ships. In response to recent design requirements, ship hydrodynamic laboratories have attempted to measure and evaluate these time-variable forces.(15,16,17) The instruments used for these measurements have all been elaborate in design and construction; the most successful and have been those of the Netherlands

Ship Model Basin, the Hamburg Ship Model Basin, and DTMB. Fortunately, the electronics industry is continuously producing better measuring equipment, and it should soon be possible to simplify existing designs materially. In case of a propeller, the ideal solution would be to locate the dynamometer in the hub, and we feel that such a dynamometer can be built. The availability of such a device would allow the immediate start of a study of the fundamental aspects of non-steady propeller phenomena in conjunction with the study of non-steady flow conditions.

In view of the above considerations, we recommend that the Maritime Administration sponsor, at The University of Michigan, the design and construction of a hub-enclosed propeller dynamometer. The instrument should be capable of measuring all forces acting on the propeller, and their time-dependent variations.

5. Hot Film Anemometer: R. L. Townsin(13) has recently developed a hot film anemometer by which he has been able to determine regions of laminar flow without introducting any disturbance to the flow itself. This anemometer may prove capable of determining areas of flow separation around the run of a model. It should therefore be studied more closely and, if proven successful, be included as a research instrument.

6. Television Camera: We have made successful use of a borrowed television camera as a means of studying flow around a model. We are convinced that such an item of equipment would be of great benefit, particularly in analyzing the flow of water to propellers. We would therefore recommend that the Maritime Administration support the purchase of a suitable television camera, together with the necessary strut and control devices. The Netherland Model Basin and the DTMB have already developed such systems.

# APPENDIX II

## THE DETERMINATION OF THE WAVE-RESISTANCE OF A MODEL FROM THE WAVE PATTERN (Eggers' Method)

### A. The Wave Resistance for Steady Motion Derived from the Flow of Energy in the Wave Motion

The ship is assumed to move at constant velocity c in a channel of constant width b and constant depth h. Considering the fluid occupied by the region between two fixed planes A and B it can be said that the rate at which work is being done on the fluid is equal to energy transport out of the region plus the time rate of change of energy within the region. It will be assumed that plane A is located so far ahead of the ship that the velocity there is equal to zero (no waves). Only flow conditions at plane B need therefore be considered.

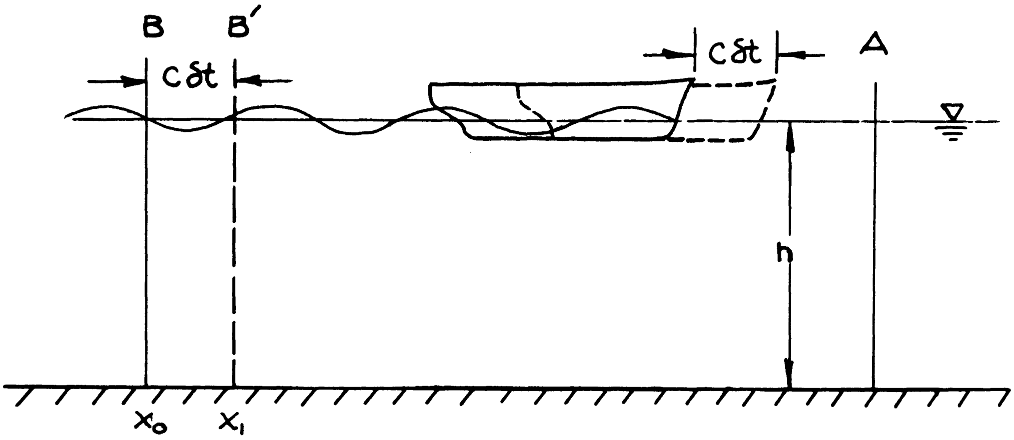

Figure II-1. Definition of Control Planes and Coordinates.

Owing to the constant speed of the ship, it is clear that the energy between the planes B and A (see Figure II-1) at the time $t_o + \delta t$ is the same as the energy between the planes B and A at time $t_o$. It follows that the energy in the fluid between B and B' represents the increase in energy of the fluid in the region R over a small time interval $\delta t$. The kinetic energy of the region between the planes B and B' is given by

$$\delta T = -\frac{\rho}{2} \int \phi \frac{\partial\phi}{\partial n} ds = \frac{\rho}{2} \int (\nabla\phi)^2 dv \tag{1}$$

where $\partial\phi/\partial n$ is differentiation with respect to the inward normal. Limiting our attention to the first integral, Equation (1) can be written as

$$\delta T = \frac{\rho}{2} \left\{c\delta t \int_{-\frac{b}{2}}^{\frac{b}{2}} (\phi\phi_z)_{z=o}\, dy - \int_{-\frac{b}{2}}^{\frac{b}{2}} dy \int_{-h}^{o} [(\phi\phi_x)_{x=x_o} - (\phi\phi_x)_{x=x_1}]\, dz\right\} \tag{2}$$

The contributions from the bottom and the side walls are clearly equal to zero. Expanding $(\phi\phi_x)$ in a Taylor series it follows that

$$(\phi\phi_x)_{x=x_1} \simeq (\phi\phi_x)_{x=x_o} + c\delta t(\phi\phi_x)_x$$

and Equation (2) becomes

$$\delta T = \frac{\rho c}{2} \delta t \left\{ \int_{-\frac{b}{2}}^{\frac{b}{2}} (\phi\phi_z)_{z=o} + \int_{-\frac{b}{2}}^{\frac{b}{2}} dy \int_{-h}^{o} [(\phi_x)^2 + \phi\phi_{xx}]_{x=x_o}\, dz\right\} \tag{3}$$

The free surface condition is given by

$$\phi_z = -\frac{1}{K_o} \phi_{xx} \qquad \text{where} \qquad K_o = \frac{g}{c^2}$$

Equation (3) can therefore be written as

$$\delta T = \frac{\rho c}{2}\,\delta t\left\{\int_{-\frac{b}{2}}^{\frac{b}{2}} dy \int_{-h}^{0} [(\phi_x)^2 + \phi\phi_{xx}]_{x=x_0}\, dz - \frac{1}{K_0}\int_{-\frac{b}{2}}^{\frac{b}{2}} (\phi\phi_{xx})_{z=0}\, dy\right\} \tag{3a}$$

The potential energy of the fluid between the planes B and B', measured with respect to the undisturbed fluid, is given by

$$\delta V = \rho g c\delta t \int_{0}^{\xi} z dz \int_{-\frac{b}{2}}^{\frac{b}{2}} dy = \frac{\rho g c}{2}\,\delta t \int_{-\frac{b}{2}}^{\frac{b}{2}} \xi^2 dy \tag{4}$$

To the usual linear approximation, the free surface is obtained from

$$\xi = -\frac{c}{g}\,\phi_x$$

Substituting into Equation (4) it follows that

$$\delta V = \frac{\rho c}{2K_0}\,\delta t \int_{-\frac{b}{2}}^{\frac{b}{2}} (\phi_x)^2_{z=0}\, dy \tag{5}$$

