IV

CONTRIBUTION OF SHIP THEORY TO THE SEAWORTHINESS PROBLEM

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Introduction

Introduction

In an earlier survey [1] on the behavior of ships in a seaway we quoted A. Krylov's opinion on his famous memoir presented to the INA [2] and later published in the Enzyklopaedie der Mathematischen Wissenschaften, . . . "it is evident that these methods are quite sufficient to solve all the questions which arise regarding the influence on the seagoing qualities of a ship". . . .

We stated then that the great scientist has heavily overestimated the bearing of his investigation. However, his claim provides us with a program which we shall use as the backbone of the present lecture. We shall first give a short review of the present status of knowledge on the seagoing properties of ships as pictured by recent research work. This task is much simplified by the fact that recently in this country excellent papers have been published of original as well as of synoptical character, for example, by Korvin-Kroukowsky [4] and Lewis [5]. These publications are assumed as known, and only short reference will be made to them. Emphasis will be laid on investigations which may have escaped attention in this country although, unfortunately, the present writer's attempts to procure literature were not too successful.

We shall try to indicate some trends in the methodology of research and some important results without going into details of the analysis. Secondly, the significance of scientific results for *future* design will be discussed after having indicated sketchily some shortcomings of the present state. Here again an excellent foundation is given in reference 5. Beside promoting problems of design, a consistent theory of ship behavior will have to furnish basic information for ship operation. The task of linking explicitly design and operational problems in research, appears to present a strong challenge, but is beyond the scope of this lecture.

Finally, some ideas are developed as to future research in our field.

Seaworthiness we define as the property of a ship to perform her duties safely and well in a seaway. For a more detailed definition of seakindliness reference is made to an article by Kent [7].

Ship theory embraces in general the application of geometry and rational mechanics, especially of general mechanics and hydrodynamics, to problems presented by design and operation of ships. A narrower concept of ship theory, excluding problems of structural strength, will be especially useful for our present review, although obviously a clear-cut separation between ship dynamics and strength cannot be made, problems of elastic vibrations by definition belonging to ship theory. In fact, the unity of shipbuilding science is stressed at this point.

Introduction of the concept—*"ship mechanics"*—as analogue to flight mechanics when dealing with the behavior of a ship in a seaway, is suggested, to exclude any overemphasizing of geometrical topics, a characteristic of earlier ship theory.

When speaking about ships we have actually to deal with two different classes of vessels—Archimedean and hydrodynamic, which in turn each divide into two subclasses—surface and submarine ships, and planing and hydrofoil craft. From the point of view of analysis this means that we may have to create different *mechanical* models, each of which has to embody the most important properties of the vessel in question. So for the displacement vessel the appropriate hydrodynamic singularity is the source (sink, doublet), while the hydrofoil is treated by the vortex concept. We must add that beside ships, other floating or waterborn bodies have to be considered and should profit from the activities in our field.

If governmental stipulations [6] were completely indicative of the general trend in design practice, the present speaker should confine himself to a discussion of elementary stability principles. Fortunately, design practice is a mental activity which only to a certain extent is regulated by legal prescriptions, and the actual practical contributions of ship theory in our field are more impressive than can be deduced from such regulations. Especially the navies have in general displayed a more progressive attitude.

Denying any possibility of the *sacrificium intellecti* in our profession the author admits that in the light of *present* requirements of shipbuilding and shipping practice the importance of some scientific investigations and results may somewhat shrink. The situation becomes completely different, however, when we accept the author's contention that a considerable development of the ship is to be expected in the future.

It is already a truism that a strong incentive for further research is to increase the sustained ship speed in heavy seas. Numerous problems which at low speeds of advance could be treated hopefully by hydrostatic methods require more detailed hydrodynamic consideration at higher Froude numbers.

Several years ago we used to paraphrase Hilbert's well known remark on physics by stating that ship theory is becoming too difficult for naval architects. On the other side, because of the complex character of problems, it may be too complicated for mathematicians and physicists. The best approach may attempt to establish a fruitful cooperation between different directions of research.

The last five or six years have seen a tremendous increase of interest in our field, and considering the current rapid rate of progress, the author wishes to point out that the picture sketched by him refers to a transitory condition only, and even so is essentially incomplete.

I. THE INVESTIGATION OF SHIP BEHAVIOR IN A SEAWAY

Giving full credit to experimental research in the model and full scale range, we find it nonetheless advantageous to describe the present state of knowledge primarily in terms of analytic methods.

1. The Seaway Concept

Times are bygone, fortunately, when an amateur-oceanographer like the author could gain an easy reputation by measuring big waves. In what follows we confine ourselves to some remarks on the subject from a naval architect's point of view, since problems of oceanography have been dealt with by Professor W. Munk.

One of the most important recent achievements was the detection of long wave components by measuring ship motions [8]. An impressive development of the theory of the irregular seaway has taken place especially in this country and in Great Britain; apparently, parallel important work has been done by the Russian School although from the meager information available [9] it seems that the results reached are less definite.

Successes in oceanography have an important bearing on naval architecture. Obviously, no rational theory of seaworthiness of ships can be developed without a thorough knowledge of actual seaway phenomena; in fact, the lack of the latter was one of the reasons why the study of ship behavior remained somewhat academic and failed to find a wider response in practice.

Design procedures require the knowledge of *safety limits and of average performance* of a ship in a seaway.

Let us remember by what crude assumptions experienced model investigators attempted to cope with the latter problem: an "equivalent" regular wave was arbitrarily substituted for the actual seaway.

Under these circumstances, the work by St. Denis, Pierson and Neumann proved to be extremely successful after the first shock over the unfamiliar mathematical formulation had faded away [10]. The link with reality appears to be established, although from a hydrodynamic viewpoint Neumann's seaway formula may be no more than a successful heuristic approach. Thus only by the introduction of the irregular seaway concept can problems of average performance, especially of sustained average sea speed, be handled in an appropriate manner. This fact will allow us to appraise correctly the importance of seakindliness of vessels with respect to other basic qualities of a ship when the necessary statistical data will be collected. Again, there is a brighter outlook in this respect after pertinent research facilities have been developed.

There appear still to exist some differences in opinion on the fundamentals of the irregular seaway concept and the resulting ship motions. However, for the present purpose I shall assume that the principle of superposition is valid for elementary waves as well as ship motions and restrict myself to the study of ship behavior in a regular seaway till we later come to a discussion of design problems.