From Bernoulli's equation the pressure is given by

$$p = -\frac{1}{2}\rho q^2 - \rho g z - c\rho\phi_x$$

The work done on the plane B during the time interval $\delta t$ is therefore

$$\delta W_p \int_{-\frac{b}{2}}^{\frac{b}{2}} dy \int_{-h}^{0} \rho u\delta t dz$$

$$- \int_{-\frac{b}{2}}^{\frac{b}{2}} dy \int_{-h}^{0} \frac{1}{2}\rho q^2 u\delta t dz - \int_{-\frac{b}{2}}^{\frac{b}{2}} dy \int_{-h}^{0} \rho g z u\delta t dz \tag{6}$$

$$+ c\rho\delta t \int_{-\frac{b}{2}}^{\frac{b}{2}} dy \int_{-h}^{0} (\phi_x)^2 dz$$

The energy density per unit volume is defined by

$$e = \frac{1}{2}\rho q^2 + \rho g z$$

Thus the energy flux into the region R can be expressed as

$$\delta E = \delta t \int_{-\frac{b}{2}}^{\frac{b}{2}} dy \int_{-h}^{0} \frac{1}{2}\rho q^2 u\,dz + \delta t \int_{-\frac{b}{2}}^{\frac{b}{2}} dy \int_{-h}^{0} \rho g z u\,dz \qquad (7)$$

The work done by the ship is, by definition,

$$\delta W_S = R_t c \delta t \qquad (8)$$

and the total energy balance becomes

$$\delta W_P + \delta W_S + \delta E = \delta T + \delta V$$

Substituting Equations (3a), (5), (6), (7) and (8) one obtains an expression for the resistance as follows

$$R_t = \frac{\rho}{2K_0} \int_{-\frac{b}{2}}^{\frac{b}{2}} [(\phi_x)^2 - \phi\phi_{xx}]_{z=0}\, dy - \frac{\rho}{2} \int_{-\frac{b}{2}}^{\frac{b}{2}} dy \int_{-h}^{0} [(\phi_x)^2 - \phi\phi_{xx}]_{x=x_0} dz \qquad (9)$$

Returning to Equation (1), the use of the right hand volume integral will lead to a slightly different expression for the model resistance.

Letting

$$dv = c\delta t\,dy\,dz$$

$$\delta T = \frac{c\rho}{2}\delta t \int_{-\frac{b}{2}}^{\frac{b}{2}} dy \int_{-h}^{0} (\nabla\phi)^2 dz$$

and

$$\delta T - \delta W_P - \delta E = \frac{c\rho}{2} \delta t \int_{-\frac{b}{2}}^{\frac{b}{2}} dy \int_{-h}^{o} [\phi_y^2 + \phi_z^2 - \phi_x^2] \, dz$$

Substituting into (8)

$$R_t = \frac{\rho g}{2} \int_{-\frac{b}{2}}^{\frac{b}{2}} \xi^2 dy + \frac{\rho}{2} \int_{-\frac{b}{2}}^{\frac{b}{2}} dy \int_{-h}^{o} [\phi_y^2 + \phi_z^2 - \phi_x^2 ] \, dz \qquad (10a)$$

or

$$R_t = \frac{\rho}{2K_o} \int_{-\frac{b}{2}}^{\frac{b}{2}} (\phi_x)^2_{z=o} + \frac{\rho}{2} \int_{-\frac{b}{2}}^{\frac{b}{2}} dy \int_{-h}^{o} [\phi_y^2 + \phi_z^2 - \phi_x^2] \, dz \qquad (10b)$$

Assume the velocity potential far aft of the model to be given by

$$\phi(x,y,z) = \frac{g}{c} \sum_{n=1}^{\infty} \frac{1}{\omega_n} \{\alpha_n \cos\omega_n x + \beta_n \sin\omega_n x \} \frac{\cosh \overline{K}_n(h+z)}{\cosh \overline{K}_n h} \cos \frac{n\pi}{b}(\frac{b}{2} - y) \qquad (11)$$

$$+ \frac{g}{2\omega_o c} \{\alpha_o \cos\omega_o x - \beta_o \sin\omega_o x\} \frac{\cosh \omega_o(h+z)}{\cosh \omega_o h}$$

where

$$\overline{K}_n^2 - \omega_n^2 - (\frac{n\pi}{b})^2 = 0 \qquad (12)$$

It is noted that the boundary conditions at $y = \pm \frac{b}{2}$ and $z = -h$ are satisfied by this potential. At the free surface

$$\phi_{xx} + K_o\phi_z = 0 \; ; \qquad z = o$$

which gives

$$\omega_n^2 - K_o\overline{K}_n \tanh(\overline{K}_n h) = 0$$

but

$$\omega_n^2 = \overline{K}_n^2 - (\tfrac{n\pi}{b})^2 \quad \text{or} \quad \omega_n = \sqrt{\overline{K}_n^2 - (\tfrac{n\pi}{b})^2} \geq 0$$

$$n = 0,1,2,\ldots$$

so that

$$\overline{K}_n^2 - (\tfrac{n\pi}{b})^2 - K_o\overline{K}_n \tanh(\overline{K}_n h) = 0 \tag{13}$$

In case Equation (13) has no real root for a given $n$ it will be required that $\alpha_n = \beta_n = 0$ . The velocity components are given as follows

$$-u = \phi_x = \frac{g}{c} \sum_{n=1}^{\infty} \{-\alpha_n \sin \omega_n x + \beta_n \cos \omega_n x\}$$

$$\frac{\cosh \overline{K}_n(h+z)}{\cosh \overline{K}_n h} \cos \frac{n\pi}{b}(\frac{b}{2} - y)$$

$$+ \frac{g}{2c} \{-\alpha_o \sin \omega_o x + \beta_o \cos \omega_o x\} \frac{\cosh \omega_o(h+z)}{\cosh \omega_o h}$$

$$-v = \phi_y = \frac{g}{c} \sum_{n=1}^{\infty} \{\alpha_n \cos \omega_n x + \beta_n \sin \omega_n x\} \frac{n\pi}{b\omega_n}$$

$$\frac{\cosh \overline{K}_n(h+z)}{\cosh \overline{K}_n h} \sin \frac{n\pi}{b}(\frac{b}{2} - y)$$

Introducing the following functions

$$A_n(x) = A_{-n}(x) = \frac{1}{2}(\alpha_n \cos \omega_n x + \beta_n \sin \omega_n x)$$

$$B_n(x) = B_{-n}(x) = \frac{1}{2}(\beta_n \cos \omega_n x - \alpha_n \sin \omega_n x) \tag{14}$$

the derivatives of the velocity potential can be written

$$\phi_x = \frac{g}{c} \sum_{n=-\infty}^{\infty} B_n(x) \frac{\cosh \overline{K}_n(z+h)}{\cosh \overline{K}_n h} \cos \frac{n\pi}{b}(\frac{b}{2} - y)$$

$$\phi_y = \frac{g}{c} \sum_{n=-\infty}^{\infty} A_n(x) \frac{n\pi}{b\omega_n} \frac{\cosh \bar{K}_n(z+h)}{\cosh \bar{K}_n h} \sin \frac{n\pi}{b}(\frac{b}{2} - y) \tag{15}$$

$$\phi_z = \frac{g}{c} \sum_{n=-\infty}^{\infty} A_n(x) \frac{\bar{K}_n}{\omega_n} \frac{\sinh \bar{K}_n(z+h)}{\sinh \bar{K}_n h} \cos \frac{n\pi}{b}(\frac{b}{2} - y)$$

The free surface, given by

$$\xi = \frac{c}{g} \phi_x \Big|_{z=o}$$

can now be written

$$\xi = \sum_{n=-\infty}^{\infty} B_n(x) \cos \frac{n\pi}{b}(\frac{b}{2} - y) \tag{16}$$

and also

$$\xi_x = \sum_{n=-\infty}^{\infty} A_n(x)\, \omega_n \sin \frac{n\pi}{b}(\frac{b}{2} - y) \tag{17}$$

Due to orthogonality,

$$\int_{-\frac{b}{2}}^{\frac{b}{2}} \cos \frac{n\pi}{b}(\frac{b}{2} - y) \cos \frac{m\pi}{b}(\frac{b}{2} - y)\, dy = 0; \quad m \neq n$$

$$= \frac{b}{2}; \quad m = n$$

and similarly for the sine functions. Substitution of (15) and (16) into (10a) therefore gives

$$R = \frac{\rho g b}{2} \sum_{n=-\infty}^{\infty} B_n^2(x) + \frac{g^2 \rho b}{2c^2} \sum_{n=-\infty}^{\infty} \Big\{ A_n^2(x) \Big[ \int_{-h}^{o} \left(\frac{n\pi}{b\omega_n}\right)^2 \frac{\cosh^2 \bar{K}_n(z+h)}{\cosh^2 \bar{K}_n h}\, dz$$

$$+ \int_{-h}^{o} \frac{\sinh^2 \bar{K}_n(h+z)}{\cosh^2 \bar{K}_n h} \frac{\bar{K}_n^2}{\omega_n^2}\, dz \Big]$$

$$- B_n^2(x) \int_{-h}^{o} \frac{\cosh^2 \bar{K}_n(z+h)}{\cosh^2 \bar{K}_n h}\, dz \Big\} \tag{18}$$

The last two integrals can be evaluated, thus

$$\int_{-h}^{0} \cosh^2 \bar{K}_n(z+h)dz = \frac{\sinh 2\bar{K}_n h + 2\bar{K}_n h}{4\bar{K}_n}$$

$$\int_{-h}^{0} \sinh^2 \bar{K}_n(z+h)dz = \frac{\sinh 2\bar{K}_n - 2\bar{K}_n h}{4\bar{K}_n}$$

Furthermore

$$\tanh (\bar{K}_n h) = \frac{\omega_n^2 c^2}{g\,\bar{K}_n}$$

and since

$$\cosh^2 x = \frac{1}{2} \sinh 2\,x \;\mathrm{ctgh}\; x$$

it follows that

$$\cosh^2(\bar{K}_n h) = \sinh (2\bar{K}_n h) \frac{g\,\bar{K}_n}{2\omega_n^2 c^2}$$

Equation (18) can therefore be written

$$R = \frac{\rho g b}{4} \sum_{n=-\infty}^{\infty} [B_n^2(x)(2 - \frac{(\sinh 2\bar{K}_n h + 2\bar{K}_n h)\omega_n^2}{(\sinh 2\bar{K}_n h)\; \bar{K}_n^2}]$$

$$+ A_n^2(x)(\frac{\sinh(2\bar{K}_n h) + 2\bar{K}_n h}{\sinh 2\bar{K}_n h} (\frac{n\pi}{b\bar{K}_n})^2 + \frac{\sinh(2\bar{K}_n h) - 2\bar{K}_n h}{\sinh 2\bar{K}_n h} \qquad (19)$$

or, with

$$\omega_n = \sqrt{\bar{K}_n^2 - (\frac{n\pi}{b})^2}$$

$$R = \frac{\rho g b}{4} \sum_{n=-\infty}^{\infty} \{A_n^2(x) + B_n^2(x)\}\{2 - \frac{\sinh(2\bar{K}_n h) + 2\bar{K}_n h}{\sinh \bar{K}_n h} (\frac{\omega_n}{\bar{K}_n})^2\} \qquad (20)$$

From Equation (16) and (17)

$$\int_{-\frac{b}{2}}^{\frac{b}{2}} \xi(x,y) \cos \frac{n\pi}{b}(\frac{b}{2} - y)\; dy = b\; B_n(x)$$

$$\int_{-\frac{b}{2}}^{\frac{b}{2}} \xi_x(x,y) \sin \frac{n\pi}{b}(\frac{b}{2} - y)\, dy = b\, A_n(x)\omega_n$$

It follows therefore that

$$R = \frac{\rho g}{4b} \sum_{n=-\infty}^{\infty} [\{ \int_{-\frac{b}{2}}^{\frac{b}{2}} \xi(x,y) \cos \frac{n\pi}{b}(\frac{b}{2} - y)\, dy\}^2$$

$$+ \frac{1}{\omega_n^2} \{ \int_{-\frac{b}{2}}^{\frac{b}{2}} \xi_x(x,y) \sin \frac{n\pi}{b}(\frac{b}{2} - y)\, dy\}^2] \tag{21}$$

$$[2 - \frac{\sinh(2\bar{K}_n h) + 2\bar{K}_n h}{\sinh 2\bar{K}_n h} (\frac{\omega_n}{\bar{\bar{K}}_n})^2]$$

Defining the quantities $A_n^*$ and $\epsilon_n^*$ by the relationships

$$A_n(x) = A_n^* \sin(\omega_n x + \epsilon_n^*) \tag{22}$$

$$B_n(x) = A_n^* \cos(\omega_n x + \epsilon_n^*) \tag{23}$$

where

$$A_n^* = \frac{1}{4}\sqrt{\alpha_n^2 + \beta_n^2}$$

$$\mathrm{tg}\, \epsilon_n^* = \frac{\alpha_n}{\beta_n}$$

a substitution of Equation (23) into (16) leads to

$$\xi(x,y) = \sum_{n=-\infty}^{\infty} A_n^* \cos(\omega_n x + \epsilon_n^*) \cos \frac{n\pi}{b}(\frac{b}{2} - y)$$

$$= \sum_{n=-\infty}^{\infty} A_n^* \cos(\omega_n x + \epsilon_n^* + \frac{n\pi}{2} - \frac{n\pi}{b} y)$$

$$- \sum_{n=-\infty}^{\infty} A_n^* \sin(\omega_n x + \epsilon_n^*) \sin \frac{n\pi}{b}(\frac{b}{2} - y)$$

The last summation is equal to zero. Hence

$$\xi(x,y) = \sum_{n=-\infty}^{\infty} A_n^* \cos(\omega_n x + \epsilon_n^* + \frac{n\pi}{2} - \frac{n\pi}{b} y) \tag{24}$$