Attempts to establish *safety limits* for ships by statistical observations had been made long before a consistent theory of the actual seaway existed. It is evident that the statistical approach is a necessary condition for dealing with the safety problem but it is questionable if it is a sufficient one. Thus it is the present writer's contention that the old-fashioned approach based on the investigations of transient conditions should not be completely disregarded, although it is admitted that no proposal so far exists as to how to formulate these conditions.

The present theory of ship behavior in an irregular seaway as a linear theory is not fit to deal with the safety problem as far as large displacements, such as those in roll, are concerned. The same objection must be raised against the linear theory of ship motions in a regular seaway.

2. *Preliminary Survey on the Development of the Theory of Ship Behavior*

A. Krylov's study of ship behavior, based on the undisturbed wave hypothesis, remains classic because of its general character and its consistent formal approach. Recently his method has been reviewed by at least six authors. It should be kept in mind that Krylov's work was originally stimulated by a study of extraneous forces causing bending moments and shearing forces, thus indicating the close interconnection of shipbuilding science branches.

One could surmise that Krylov, by neglecting the influence of speed of advance on forces, and by rather aggressively disregarding the importance of damping in heave and pitch, might have detrimentally influenced further development. However, his scientific achievements have been grasped by the profession so slowly, that their weak points did little harm. Indeed, by failing to use Krylov's theory as a guide for model research, some experimenters were derailed into a rather sterile empiricism. Thus the need for sometimes tedious computations has occasionally slowed progress in understanding basic phenomena in our field.

The determination of exciting forces as functions of the waterline form, (to some extent of the sectional area curve), of the ratio $\lambda^* = \lambda/L$, and then of the heading angle, was the main problem attacked by Krylov. While Krylov himself still cherished the idea that he had solved the problem of ship behavior completely, his moderate adepts were critical enough to consider their investigations as attempts to obtain some general ideas of the phenomena. At the prevailing state of knowledge that was already a useful task.

By 1930 a standard form of linearized equations of motion for a ship in a seaway was established [11].

Simple equations for heave and pitch are

$$(m + m_{33}) \frac{d^2z}{dt^2} + N_{33} \frac{dz}{dt} + \rho g A_w z = \rho g r_m A_w E_{33} e^{i(\omega t - \epsilon_{33})}, \tag{1}$$

$$(Jy + m_{55}) \frac{d^2\psi}{dt^2} + N_{55} \frac{d\psi}{dt} + \rho g D\overline{M_L G}_\psi = \rho g \vartheta_m D\overline{M_L G} E_{55} e^{i(\omega t - \epsilon_{55})}. \tag{2}$$

"Relative motion" in heave is considered by the following expression:

$$m \frac{d^2z}{dt^2} + m_{33} \frac{d^2}{dt^2} (z - r) + N_{33} \frac{d}{dt} (z - r) + \rho g A_w z = \rho g r_m A_w E_{33} e^{i(\omega t - \epsilon_{33})} \tag{3}$$

where

$$\frac{d^2r}{dt^2} = - \omega_0{}^2 r_m e^{i\omega t}; \qquad \frac{dr}{dt} = i\omega_0 r_m e^{i\omega t}.$$

Known hydrostatic coupling terms were neglected for simplicity, although more recent research in hydrodynamics has led to the conclusion, that this involves an appreciable loss of accuracy [4]. It was realized comparatively early that nonlinearities of the restoring moment in roll must be considered, although the application of this finding to forced motions was slow. Special phenomena later required more attention to coupling terms and finally rheo-linear effects were treated.

The computation of *damping forces* by hydrodynamic means was initiated by Schuler [12] and Holstein [13], and put on safe ground by Havelock [14].

Although quite a bit had been achieved in this way there was an uneasy feeling about the applicability of the formal apparatus to concrete design problems, stemming from the distrust in the Froude-Krylov hypothesis underlying the computation of the *exciting forces.*

It turned out that the wholly submerged body was a mechanical model easier to handle than the surface ships. The classical theory of solids moving in a liquid developed mainly by Kirchhoff and Kelvin was rediscovered for our purposes after it had been considered (by our profession) as a kind of mathematical exercise only. Progress was essentially due to the application of the concept of hydrodynamic singularities. Lagally's theorem and its generalization by Cummins [15] were important steps in this direction. Reference is made, for example, to the work by Haskind [16] who asserted, not quite justly, that he had found the solution of the hydrodynamic problem neglected by Krylov.

In the present writer's opinion the procedure of building up equations of motion by intuitive synthesis will continue, notwithstanding its obvious shortcoming, i.e., the need to add new terms in the pertinent equations when dealing with special applications, such as ship stabilization [17]. Nonetheless, there exists an encouraging analogy with flight mechanics, the theory of which has reached a comparatively very satisfactory state by much the same path. It should not be overlooked that the directional stability of ships has been successfully attacked only after methods borrowed from aerodynamics have been applied.

The use of hydrodynamic singularities is one method of attacking the boundary value problem involved. Since, however, one ordinarily uses a first approximation only when substituting effects due to singularities for effects caused by bodies, it makes sense to speak about a "singularity theory" as distinct from a "rigorous theory" based on a more exact solution of the boundary value problem.

Beside the work of Havelock [18] we mention the well-known investigation by Ursell [19] on the heaving of a cylinder, as an example of a rigorous procedure which becomes indispensable when added masses, the magnitudes of which depend upon the flow field in the neighborhood of the body, are investigated.

The determination of the ship behavior in a seaway as a boundary-value problem was formulated in its full generality first by F. John, whose papers on the motion of floating bodies [20] are already classical. It is impressive that this investigation led immediately to important practical results in a special case, thus defying classification as only a mathematical exercise.

Stoker and Peters [21] attacked the explicit solution of the boundary problem in a more general way, restricting it, however, to symmetric motions of the "Michell" (thin) ship. From a methodological point of view this work produced important progress, which is enhanced by a study [22] dealing with the "Stoker-Peters" problem on arbitrary heading angles. It has been pointed out by the present writer that the results achieved by these authors in their first paper indicate that the Michell ship cannot be considered as an adequate mechanical model of an actual ship as far as heaving and pitching motions are concerned. However, quite recently Stoker and Peters have obtained farther rearching results in the case of the general problem [23]. Although explicit solutions apparently can be worked out only with great difficulties, their method represents the ideal goal aimed at in our field of research, since it derives the motion of the ship from the pressure forces on its hull.

In the case of plane motions, methods of solving the boundary problem have been established by Ursell and Grim [24]. The results obtained represent already an indispensable part of useful knowledge in our field.