From (12)

$$\omega_n^2 + (\frac{n\pi}{b})^2 = \overline{K}_n^2$$

It is therefore advantageous to introduce the variable $\Theta_n$ such that

$$\frac{n\pi}{b} = \overline{K}_n \sin \Theta_n; \quad \omega_n = \overline{K}_n \cos \Theta_n \tag{25}$$

Equation (24) now becomes

$$\xi(x,y) = \sum_{n=-\infty}^{\infty} A_n^* \cos(\overline{K}_n x \cos \Theta_n - \overline{K}_n y \sin \Theta_n + \epsilon_n^* + \frac{b}{2} \overline{K}_n \sin \Theta_n) \tag{26}$$

If the angle $\Theta_n$ is the angle between a line and the positive x-axis, Equation (26) represents a separation of the free surface into waves of length equal to $2\pi/\overline{K}_n$. The group velocity of such a wave is

$$U_n = \frac{1}{2} \frac{\sinh(2\overline{K}_n h) + 2\overline{K}_n h}{\sinh(2\overline{K}_n h)} v_{ph}^n \tag{27}$$

where

$$v_{ph}^n = \sqrt{\frac{g}{\overline{K}_n} \tanh(\overline{K}_n h)} \tag{28}$$

Because the waves are being generated by a model moving at a constant speed $c$ along the x-axis, the crest of a wave propagating in the direction $\Theta_n$ has a velocity $c$ along the x-axis. This condition is given by

$$v_{ph}^n = c \cos \Theta_n \tag{30}$$

The flux of energy in the x-direction is similarly given by

$$C_E^n = U \cos \Theta_n = \frac{1}{2} c \cos^2 \Theta_n \frac{\sinh(2\overline{K}_n h) + 2\overline{K}_n h}{\sinh(2\overline{K}_n h)} \qquad (31)$$

It is noted from (22) and (23) that

$$\{A_n^2(x) + B_n^2(x)\} = (A_n^*)^2$$

From (20) it then follows that the wave resistance can be written

$$R = \frac{\rho g b}{2} \sum_{n=-\infty}^{\infty} A_n^{*2} \left(1 - \frac{C_E^n}{C}\right) \qquad (32)$$

B. Experimental Determination of the Wave-Resistance from Wave Profiles

If $\xi(x,y)$ and $\xi_x(x,y)$ were known along some line perpendicular to the direction of motion, it should be possible to determine the wave resistance from Equation (21). To avoid the difficulty of the determination of the wave slope, however, it will be necessary to make use of two parallel sections a distance $2\Delta$ apart. The free surface $\xi(x,y)$ is by (14) and (16)

$$\xi(x,y) = \frac{1}{2} \sum_{n=-\infty}^{\infty} (\beta_n \cos \omega_n x - \alpha_n \sin \omega_n x) \cos \frac{n\pi}{b}\left(\frac{b}{2} - y\right) \qquad (33)$$

Defining the free surface along the sections as

$x = x_s + \Delta$ and $x = x_s - \Delta$ by $\xi^+(y)$ and $\xi^-(y)$

respectively then

$$\xi^+(y) = \frac{1}{2} \sum_{n=-\infty}^{\infty} \{\beta_n \cos \omega_n(x_s + \Delta) - \alpha_n \sin \omega_n(x_s + \Delta)\} \cos \frac{n\pi}{b}\left(\frac{b}{2} - y\right)$$

(34)

and

$$\xi^{-}(y) = \frac{1}{2} \sum_{n=-\infty}^{\infty} \left\{ \beta_n \cos \omega_n (x_s - \Delta) - \alpha_n \sin \omega_n (x_s - \Delta) \right\} \cos \frac{n\pi}{b}\left(\frac{b}{2} - y\right) \tag{35}$$

Hence

$$\xi^{+}(y) + \xi^{-}(y) = \sum_{n=-\infty}^{\infty} \left\{ \beta_n \cos \omega_n x_s \cdot \cos \omega_n \Delta - \alpha_n \sin \omega_n x_s \cdot \cos \omega_n \Delta \right\} \times \cos \frac{n\pi}{b}\left(\frac{b}{2} - y\right) \tag{36}$$

$$\xi^{+}(y) - \xi^{-}(y) = \sum_{n=-\infty}^{\infty} \left\{ -\beta_n \sin \omega_n x_s \sin \omega_n \Delta - \alpha_n \cos \omega_n x_s \sin \omega_n \Delta \right\} \times \cos \frac{n\pi}{b}\left(\frac{b}{2} - y\right) \tag{37}$$

It is noted, however, that

$$\xi^{+}(y) + \xi^{-}(y) = 2 \sum_{n=-\infty}^{\infty} \cos \omega_n \Delta \, B_n(x_s) \cos \frac{n\pi}{b}\left(\frac{b}{2} - y\right) \tag{38}$$

and

$$\xi^{+}(y) - \xi^{-}(y) = -2 \sum_{n=-\infty}^{\infty} \sin \omega_n \Delta \, A_n(x_s) \cos \frac{n\pi}{b}\left(\frac{b}{2} - y\right) \tag{39}$$

from which it follows that

$$B_n(x_s) = \frac{1}{2b \cos \omega_n \Delta} \int_{-\frac{b}{2}}^{\frac{b}{2}} (\xi^{+}(y) + \xi^{-}(y)) \cos \frac{n\pi}{b}\left(\frac{b}{2} - y\right) dy$$

$$A_n(x_s) = \frac{1}{2b \sin \omega_n \Delta} \int_{-\frac{b}{2}}^{\frac{b}{2}} (\xi^{+}(y) - \xi^{-}(y)) \cos \frac{n\pi}{b}\left(\frac{b}{2} - y\right) dy$$

By definition

$$A_n^{*} = A_n^2(x_s) + B_n^2(x_s) = \frac{1}{4}(\beta_n^2 + \alpha_n^2)$$

Hence

$$\alpha_n^2 + \beta_n^2 = \frac{1}{b^2 \cos^2 \omega_n\Delta} \left( \int_{-\frac{b}{2}}^{\frac{b}{2}} (\xi^+ + \xi^-) \cos \frac{n\pi}{b}\left(\frac{b}{2} - y\right) dy\right)^2$$

$$+ \frac{1}{b^2 \sin^2 \omega_n\Delta} \left( \int_{-\frac{b}{2}}^{\frac{b}{2}} (\xi^+ - \xi^-) \cos \frac{n\pi}{b}\left(\frac{b}{2} - y\right) dy\right)^2 \tag{40}$$

provided

$$\sin \omega_n\Delta \cdot \cos \omega_n\Delta \neq 0$$

Introducing the identity

$$\cos \frac{n\pi}{b}\left(\frac{b}{2} - g\right) = \cos \frac{n\pi}{2} \cos \frac{n\pi}{b} y + \sin \frac{n\pi}{b} \sin \frac{n\pi}{b} y$$

one can finally write

$$R = \frac{\rho g}{4b} \sum_{n=-\infty}^{\infty} \Big[\frac{1}{\cos^2\omega_n \Delta} \left\{\tau_n I_{c+}^{n^2} + (1 - \tau_n) I_{s+}^{n^2}\right\}$$

$$+ \frac{1}{\sin^2 \omega_n\Delta} \left\{\tau_n I_{c-}^{n^2} + (1 - \tau_n) I_{s-}^{n^2}\right\}\Big]$$

$$\left\{2 - \frac{\sinh 2\bar{K}_n h + 2\bar{K}_n h}{\sinh 2\bar{K}_n h} \frac{\omega_n^2}{\bar{K}_n^2}\right\} \tag{41}$$

where

$$I_{c\pm}^n = \int_{-\frac{b}{2}}^{\frac{b}{2}} (\xi^+ \pm \xi^-) \cos \frac{n\pi}{b} y \, dy \tag{42}$$

$$I_{s\pm}^n = \int_{-\frac{b}{2}}^{\frac{b}{2}} (\xi^+ \pm \xi^-) \sin \frac{n\pi}{b} y \, dy \tag{43}$$

$$\tau_n = 1 \quad n \text{ even}$$
$$= 0 \quad n \text{ odd}$$

It is noted that values of $I^n_{c\pm}$ and $I^n_{s\pm}$ are obtained from a harmonic analysis of $(\xi^+ \pm \xi^-)$. Substitution of these values into Equation (41) together with the appropriate values of $\omega_n$ and $K_n$, as given by Equations (12) and (13) (in addition to $\Delta$ and h) provides a numerical expression for the resistance of the model. Because the fluid is assumed to be inviscid this resistance is taken to be the wave resistance.

# APPENDIX III

## WAVE RESISTANCE OF SHIPS

By L. Landweber

Ship wave resistance theory has hardly advanced beyond the Michel integral for the wave-making resistance of thin ships. This formula successfully depicts the nature of the variation of wave-making resistance with Froude number and, because the hull function appears explicitly in the integrand, has been useful in showing the effects of variations in hull form. Because of the restrictive assumptions on which it is based, however, it cannot yield resistance values of the accuracy usually required for ship resistance calculations.

Inui has attempted to improve upon the Michel theory by satisfying the boundary condition on the hull surface more accurately. Actually the boundary condition is satisfied more accurately only at very low Froude numbers, and one cannot be certain that there would be any improvement in predictions by this method at moderate and high Froude numbers.

An interesting and important alternative to the thin-ship theory is the recently published slender-ship theory of Vossers. This is also a linearized theory, however, and cannot be expected to yield a close approximation to the solution of the exact potential-flow problem.

A well-known method for determining the potential flow about a body, when no other boundaries (nor a free surface) are present, leads to an integral equation for an unknown source distribution on the surface of the body. This same procedure has been applied by Havelock to formulate the ship wave-resistance problem so as to satisfy the hull surface condition exactly, although the free surface condition remained linearized. The resulting integral equation has been considered to be too complicated for numerical evaluation.

The purpose of the present work is to suggest practical means of obtaining more nearly exact solutions of the ship wave resistance problem by satisfying both the nonlinear free surface condition and the hull surface condition to a higher degree of accuracy.

## A. Formulation of Boundary Value Problem

It will be supposed that the ship is at rest in a channel through which a stream of constant velocity U in the negative x-direction is flowing. Take the y-axis positive to port and the z-axis positive upwards, with the origin at the undisturbed level of the free surface at the center section of the ship. Denote the equation of the hull surface by

$$y = \pm f(x,z) \qquad -\frac{L}{2} \leqq x \leqq \frac{L}{2} \qquad -H \leqq z < 0 \tag{1}$$

where L is the length of the ship and H its draft. It will be assumed that the fluid is inviscid and incompressible and that the flow is irrotational.

Under the assumed conditions, there exists a velocity potential $\Phi$ and a perturbation potential $\phi$ related by

$$\Phi = \phi - Ux \tag{2}$$

which satisfy the Laplace equations

$$\nabla^2\Phi = \nabla^2\phi = 0 \tag{3}$$

and express the velocity at a point of the fluid in the form

$$\frac{\partial \Phi}{\partial x} = u - U; \quad u = \frac{\partial \phi}{\partial x}, \quad v = \frac{\partial \phi}{\partial y}; \quad w = \frac{\partial \phi}{\partial z} \tag{4}$$

where $u, v, w$ are the components of the perturbation velocity.

The boundary condition that there is no flow across the hull surface yields the boundary condition

$$uf_x - v + wf_z = Uf_x \tag{5}$$

where

$$f_x = \frac{\partial f}{\partial x}, \quad f_z = \frac{\partial f}{\partial z}$$

Denoting the equation of the free surface by

$$z = Z(x,y) \tag{6}$$

we obtain for the boundary condition at this surface

$$(U-u)Z_x - vZ_y + w = 0 \tag{7}$$

The Bernoulli equation in the present case is

$$p + \frac{1}{2} \rho[(U-u)^2 + v^2 + w^2] + \rho gz = \frac{1}{2} \rho U^2 \tag{8}$$

and the condition $p = 0$ at the free surface yields

$$gZ = uU - \frac{1}{2} q^2, \quad q^2 = u^2 + v^2 + w^2 \tag{9}$$

Eliminating $Z$ between (7) and (9), we obtain

$$U^2 \frac{\partial^2 \phi}{\partial x^2} + g \frac{\partial \phi}{\partial z} = U \frac{\partial}{\partial x} (u^2 + v^2 + \frac{1}{2} w^2) - \frac{1}{2}[u \frac{\partial (q^2)}{\partial x} + v \frac{\partial (q^2)}{\partial y}] \tag{10}$$

Thus it is required to find a solution of Laplace's equation which satisfies the linear Equation (5) on the surface of the hull and the nonlinear Equation (10) on the free surface (6).

The free surface condition (10) is inconvenient because it is to be applied on a surface of unknown location, and because it is nonlinear, so that superposition techniques are not applicable. The condition may be transferred to the plane $z = 0$ by means of Taylor expansions, such as

$$\frac{\partial^2\phi}{\partial x^2}(x,y,Z) = \frac{\partial^2\phi}{\partial x^2}(x,y,0) + Z\,\frac{\partial^3\phi}{\partial x^2\partial z}(x,y,0) + \frac{Z^2}{2!}\,\frac{\partial^4\phi}{\partial x^2\partial z^2}(x,y,0) + \dots$$

$$\frac{\partial\phi}{\partial z}(x,y,Z) = \frac{\partial\phi}{\partial z}(x,y,0) + Z\,\frac{\partial^2\phi}{\partial z^2}(x,y,0) + \frac{Z^2}{2!}\,\frac{\partial^3\phi}{\partial z^3}(x,y,0) + \dots$$

which, substituting into (10) and applying (9), give, to terms of second order,

$$U^2\,\frac{\partial^2\phi}{\partial x^2} + g\,\frac{\partial\phi}{\partial z} = U\Big[\frac{\partial}{\partial x}\big(u^2 + v^2 + \frac{1}{2}\,w^2\big) - u_o\Big(\frac{U^2}{g}\,\frac{\partial^3\phi}{\partial x^2\partial z} \quad \frac{\partial^2\phi}{\partial z^2}\Big)\Big] \tag{11}$$

applied on the plane $z = 0$. Let $\phi_o$ denote a solution which satisfies (11) with the right member zero - i.e.,

$$U^2\,\frac{\partial^2\phi_o}{\partial x^2} + g\,\frac{\partial\phi_o}{\partial z} = 0 \tag{12}$$