A significant present trend is to treat problems as two dimensional and to solve them as rigorously as possible, although solutions for the three-dimensional potential of pulsating and advancing singularities are known. A strip model is then applied. Because of the inherent limitations of the plane-motion concept it is expected that this trend may be changed rather soon, although Haskind, in an interesting recent paper [25], takes advantage of the simpler procedures used in the two-dimensional case, and at the same time gets rid, as far as possible, of their shortcomings.

Having given what is thought due credit to strategists of a rigorous approach, we must still pay attention to problems whose treatment by rigorous methods may still prove impossibly cumbersome. An important example is the problem of hydrodynamic impacts associated with the emergence and reentry of parts of the hull, especially of the bottom from and into the water [26].

Unfortunately, we have not been able to deal adequately with the resistance problem in this paper. This is partly due to the unsatisfactory status of knowledge in this field, and partly to our inability to obtain literature on valuable work by Japanese researchers, in time for this writing. Research conducted at the present writer's institute at a simplified level has so far led to promising, but not yet conclusive results.**

3. *More Detailed Survey of Problems Connected with Ship Behavior*

The brief sketch of the scientific status in our field leads to the conclusion that beside the promising first efforts to establish a general rigorous theory we have still essentially to rely, probably for a long time, on partial solutions of our problem, resting to a large extent upon inductive and rather intuitive methods. We shall therefore discuss in more detail results obtained by the latter approach.

** Reference is made to recent publications by Hanaoka and Maruo.

The ship will be considered as rigid and the fluid as ideal. In fact, according to our present ideas viscosity plays an important part almost only in the damping of roll. The insight that viscosity effects can be disregarded in most cases represents in itself an important achievement.

A large part of current investigations deals with forced motions of ships in calm water; effects due to wave action are added using the principle of superposition.

3.1. *Dimensionless Parameters*

In the absence of a consistent theory the determination of similitude parameters is a necessary prerequisite for research and application; in a later stage appropriate expressions are indispensible working tools. At the same time, this absence of theory hinders discovery of the most advantageous and significant similitude parameters for a particular problem. Up to the present time, varied experiences and personal preferences have produced a rather wide variety of dimensionless parameters for the study of ship mechanics, and some kind of standardization appears desirable. Once these parameters will have been standardized, it should become customary to characterize a vessel's oscillatory properties by them in the same way that this is being done for the resistance by the Froude number. (The author's preferences in choice of parameters is indicated in the list of symbols and throughout the remaining text.)

For purposes of any general discussion, it is convenient to have in mind some standardized ship geometry or series of shapes. Submerged elongated vessels can be approximated by bodies of revolution (especially their most distinguished of such—the spheroid), even a moderate departure from axial symmetry being permissible; and it appears that in the case of surface ships a two-dimensional treatment can be founded with success upon the well-known class of F. Lewis sections [27] which have been used independently by Grim and Haskind.

A section of the Lewis class is determined by the ratio $\frac{B}{2H}$ and the area coefficient β.

The velocity potential which governs fluid perturbations caused by motions of such bodies has been established also in the presence of a free surface.

3.2. *Added Masses*

The determination of added masses has become a central problem in the study of ship behavior, since the computation not only of inertia but also of exciting and even damping forces depends upon it.

To my knowledge, Haskind [28] was the first to establish theoretically the influence of a frequency parameter, say $\omega_B^* = \omega\sqrt{B/g}$, upon the magnitude of added mass values $m_{ij}\ (\omega_B^*)$ already found experimentally by Holstein [13]. Unfortunately, our information rested on a part of Haskind's publications only, so that the method by which he obtained his important results in the three-dimensional case remains unknown, although further details of his work have become available [25].* In the meanwhile contributions have been made by Ursell, Grim, and Havelock. Japanese authors [29] investigated the submerged spheroid under the free boundary condition $\Phi = 0$, while the other extreme case $\frac{\partial \Phi}{\partial z} = 0$ has been treated by Eisenberg [30].

There are several methods in use to formulate dimensionless added mass coefficients; the most popular are those found in Lamb and those proposed by F. Lewis. However, especially in the case of rotational motions there is still a wide variety of definitions.

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* In the two-dimensional case of heaving the result $m_{33}\ (0) \rightarrow \infty$ is obtained while Haskind's investigation yielded a finite value supported by experiments.

Reference is made to some results obtained by Grim [31] for sections of the Lewis class and circular segments. These findings have been recently supplemented by values $m_{44}(0)$, i.e. of the hydrodynamic moment of inertia of cylindrical bodies in roll for a frequency parameter $\omega_B^* \rightarrow 0$, which change somewhat the shape of curves communicated earlier.

For the elliptic section we have the well-known result $\dfrac{\bar{m}_{22}(\infty)}{\bar{m}_{22}(0)} = \dfrac{4}{\pi^2}$ which pictures the conditions $\Phi = 0$ and $\dfrac{\partial \Phi}{\partial z} = 0$ respectively; and for a flat plate Haskind [25] obtained the relation $\dfrac{\bar{m}_{44}(0)}{\bar{m}_{44}(\infty)} \approx 1.6$. In Grim's presentation the inertia coefficient K_{44} is referred to the moment of inertia of the homogeneous elliptic halfcylinder.

The variability of the added mass coefficients with the frequency parameter is impressive. Nonetheless, Haskind proposed recently to use in heave and pitch the approximations $m_{33} = \bar{m}_{33}(\infty)$ and $\bar{m}_{55} = \bar{m}_{55}(\infty)$; in sway and roll $m_{22} = m_{22}(0)$ and $m_{44} = m_{44}(0)$, since free heave and pitch oscillations are in general short perioded as compared with those of sway and roll. This means in effect that the earlier practice of substituting the deeply immersed double body for the ship should be applied as first approximation. We do not agree with this proposal which, in our opinion, is permissible not as a first *approximation* but as a first *orientation* only. In the later part of our study it will be pointed out that it can become quite important to determine added mass values more rigorously.

In [25] expressions are communicated for added masses $\bar{m}_{22}$, $\bar{m}_{44}$, $\bar{m}_{24}$ of bodies belonging to the class of Lewis' forms. Previously, only $\bar{m}_{33}$ was known. The total added masses of the ship are determined by a strip method. Approximate expressions are given in the form $m_{33} = \bar{m}_{033}\, L\, \dfrac{2\alpha^2}{1+\alpha}$ $m_{22} = \bar{m}_{022}\, L\, \dfrac{2\beta_o^2}{1+\beta_o}$ with $\bar{m}_0$ the added mass of the midship section, α the waterline area coefficient, and β_o the area coefficient of the *longitudinal* section generally close to 1. These formulas are based on a rather rough assumption on the average distribution of $\bar{m}_{33}$ etc. and on Chapman's parabolas as waterline equation; a correction coefficient has to be used for the finite length of the ship.