Then, setting $u_o = \frac{\partial\phi_o}{\partial x}$, etc., one obtains, to terms of second order,

$$U^2\,\frac{\partial^2\phi}{\partial x^2} + g\,\frac{\partial\phi}{\partial z} = U\Big[\frac{\partial}{\partial x}\big(u^2 + v^2 + \frac{1}{2}\,w^2\big)\Big] \tag{13}$$

a linear equation, applied on the plane $z = 0$. This procedure can clearly be continued to obtain linear approximations of higher order of Equation (10).

Consider a source of unit strength at the point $(\xi, \eta, \zeta)$ within the channel through which the stream of velocity U is flowing in the negative x-direction. It will be assumed that one can obtain the disturbance velocity potential corresponding to this source which satisfies the condition of impermeability at the solid channel boundaries, a linear free surface condition such as (13) or its extension to higher order, and a radiation condition that surface waves are propagated only downstream. This velocity potential, $G(x,y,z;\xi,\eta,\zeta)$, may be expressed in the form

$$G(x,y,z;\xi,\eta,\zeta) = -\frac{1}{r} + F(x,y,z;\xi,\eta,\zeta) \qquad (14)$$

where

$$r = [(x-\xi)^2 + (y-\eta)^2 + (z-\zeta)^2]^{1/2}$$

and $F(x,y,z;\xi,\eta,\zeta)$ is a regular, harmonic function within the channel which may be considered as the potential of the image system of the source at $(\xi,\eta,\zeta)$ in the solid boundaries of the channel and the free surface.

## B. Source Distribution on Hull Surface

Assume that the boundary value problem for a ship form can be satisfied by a distribution of sources of strength $m(\xi,\eta,\zeta)$ on the hull surface. The potential at a point $(x,y,z)$ of the surface due to a source element $m(\xi,\eta,\zeta)dS$ is

$$m(\xi,\eta,\zeta)G(x,y,z;\xi,\eta,\zeta)dS$$

which contributes to the normal derivative at $(x,y,z)$

$$m(\xi,\eta,\zeta)\,\frac{\partial G}{\partial \eta}(z,y,z;\xi,\eta,\zeta)dS$$

By application of Gauss's flux theorem, it may be shown that the source element $m(x,y,z)dS$, in the neighborhood of the point at which the component of the velocity normal to the surface is being evaluated, contributes $2\pi m(x,y,z)$ to the normal derivative. Thus the hull boundary condition becomes

$$2\pi m(x,y,z) + \int_S m(\xi,\eta,\zeta)\frac{\partial G}{\partial n}(x,y,z;\xi,\eta,\zeta)dS = U\frac{\partial x}{\partial n} \qquad (15)$$

a Fredholm integral equation of the second kind for $m(\xi,\eta,\zeta)$. Since the direction cosines of the normal directed outward from the hull surface are

$$-\frac{f_x}{\sqrt{1+f_x^2+f_z^2}},\ \frac{1}{\sqrt{1+f_x^2+f_z^2}},\ -\frac{f_z}{\sqrt{1+f_x^2+f_z^2}}$$

we have

$$\frac{\partial G}{\partial n} = -\frac{f_xG_x - G_y + f_zG_z}{\sqrt{1+f_x^2+f_z^2}}$$

or, by (14),

$$\frac{\partial G}{\partial n} = -\frac{f_xF_x - F_y - f_zF_z}{\sqrt{1+f_x^2+f_z^2}} - \frac{(x-\xi)f_x - (y-\eta) + (\xi-\zeta)f_z}{r^3\sqrt{1+f_x^2+f_z^2}} \qquad (16)$$

The factor $r^{-3}$ in the last term of (16) indicates that the integral in (15) is improper, although, as is shown in texts on potential theory, the integral converges.

In terms of $m(\xi,\eta,\zeta)$, the velocity potential is

$$\phi(x,y,z) = \int_S m(\xi,\eta,\zeta)G(x,y,z;\xi,\eta,\zeta)dS \qquad (17)$$

and the wave-making resistance, given by the Lagally theorem, is

$$R = -4\pi\rho \iint_{S\,S} m(\xi,\eta,\zeta)m(x,y,z)F_x(x,y,z;\xi,\eta,\zeta)dSdS \qquad (18)$$

The theory of Fredholm integral equations of the second kind gives assurance that (15) can be solved for $m(\xi,\eta,\zeta)$. Practically, however, because of the complexity of the function $F(x,y,z;\xi,\eta,\zeta)$, the presence of singularities, and the necessity of integrating over a curved surface, a numerical procedure for solving (15) has not yet been developed. A long computing program, which overcomes the two latter difficulties in connection with the potential flow about bodies in an unbounded fluid, has recently been developed. It is suggested that research be continued to shorten the computing program for this case, which would yield means for calculating the last term in (16) and to develop an efficient means of computing the gradient of $F(x,y,z;\xi,\eta,\zeta)$.

## C. Source Sink Distribution on Hull Centerplane

Assume a source distribution $m(\xi,\zeta)$ on the centerplane within the hull. The hull boundary condition is now

$$\int_{S_o} m(\xi,\zeta) \frac{\partial}{\partial n} G(x,y,z;\xi,o,\zeta)dS_o = U \frac{\partial x}{\partial n} \qquad (19)$$

in which the normal derivative is taken at a point $(x,y,z)$ of the hull surface and the integral extends over the centerplane within the hull. This is a Fredholm integral equation of the first kind with the same kernel (16) as the integral equation (15), but with $\eta = 0$.

An iteration formula for solving (19) is

$$m_{n+1}(x,z) = m_n(x,z) + \frac{1}{I} [U \frac{\partial x}{\partial n} - \int_{S_o} m_n(\xi,\zeta) \frac{\partial G}{\partial n} dS_o] \qquad (20)$$

where

$$I = \int_{S_o} \frac{\partial G}{\partial n}\, dS_o = \int_{S_o} \left[\frac{\partial F}{\partial n} - \frac{\partial}{\partial n}\left(\frac{1}{r}\right)\right] dS_o \tag{21}$$

$$r = [(x-\xi)^2 + y^2 + (z-\zeta)^2]^{1/2}$$

In the numerical evaluation of (20), the integrals in (20) and (21) are replaced by a quadrature formula and one then has a set of linear algebraic equations to solve by iteration. Since the part of the kernel $\frac{\partial}{\partial n}(\frac{1}{r})$ peaks sharply in the neighborhood of $(\xi,\zeta) = (x,z)$, it would be necessary to use very small intervals, or a quadrature formula of very high order to obtain sufficient accuracy. It is desirable, practically, to eliminate the peak in order to permit the use of quadrature formulas of moderate order. This may be accomplished as follows.

First we note, by Gauss's flux theorem, that if the point $(\xi,\zeta)$ on the centerplane is held fixed, and the integration extends over the hull surface $S$, we have

$$\int_S \frac{\partial}{\partial n}\left(\frac{1}{r}\right) dS = -4\pi \tag{22}$$

or, since

$$dS_o = \frac{\partial y}{\partial n}\, dS = \frac{dS}{[1 + f_x^2 + f_z^2]^{1/2}} \tag{23}$$

and

$$\sqrt{1 + f_x^2 + f_z^2}\, \frac{\partial}{\partial n}\left(\frac{1}{r}\right) = \frac{1}{r^3}[(x-\xi)f_x \mp f(x,z) + (z-\zeta)f_z] \tag{24}$$

Then substituting (23) and (24) into (22) and interchanging the variables $(x,z)$ and $(\xi,\zeta)$, we obtain

$$\int_{s_o} \frac{(x-\xi)f_\xi \pm f(\xi,\zeta) + (z-\zeta)f_\zeta}{[(x-\xi)^2 + f(\xi,\zeta)^2 + (z-\zeta)^2]^{1/2}}\, dS_o = 4\pi \tag{25}$$

Let us now write (21) in the form

$$I = \int_{s_o} \left[\frac{\partial F}{\partial n} - \frac{K(x,z;\xi,\zeta)}{[1 + f_x^2 + f_z^2]^{1/2}}\right] dS_o \ , \ K = \frac{(x-\xi)F_x = f(x,z) + (z-\zeta)f_z}{[(x-\xi)^2 + f(x-z)^2 + (z-\zeta)^2]^{3/2}} \tag{26}$$

Then, noting that (25) may be expressed in the form

$$\int_{s_o} K(\xi,\zeta;x,z)\, dS_o = -4\pi \tag{27}$$

we have

$$I = \int_{s_o} \left[\frac{\partial F}{\partial n} - \frac{K(x,z;\xi,\zeta) - K(\xi,\zeta;x,z)}{\left[1 + f_x^2 + f_z^2\right]^{1/2}}\right] dS_o + \frac{4\pi}{\left[1 + f_x^2 + f_z^2\right]^{1/2}} \tag{28}$$

the integrand of which does not peak in the neighborhood of the point $(\xi,\zeta) = (x,z)$; in fact, the term giving rise to the peak has been annulled at this point.

The integral occurring in (20) can be altered in a similar way. We have

$$\int_{s_o} m(\xi,\zeta)\, \frac{\partial G}{\partial n}\, dS_o = \int_{s_o} m(\xi,\zeta)\, \frac{\partial F}{\partial n}\, dS_o - \int_{s_o} \frac{m(\xi,\zeta)K(x,z;\xi,\zeta)}{[1 + f_x^2 + f_z^2]^{1/2}}$$

$$= \int_{s_o} \left[m(\xi,\zeta)\, \frac{\partial F}{\partial n} - \frac{m(\xi,\zeta)K(x,z;\xi,\zeta) - m(x,z)K(\xi,\zeta;x,z)}{[1 + f_x^2 + f_z^2]^{1/2}}\right] dS_o$$

$$+ \frac{4\pi m(x,z)}{[1 + f_x^2 + f_z^2]^{1/2}} \tag{29}$$

Again, it is seen that the term giving rise to the peak in this integral has been annulled.

This is as far as the development will be carried here. The programming of the suggested procedure for solving the integral Equation (19) should be undertaken. It is believed that such a program would be well within the capacity of existing high speed computers.

Since the integral Equation (19) is of the first kind, it may not possess an exact solution. Nevertheless, such equations are capable of producing excellent approximations to a solution of a physical problem. In practice, when an iteration formula such as (20) is used to solve an integral equation of the first kind, the error, given by the term in brackets in (20), is observed after each iteration, and the iteration is stopped when the error is uniformly sufficiently small over the entire surface or when the error begins to grow and becomes unacceptably large at some point or points with an increasing number of iterations.

The above procedure for eliminating the peak in the integrands can also be applied in the integral equation of the second kind (15) to eliminate the singularity at the point $(\xi,\eta,\zeta) = (x,y,z)$. For numerical evaluation, the principal advantage of the method of a distribution over the centerplane over that of a distribution over the hull surface may be in the greater ease of evaluating the function $F(x,y,z;\xi,\eta,\zeta)$ and its derivatives on the centerplane.

When $m(\xi,\zeta)$ has been determined from (19), the velocity potential is given by

$$\phi(x,y,z) = \int_{S_0} m(\xi,\zeta)G(x,y,z;\xi,0,\zeta)dS_0 \tag{30}$$

and the wave-making resistance is

$$R = -4\pi\rho \int_{S_0}\int_{S_0} m(x,z)m(\xi,\zeta)F_x(x,0,z;\xi,0,\zeta)dS_0dS_0 \tag{31}$$

# APPENDIX IV

## SHIP RESISTANCE IN RECTANGULAR CHANNELS

By L. Landweber

### A. Introduction

The problem is to determine the influence of the finite dimensions of the section of a towing tank on the resistance of a ship model. Although empirical criteria for avoiding this so-called blockage effect are known, these are frequently violated either in connection with tests of a geosim series, or in the deliberate selection of a larger model scale so as to obtain a propeller size large enough for self-propulsion studies. Consequently a procedure for correcting towing tank data for boundary effects is desired.

### B. Statement of Problem

It will be supposed that a ship model of length $L$ is being towed along the centerline of a rectangular towing tank of depth $h$ and width $w$, of relative dimensions

$$h \geqq \frac{L}{2}, \qquad w \geqq L \tag{1}$$

at towing speeds $U$ in the range of Froude numbers

$$F_L = \frac{U}{\sqrt{gL}} \leqq 0.30 \tag{2}$$

These limits appear appropriate for the purpose. It is unlikely, for example, that a model longer than 20 feet would normally be tested in a tank 20 feet wide and 10 feet deep. Furthermore, the speed range given by (2) is more than adequate for merchant ship forms. For a 400-foot ship condition (2) corresponds to a top speed of 20 knots.

Conditions (1) and (2) may be combined to give a restriction on the Froude number based on depth,

$$F_H = \frac{U}{\sqrt{gh}} = \frac{U}{\sqrt{gL}} \sqrt{\frac{L}{h}} \leqq 0.42 \tag{3}$$

Thus the radical changes in flow phenomena associated with depth-Froude numbers near unity need not be considered within the scope of this problem. In the indicated ranges of interest the effects of the vertical walls and bottom may be expected to be small, advantage of which should be taken to simplify an otherwise extremely complex problem.