Haskind suggests use of the condition $\dfrac{\partial \Phi}{\partial z} = 0$ to determine added masses in the aperiodic motions of sway and yaw, which again appears to be rather arbitrary.

The vertical added mass of half a sphere oscillating at the free surface has been calculated by Havelock [32]. Its dependency upon the frequency parameter is similar to that found by Haskind for a ship; the ratio $\dfrac{m_{33}(0)}{m_{33}(\infty)} \approx 1.6$, is somewhat lower than for the latter.

The magnitude of added mass values in transient conditions depends upon the time history. There exists a solution [33] for the wholly immersed circular cylinder moving sidewise from rest with a constant acceleration, which yields an added mass value $\bar{m}_{22}(\infty)$, i.e. corresponding to the assumption $\Phi = 0$. Suggestions have been made to approximate transient motions by parts of a sine curve and thus to determine a frequency parameter. This procedure, obviously, is questionable.

So far, no consistent theory is known to us which deals with the influence of speed of advance on added masses of bodies moving at or near the free surface. Haskind indicates however, that following his theoretical and experimental work, this influence is not strong in case of the heave motion, and recent experiments by Golovato [34] support this statement reasonably well.

3.3. Damping

Beginning with Froude [3], considerable efforts have been made to determine the damping of roll by experimental methods. It is known that Froude possessed sound ideas on the wave damping in this case, but his plotting of extinction curves without deriving therefrom orthodox dimensionless damping coefficients has hampered progress.

To the present writer's knowledge, pertinent experiments on heave and pitch were first carried out by him at the Berlin Tank on a very full and medium full cargo ship model. They yielded added mass coefficients of about unity for heave and somewhat less for pitch. Dimensionless damping coefficients were $\kappa \approx 0.4 \rightarrow 0.5$ for both motions; there being no measurable difference in these values for $F = 0$ and $F = 0.20$. These results were later checked by Igonet [35].

Experiments conducted in Göttingen by Schuler and his school to check theoretical findings yielded a frequency dependence of damping as well as of added masses. Havelock [18] interpreted an important result due to Holstein by indicating the underlying source distribution, and treated the three-dimensional case of heave and pitch by alternating sources. Almost all work mentioned below refers to the damping experienced by bodies moving in calm water and performing forced oscillations. Such is in fact, the mechanical scheme used at present in this kind of research, (except for *model* investigations in a seaway). Similar studies were independently performed by Kochin and followers primarily on the damping of submerged bodies including shallow water effects. Haskind gave an extended general treatment of the subject and developed formulas for the heave and pitch damping of thin ships in a regular very long seaway. We mention Brard's important work on pulsating singularities advancing in calm water. In the two-dimensional case Ursell and Grim satisfied more accurately the boundary conditions on the body which otherwise remained somewhat undeterminate.

Further work of Haskind [25] discusses approximate methods to determine hydrodynamic forces. Finally, Havelock [36] has made an investigation on the limits of applicability of the strip method for determining the damping of submerged bodies as function of the frequency parameter. So far no systematic investigations are known on the magnitude of damping coefficients in a regular *seaway.*

a. Damping in the two-dimensional case

A strip method is now widely in use to determine pitch and heave damping of ships; it can be applied to roll also. Results have been given in the form of rate of energy dissipated, wave amplitude at infinity, and damping coefficient N, from which the dimensionless damping coefficient κ can be derived.

In Holstein's case of a uniform alternating source distribution, the wave amplitude referred to the heaving amplitude amounts to

$$\frac{r_m}{z_m} \approx \omega^2 \frac{B}{g} \exp\left[- \frac{\omega^2 H}{g} \right] \tag{4}$$

Therefrom

$$\overline{N} = \frac{\rho g^2 r_m{}^2}{\omega^3 z_m{}^2} \approx \rho \omega B^2 \exp\left[- \frac{2\omega^2}{g} H \right] \tag{5}$$

$$\kappa \approx \frac{\omega B}{\sqrt{(1+K_z)Hg}} \exp\left[- \frac{2\omega^2}{g} H \right] = \omega_B{}^* \sqrt{\frac{B}{H} \frac{1}{1+K_z}} \exp\left[- \omega_B{}^{*2} \frac{2H}{B} \right] \tag{6}$$

Holstein's result has been generalized by St. Denis [37] for arbitrary section forms.

We note that for small ω, the damping and its dimensionless coefficient is proportional to ω. The same applies to results found by Ursell for the circular cylinder and by Grim for the class of Lewis sections. There is a good agreement between Ursell's and Grim's findings in the case of the circular cylinder; however, a wide discrepancy has been stated between Grim's results and those found by the "source theory" for larger frequency parameters ω_B^*. In the latter case, one should have more confidence in Grim's and Ursell's results since they rest upon a more advanced approach; recent measurements by Golovato support the correctness of Grim's findings. Further investigations will be conducted to settle this problem finally.

From the point of view of ship design, the range of frequency parameters close to synchronism only is of primary importance, say corresponding to $0.6 \leqslant \Lambda \leqslant 1.2$, or expressed in ship parameters roughly $0.5 \leqslant \nu_B^* \leqslant 2$.

b. The Three-Dimensional Problem

The velocity potential is known for the harmonically pulsating source and doublet advancing with a constant speed, from which in principle a solution can be built up for a system picturing the actual ship [38]. Neglecting the speed of advance Havelock [18] has given his well-known analysis of heave and pitch. The damping coefficients for an elliptic waterline are:

$$N_z = \frac{\pi}{4}\frac{\rho}{g} B^2L^2\omega^3 \exp\left[-2\omega^2H/g\right]N_z^* \tag{7}$$

$$N_\psi = \frac{\pi}{16}\frac{\rho}{g} B^2L^4\omega^3 \exp\left[-2\omega^2H/g\right]N_\psi^* \tag{8}$$

for small ω $N_z \sim \omega^3$, as against $\overline{N} \sim \omega$ in the two-dimensional case. N_z^* and N_ψ^* are dimensionless coefficients.

For a wholly submerged body, oscillations are pictured by dipole distributions. In the range of small ω

$$N_z \approx \omega^5, \qquad N_z^{(s)} \approx \omega^5, \qquad N_\psi \approx \omega^7, \tag{9}$$

where $N_z^{(s)}$ is the damping coefficient of the body calculated by a strip method. While it had been earlier established [16] that for heave the strip method is appropriate for $\omega^{*2} = \dfrac{\omega^2 L}{g} \geqslant 6$, it follows that in pitching the corresponding lower limit of applicability is higher, say $\omega^{*2} \geqslant 8$. It should be remembered that for application damping values become decisive in the neighborhood of synchronism only.

Haskind's results for low frequency parameters are given in a different form [16]. However, an agreement with Havelock's expressions can be obtained.

From [25] we reproduce two diagrams. The full lines in Fig. 1 represent dimensionless damping coefficients of heave, $C_{33} = C_z = \dfrac{N_{33}}{\pi\rho\sqrt{gL}\,B^2}$, for $F = 0$, as a function of the frequency parameter ω^*, apparently based on Reference [16], for a full ($\alpha = 0.8$) and a fine waterline ($\alpha = 0.64$). The marked points in this diagram refer to damping at the Froude numbers indicated. This diagram and another showing experimentally-obtained heaving amplitude ratios plotted versus ω^*, support Haskind's assertion, that within a wide range the damping coefficient is roughly independent of the Froude number. Phase lag curves corroborate the statement.

In principle there is, however, no reason to expect that Haskind's finding is more than an approximate rule which may be valid within certain ranges of the frequency parameter and Froude number. Eggers, of my institute, has investigated this question using Brard's results for simple combinations of singularities and found that outside of the range considered by Haskind important deviations from the rule can occur. Of special interest in this connection appears to be Japanese work [29].

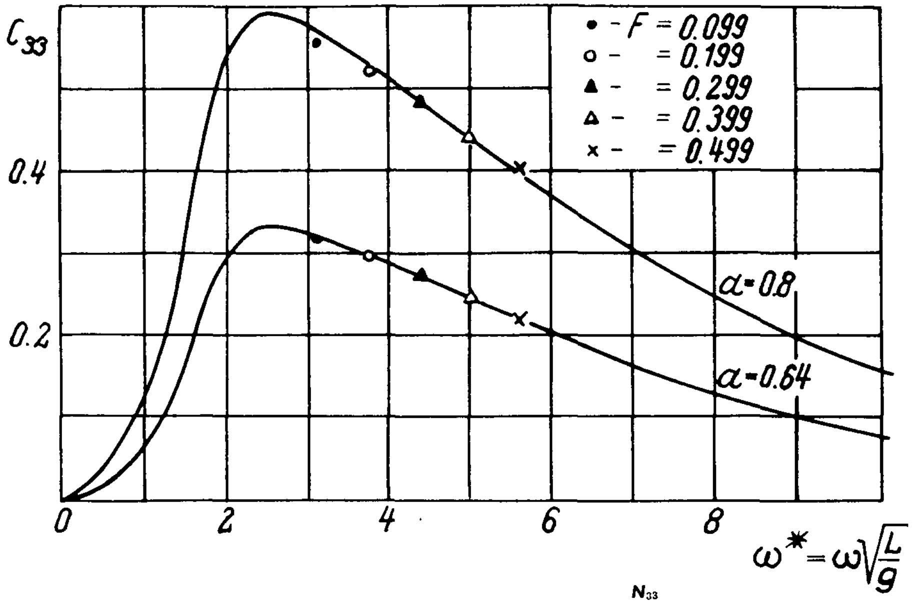

Figure 1. Dimensionless damping coefficient in heave, $C_{33} = \frac{N_{33}}{\pi\rho B^2\sqrt{gL}}$, as a function of the frequency parameter ω^*. (From Haskind, Reference 25.)

There are some experimental findings for submerged bodies where a definite speed dependence of damping at a constant frequency was established.

Thus the problem of dependency upon the Froude number is not yet settled, although recent experimental results by Golovato indicate that one is entitled to accept Haskind's result as a useful working hypothesis within the most important speed range. Conditions may be different in the case of roll. Japanese writers [29] have indicated an increase of wave damping with increasing Froude number. Further, effects due to viscosity become important.

3.4. Simplified Theory of Heave and Pitch

We shall classify all investigations based on the Froude-Krylov hypothesis as simplified and, when in addition coupling terms are neglected, as simple. It is quite significant that investigations of such a character still appear today.

A consequent work of this character has been published recently by Gerritsma [39] on heave and pitch in longitudinal waves. Coupling terms following Korvin-Kroukovsky have been considered separately; but their contribution is not large in the present case.

Regarding the importance of Smith effect and relative-motion corrections to the simplified theory, I take note of recent research on diffraction and do not quite agree with a remark made by Cartwright and Rydill [40], that it may not pay to consider anything else beyond the simplest theory for interpreting full-scale experiments in an actual seaway.

3.5. Investigations on Exciting Forces

The classical theory of motion of bodies in an unbounded fluid, with approximations introduced to deal with a non-uniform and non-steady flow, showed that the heaving force depends upon such factors as K_{33}-K_{11} and $\frac{U}{c}$.

The shortcomings of the Froude-Krylov hypothesis have first been overcome in the case of submerged bodies moving uniformly and horizontally close to the corrugated free water surface. Later Havelock [41] gave a solution for the spheroid, and Cummins [42] applied his generalized singularity theorem to determine the hydrodynamic part of the exciting force experienced by bodies of revolution. The distortion of the wave shape is not considered by this approach. The application of Cummins' method to general problems of ship mechanics is promising, although some difficulties still exist in the case of rotational motions [43].

The question arises if use can be made of the results found for the rectilinear horizontal motion of submerged bodies, when dealing with surface ships. The problem of heave and pitch has been attacked by Korvin-Kroukovsky. By using an analogy with submerged bodies, he obtained expressions for the exciting force per unit ship length which agree in structure with the corresponding ones for wholly-submerged bodies. A dependence of the total force and moment upon the speed ratio $\frac{U}{c}$ arises. Although this dependence is not supported by Korvin's own experiments, and its existence is denied by Haskind [25], one would feel inclined to assert by analogy that some speed effect should exist. At least one curve published by Haskind appears to support this conjecture. (See Fig. 2.) Difficulties presented by free surface effects have been discussed by Professor Korvin himself; some of them dealing with the strip method used for computation of damping have been clarified in the meantime by Havelock. It appears that in the most important range of natural periods, the strip method has its definite merits.