## C. Proposed Research

First consider the case of very low Froude numbers, for which the free surface boundary condition may be taken to be that for a rigid surface. There is no wave making and the principal effect of the walls is to increase the velocity of flow relative to the model. As is well known from wind tunnel practice, the velocity field produced by the presence of the walls may be determined by the method of images in potential theory; see section (b) below. The viscous drag of the body is then assumed to be that associated with the increase in the mean velocity of flow. The induced flow also modifies the pressure gradients at the stern of the model, but these are small, and an examination of their effects has indicated that they are of secondary importance.

One would expect then, that, by the method which has been applied so successfully in wind tunnels, it would be possible to predict wall effects at low Froude numbers. It appears, however, that the velocity correction, computed by treating the free surface as rigid, is only about one-half of the value observed at a Froude number of about F = 0.15, at which the wave-making resistance is still negligible. This unexpected disagreement has been reported by several investigators and, as a consequence, empirical formulas for the velocity increase have been based on a crude one-dimensional flow analysis rather than on the sounder method of images.

Although the accumulated evidence for the aforementioned disagreement is convincing, it is indirect. It is proposed, then, that research be undertaken to measure the change in velocity of flow about a ship model due to the finite width and depth of a towing tank, at various Froude numbers, beginning from as low a value as possible. For this purpose an accurate set of pressure measurements taken around the girth at midships should suffice, by means of the Bernoulli equation, to give the change in the mean velocity.

A possible explanation of the apparent discrepancy between theory and experiment is that, with increasing Froude numbers, appreciable changes in flow about a ship model occur at a much lower Froude number than for wave making resistance. The validity of this hypothesis, which seems to fit the known facts, would be determined by the set of flow measurements proposed above.

The velodity about a ship model can also be otained from potential flow, gravity wave theory. For the case of a rectangular channel, the velocity potential which satisfies the linearized boundary-value problem is known, so that, in principle, the velocity of flow about the hull can be computed. This suggests that it would be desirable to select, for the proposed pressure measurements, a form for which flow and wave-resistance calculations can conveniently be performed.

A successful culmination of the above program would not of itself yield a practical solution. The formulae of gravity wave theory are too complex to yield a direct insight into the effects of hull form, width and depth of channel, and the Froude numbers on the change in speed or resistance. Since these effects are small, owing to the restrictions of the problem in (1) and (2), it is suggested that attempts be made to simplify the expressions for the velocity potential and the wavemaking resistance, either by means of power series in small quantities or by asymptotic expansions. If this can be accomplished for a mathematically simple form, such as one generated by a source and a sink near the free surface, the resultant expressions would probably be considerably better suited for displaying the desired effects.

### 1. Wall Correction at Very Low Froude Numbers

Consider a source of strength $M$ in a rectangular channel of width $w$ and height $h$. Take coordinate axes $(y, z)$ with origin at the center of the channel at which a source is situated. Then there is an image system in the walls consisting of sources situated at the points $(mw, nh)$, $m, n = 0, \pm 1, \pm 2, \ldots$, but not both zero. The velocity potential due to these images is

$$\phi = -M \sum_{M = -\infty}^{\infty} \sum_{N = -\infty}^{\infty} [x^2 + (y - mw)^2 + (z - nh)]^{-1/2} \quad (1)$$

If there is a source $M$ at $x = -c$ and a sink $-M$ at $x = c$ in a uniform stream of unit strength, the velocity potential owing to the image system is

$$\phi = M \sum_m \sum_n \left\{ [(x-c)^2 + (y-mw)^2 + (z-nh)^2]^{-1/2} - [(x+c)^2 + (y-mw)^2 + (z-nh)^2]^{-1/2} \right\} \qquad (2)$$

The x-component of the velocity at (0, 0, 0) is then

$$U_o = 2Mc \sum_m \sum_n (c^2 + m^2 w^2 + n^2 h^2)^{-3/2} \qquad (3)$$

By Taylor's added mass theorm we have

$$\forall\ (1 + k_1) = 4\pi Mc \qquad (4)$$

where $k_1$ is the longitudinal added mass coefficient and $\forall$ the volume of the double model; i.e., the model and its image in the free surface. Here $k_1$ may be estimated from the value for an equivalent ellipsoid, i.e., one having the same length and volume as the double body. Equation (3) then becomes

$$U_o = \frac{1 + k_1}{2\pi} \forall \sum_m \sum_n (c^2 + m^2 w^2 + n^2 h^2)^{-3/2} \qquad (5)$$

In computing $U_o$ since the double infinite series converges slowly, it will be convenient to terminate it after a finite number of terms and to approximate the remainder by an integral. We obtain

$$U_o = \frac{1 + k_1}{2\pi} \forall \left[ \sum_{m,n} \frac{2k_{mn}}{(c^2 + m^2 w^2 + n^2 h^2)^{3/2}} + \frac{1}{wh} \int_{r_o}^{\infty} \int_{0}^{2\pi} \frac{r\,dr\,d\theta}{(c^2 + r^2)^{3/2}} \right]$$

$$= \frac{1 + k_1}{\pi} \forall \left[ \sum_{m,n} \frac{k_{mn}}{(c^2 + m^2 w^2 + n^2 h^2)^{3/2}} \quad \frac{\pi}{wh} \frac{1}{\sqrt{c^2 + r_o^2}} \right]$$

$$(6)$$

in which m and n assume all non-negative values such that

$$m^2w^2 + n^2h^2 \leq r_o^2 \qquad k_{mn} = \begin{cases} 1 & \text{if } m \text{ or } n = 0 \\ 2 & \text{if neither } m \text{ nor } n = 0 \end{cases} \qquad (7)$$

An important special case is that in which $w = h$, approximately the proportions of most ship model towing tanks. (Depth of towing tank is $h/2$). For this case a good approximation is obtained by replacing the entire sum by an integral, with $r_0 = 0.64\, w$, which gives

$$U_o = \frac{1 + k_1}{w^2} \frac{\nabla}{\sqrt{c^2 + 0.41w^2}} \qquad (8)$$

The the degree of accuracy to be expected from (8) it suffices to select a mean value for $k_1$, $k_1 = 0.04$, and to assume that $c = L/2$, where L is the length of the model. Then (8) becomes

$$U_o = \frac{2.08\, \nabla}{w^2 L \sqrt{1 + 1.64\, (\frac{w}{L})^2}} \qquad (9)$$

Example

University of Michigan Model 932 has the following characteristics:

Volume = 20.75 cu. ft. ($\nabla = 41.5$ ft.$^3$)

L = 14 ft., B = 2.19 ft., H = 0.876 ft.

Assume $w = 20$ ft., tank depth = 10 ft.

From Eq. (9) we obtain

$U_0 = 0.0072$

indicating an increase in velocity of about 0.7 percent.

Comparison between Michigan and DTMB data for a model of about the same block coefficient gives the following values for $U_o$:

| $V/\sqrt{L}$ | 0.380 | 0.465 | 0.535 |
|---|---|---|---|
| $U_0$ | 0.0125 | 0.0205 | 0.0230 |

The computed value $U_0 = 0.0072$, corresponding to zero speed-length ratio, is not inconsistent with the trend indicated by these data.

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