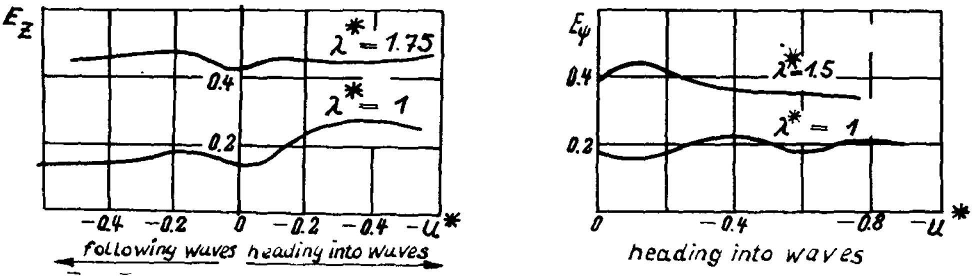

Figure 2. Coefficients of exciting force and moment in heave and pitch, E_z and E_ψ, as functions of $U^* = \frac{U}{c}$ (From Haskind.)

We discuss now the method used by Haskind to determine exciting forces [44] [45] [25]. Haskind's calculation is based on Krylov's work and on the consideration of *diffraction* effects. In quite an unusual way the ship is pictured by an infinitely long cylinder, whose axis makes the angle χ with the wave direction.

The form of the potential of the free wave suggests a complete potential constructed as the sum of a part which solves the problem of forced motions in calm water, and a part which solves the diffraction problem.

Forces due to wave diffraction can be interpreted as due to damping and added mass effects which, however, differ from the common concepts. For side waves the concepts coincide, but denoting the diffraction terms by a superscript (d) one obtains

$$\begin{array}{ll} \overline{N}^{(d)}(0) = 0, & \overline{m}^{(d)}(0) = 0, \\ \overline{N}^{(d)}(\infty) = 0, & \overline{m}^{(d)}(\infty) = 0, \end{array} \quad \frac{2\pi}{\lambda}\cos\chi \neq 0. \qquad (10)$$

Thus the general character of the curves $\overline{m}^{(d)}$ is different from that of $\overline{m}$, while the damping curves $\overline{N}^{(d)}$ and $\overline{N}$ display a certain similarity.

Approximate relations for $\overline{N}_{jm}^{(d)}$ are given when $\frac{2\pi}{\lambda}y|\sin \chi|$ is small. Formulas are developed from which the forces $\overline{Y}^{(d)}$, $\overline{Z}^{(d)}$, $\overline{M}_x^{(d)}$ per unit length can be calculated when the transverse dimensions are small compared with the length of the ship, and therefrom by a strip method *all resultant forces* and *moments experienced by the vessel* (except, obviously $\overline{X}^{(d)}$).

In the case $\chi = 0$ or π in which we are strongly interested, the present simplified method leads to a purely vertical force per unit length, which coincides in type with that for the well-known relative-motion effect. However, instead of $\overline{m}_z$ the diffraction mass $\overline{m}_z^{(d)}$ appears. If we assume for the time being that especially for larger $\frac{\omega_o^2}{g}$, $\overline{m}_z^{(d)} < \overline{m}_z$, one sees that the relative-motion correction over-emphasizes the actual effect.

In [25], the inconsistency of the relative-motion correction is emphasized. Very probably, however, this criticism applies to an erroneous computation of the velocity and acceleration field in a wave.

Exciting forces and moments calculated by Haskind depend *linearly* upon the orbital velocities of the wave particles. The important hydrodynamic reactions due to yaw and sway of an advancing ship cannot be determined by the method proposed.

Finally, we consider an unpublished investigation by Grim already referred to [24], "Die Schwingungen von schwimmenden Zweidimensionalen Koerpern." For simplicity we treat here all hydrodynamic forces involved in heave, sway and roll. While emphasis is laid on the determination of hydrodynamic characteristics when $\omega_0 \to 0$, the method is extended to finite small frequency parameters $\frac{\omega_o^2 B}{g}$.

Using Lewis' sections the velocity potential for forced roll in calm water is established when $\omega_0 \to 0$, and the hydrodynamic forces are determined. The potential for the lateral motion (sway) is obtained for $\omega_0 \to 0$ and added masses calculated; results agree with those given by Haskind.

The equation for roll without damping,

$$\left[J_{ox} + J_{xx} - \frac{(m_o\overline{OG} + m_y h_q)^2}{m_o + m_y} \right] \ddot{\phi} + D\,\overline{GM}\,\phi = 0, \qquad (11)$$

agrees with the findings by Woznessensky based on Haskind's work [25]. J_{ox} is the moment of inertia of the ship referred to the waterline point O (axis of symmetry of the load water line); $\overline{OG}$ is the distance of the center of gravity; and h_q is the lever of the lateral added mass force. The position of the axis of rotation is derived herefrom.

A strip method is suggested to compute pertinent values for the actual ship. For small ω the *damping* due to the side motion and the roll can be approximately determined by adding an appropriate potential. The results are compared with those obtained for elliptical and circular sections by a more rigorous method [24], and a reasonable agreement is stated. In connection with an earlier investigation by Ursell, it is interesting to state, that for the profile considered the sway contribution to damping is much larger than that due to roll. Thus the loss of wave damping effect which has been found by Ursell for certain sections may not be so tragic as anticipated.

The influence of the effective added moment of inertia upon the roll frequency is communicated as function of $\overline{GM}$. Beside, the influence of large bilge keels on the period is shown as the result of a rather intricate investigation. In addition, expressions are given for the lateral and rotational damping caused by such bilge (or center) keels, showing that this damping increases with the fourth power of the keel height.

The results for the ship without bilge keels are checked by another method based on a conformal transformation.

The same method is then applied to determine the heave motion in calm water. Expressions are obtained for the added mass which in principle agree with Haskind's findings; the known result for the damping is restated.

A bold attempt is further made to compute the damping (for example for an elliptic section) when the rolling angle is no more considered as small.

Boundary conditions are now fulfilled at the actual condition and not at the state of rest. The magnitude of the damping coefficient obtained in this way may be appreciably higher than by the standard approach.

The exciting hydrodynamic forces caused by *regular waves* are determined by assuming first that the body is fixed. When the body is released these generalized exciting forces determine orbital motions of the body.

By considering quadratic terms in $\frac{\omega^2}{g}$ in the development of the wave potential, further results are obtained. It can be shown within the range of validity of the development made that the heaving motion does not exceed appreciably the orbital motion even at synchronism. This statement, which represents an extension of some results due to Ursell, settles the question raised by Chadwick [4].

Expressions for the exciting moment of roll are extremely interesting. They depend appreciably upon the shape of the cross section. It is imaginable, at least in principle, to design sections which experience low exciting moment at synchronism.

Unfortunately, it was impossible so far to establish agreement between the fundamental equations of *forced* roll used by Woznessensky [9] and by Grim. A lot remains to be done to reach a satisfactory state of knowledge in this seemingly outworn field of research, and results of high interest from the viewpoint of theory as well as practice can be expected from further work.

3.6. *Coupling of Motions and Equations of Motion*

This problem has been discussed already at some length at the VII International Tank conference. In the meanwhile important contributions have been made, to some extent inspired by the analogy with flight mechanics, but otherwise following lines established primarily by Haskind. Havelock [46] has recently reconsidered the problem of coupled free heave and pitch treated by Haskind, neglecting damping of the motions. He shows that the influence of coupling on natural periods is negligible.

The interesting technical problem which involves the discussions of forced oscillations so far remains open. It was raised by Grim's experiments showing large heaving effects due to forced pitching.

Korvin-Kroukovsky has tried to give a plausible physical interpretation of coupling terms in the combined heave and pitch equations

$$m'_{33}\ddot{z} + N_{33}\dot{z} + cz + m_{35}\ddot{\psi} + N_{35}\dot{\psi} + g\psi = Fe^{i\omega t} \qquad (12)$$

$$m'_{55}\ddot{\psi} + N_{55}\dot{\psi} + C\psi + m_{35}\ddot{z} + N_{35}\dot{z} + Gz = Me^{i\omega t} \qquad (13)$$

From his general analysis of forces he obtains

$$m_{35} = m_{53},\ N_{35} = N_{53}.$$

The coefficients are calculated from added mass and damping values in heave per unit length of the ship by integration. It is further shown that C and g should be split up into $C = C_1 + C_2$ and $g = g_1 + g_2$ where C_1, g_1 are due to hydrostatic and C_2, g_2 to hydrodynamic effects. These latter effects have not been considered by Haskind. Prof. Korvin emphasizes some shortcomings in his analysis which can be eliminated only by a more profound analysis. Such an analysis apparently cannot rest on Haskind's earlier approach [16] where diffraction effects have not been considered.

Under these circumstances the experimental method is appropriate. Haskind and Riemann [28] have proposed a method by use of which one is enabled to evaluate coupling coefficients from test data under plausible assumptions.

Experimental information on the damping coefficient N_{35} has been obtained by Golovato [34], using a TMB vertical oscillator. In a rather important range of frequency parameter $\omega_B{}^* = \omega\sqrt{\frac{B}{g}}$ which, however, in general lies below synchronism of pitch and heave, there is a striking coincidence with Havelock's findings, and outside of it a strong departure. Special effects in the low frequency range are determined at the critical speed ratio $\frac{U}{c} = F_{\omega_o}{}^* = 1/4$. At its peak value, the moment $N_{35}\dot{z}_m$ is not negligible as compared with the exciting pitching moment $M_y = \theta_m \rho g I_y E_\psi$. The same applies in still higher degree to the term $m_{35}\ddot{z}_m$; but such low frequencies can be reached under exceptional conditions only.

We expect still more difficulties for unsymmetric motions. For example, Chadwick [17] showed that the so-called yaw-heel effect is essentially due to the rate of sway (drift angle) and not to the centripetal acceleration of the ship moving on a curved path as earlier thought [47].

It is reasonable to assume that the couplings of roll back into sway or yaw are negligible.

The papers reviewed represent important steps forward in some directions. However, complete solutions are still lacking even in the *calm water* case, at least in the official literature, and the general problem of arbitrary motions of a ship in a regular seaway is quite open.

What difficulties must be expected when proceeding to the seaway problem can be estimated from the author's tentative treatment on directional stability [48] which unfortunately, is mutilated by misprints. Especially the computation of resistance presents a rather formidable task.

The establishment of equations of motion requires a thorough investigation on the geometry as well as on the mechanics of the problem. Already Krylov has indicated the difficulties arising from the fact that angular displacements of roll cannot be considered small. Further, Ursell has shown that the concept of a permanent axis of roll breaks down in certain cases. Szebehely has discussed the problem of the apparent pitching axis.

One could further follow lines suggested by Haskind [16] which already led to success in the case of heave and pitch. Useful if not general results may be expected, however, in a rather cumbersome form.

A scheme for linearized equations can be established using procedures familiar in flight mechanics. Leaving aside the motion in the direction of the axis and assuming that the symmetric oscillations of heave and pitch are described by Equations (12) and (13), the following expressions can be given for the asymmetric group:

$$m'_{22}\ddot{y} + N_{22}\dot{y} + m_{26}\ddot{\theta} + N_{26}\dot{\theta} + m_{24}\ddot{\phi} + N_{24}\,\dot{\phi} = Y, \tag{14}$$

where, probably, the terms with $\ddot{\varphi}$ or $\dot{\varphi}$ can be neglected; and

$$m'_{44}\ddot{\phi} + N_{44}\dot{\phi} + C_{44}\phi + m_{42}\ddot{y} + N_{42}\dot{y} + m_{46}\ddot{\theta} + N_{45}\dot{\theta} = M_x, \tag{15}$$

and

$$m'_{66}\dot{\theta} + N_{66}\dot{\theta} + m_{64}\ddot{\phi} + N_{64}\dot{\phi} + m_{62}\ddot{y} + N_{64}\dot{y} = M_z. \tag{16}$$

In [16] the terms with $\ddot{\varphi}$ or $\dot{\varphi}$ may again be small. These equations do not represent much more than a skeleton for research.

Gyrostatic terms discussed in Ref. 1 are omitted in the process of linearization. This agrees with a recommendation made by Chadwick and can be considered as a necessary first step from a formal point of view. But the appraisal of the order of magnitude of inertia and hydrodynamic forces is a serious task in itself. Very probably in the case of roll the term $(m'_{66} - m'_{55})\ \dot{\varphi}\dot{\theta}$ is important because of the high value of the difference in added masses $m_{66} - m_{55}$ as compared with m'_{44}. In general by neglecting such coupling terms peculiar effects may be omitted.

Some further remarks on nonlinearities appear to be appropriate.

It is natural to treat the roll simultaneously with sway and heave as done so far, but separate investigations are needed because of the basic importance of *transverse* stability and the nonlinear character of the motion at large angles. In fact, studies on roll serve as a prototype when dealing with nonlinear ship motions.

Efforts are being continued to determine the actual stability in a seaway. It has been shown that stable models capsized when advancing on oblique courses in regular waves although some experiments do not support results obtained by elementary calculations with respect to heavy losses of metacentric height on wave crests in a following sea. Theoretical work has not progressed appreciably either in this field or with respect to roll at large angles. Baumann [49] has discussed the latter problem under simplifying assumptions which admit the solution of the equation of forced roll in a closed form.

Equations with higher order terms in the restoring expressions for heave and pitch have been solved by a step by step method [50], but results so obtained do not present especially interesting features.

Nonlinear effects in roll damping are well known [51]. Recent experiments on forced heave have yielded similar pronounced effects [34]. So far they have not been detected by model investigations in regular seaways of various but moderate height, which generally yield a reasonably linear relation for motion amplitudes.

4. *Hydrodynamic Impacts*

Within the last five years the application of hydrodynamic impact theory to problems of naval architecture has successfully developed. At present, shock phenomena are considered to be as important as the approximately periodic effects experienced by a ship in a seaway.

A first step has been to borrow from sea plane mechanics the fundamental theory due to Wagner; however, quite a bit remains to be done to arrive at quantitative results in the case of a ship.

Special studies had to be devoted to the investigation of conditions under which "slamming" occurs. With regard to notation, by "slamming" we denote essentially impacts which act in a direction not too far from the vertical and mostly on bottom parts of the ship. However, important impact effects can arise in other cases, e.g. when a rather blunt forebody heads into steep waves, when green water on deck hits the bridge superstructure or when wave impacts are exerted on the side of the ship. All that is needed for the occurrence of such phenomena is a high relative normal velocity between a flat part of the ship and a free water surface bounding a considerable amount of liquid.

It is, therefore, preferable to restrict the use of the expression "slamming" to the "vertical effects" only mentioned earlier and to use the expression hydrodynamic impact as the more general concept. Reference is made to the work of V. Szebehely and collaborators at TMB [52], which rests on analysis, model experiments and full-scale research. Interesting experimental studies have been performed by Akita and Ochi [53].

Although approximate calculations have been made to determine the influence of elasticity on the impact process in seaplanes, no comparable work has been performed in ship theory nor has Cauchy's Law been observed when experimenting. Possibly this elastic influence may not be too large if ship bottoms have a reasonable rise of floor.

Apparently without knowing Wagner's work, Bagnold has developed a physically consistent qualitative theory of wave impacts on hydraulic structures, especially moles. He assumes that air cushions can be sealed off at vertical walls by breaking waves. These cushions may collapse. Such effects suffice to explain qualitatively the occurrence of large impacts as has been demonstrated by model experiments. There may be some parallelism with Japanese work hinted at by Akita.

By accepting such a mechanism it is possible to cope with boundary conditions at a wall in a manner which is at least physically consistent, although the present writer does not see unsurmountable difficulties in assuming the rise of large impacts due to shallow water wave momentum by direct water action only.

5. *Full-Scale Experiments and Trials*

We distinguish between 1) collection of data on ship behavior on board a ship without ample instrumentation, and 2) full-scale experimenting in the proper sense, which is performed by competent staffs using adequate instruments, and which, at least occasionally, can rely upon special trials.

We list some purposes of full-scale experimenting:

a. Collection of statistical data on the seaway, on ship motions, accelerations, impacts, speed including propeller and engine performance, pressures, stresses etc.

b. Determination of *limiting* values of some items mentioned which can be admitted from the point of view of safety and seakindliness. For example, the establishment of upper *limits* of permissible acceleration has to rely almost exclusively on full-scale experience at least at present where facilities similar to those used in flight research are not available.

c. Exploration of effects so far unknown caused by the seaway.

d. Check of results obtained by analysis and model research under actual conditions; investigation of scale effects.

e. Acquaintance of scientific staffs with actual conditions and ship operation at sea.

As an example of the first approach we mention a rather wide enterprise organized by the Hamburg Tank before the last war. Results obtained contributed some general information which to a certain extent was deduced earlier from the simple linear differential equations. An attempt was made to classify ship behavior as a function of a vertical prismatic coefficient which agrees with our present ideas on damping properties of hulls.

a. Earlier, full-scale experiments on the M. S. "San Francisco" became famous. The ship was adequately staffed and instrumented. However, because of lack of experience, no thorough theoretical and experimental preliminary work was accomplished in the field of hydrodynamics before starting the expedition. Nonetheless, the trip was successful, mainly for two reasons:

1. the extreme luck that, close to the end of the voyage, exceptionally heavy seaways were encountered.

2. the outstanding ability of one of the leaders of the expedition, in interpreting experimental data obtained in the field of strength of the ship.

b. Such luck was absent in the case of the "Ocean Vulcan". Although investigations extended over a long time, the ship was lavishly instrumented, the scope of data obtained especially with respect to pressures is ample, and its evaluation is exemplary—no revolutionary information resulted from these thorough tests. Probably the comprehensive Report 8 [50] is being more frequently consulted because of its beautiful diagrams based on rather exhaustive routine computations than because of the experimental material collected. Further, the author's attempts to consider the influence of non-linear effects deserve attention.

c. Similar remarks apply to the Japanese report on the "Nissei Maru" [54]. Although interesting data on power, oscillations and stresses have been collected, the piece de resistance are model experiments designed to elucidate the full-scale work.

Since statistical methods have not been used in all three cases so far discussed, the latter must be considered obsolete from a methodological standpoint.

d. Modern investigations in this sense are being conducted by the David Taylor Model Basin and other agencies in this country.*

e. A prototype for future full-scale research has been supplied by Cartwright and Rydill by their recent paper "The Rolling and Pitching of a Ship at Sea" [40]: For the first time a satisfactory correlation between seaway and ship motions, which earlier investigators have aimed at, has been reached. The statistical aspect used is somewhat different from that proposed by St. Denis and Pierson and by Woznessensky insofar as it is based from the beginning on Fourier series—an approach, the validity of which has been questioned by the authors quoted.

Cartwright and Rydill show how some modes of ship motion can be related to the seaway. Waves have been measured by a ship-borne wave recorded [56]; the analysis is primarily based on an automatic Fourier analyser. To check theory, linear equations of motion are used in a "simple" and "advanced" form. Both are based on the Froude-Krylov hypothesis. Only roll and the coupled pitch and heave motions are treated, for arbitrary heading angles.

Numerous graphs show the comparison of results obtained by experiment and calculation. The agreement is from reasonable to good, especially considering the fact that basic parameters had to be estimated.

The statistical results are thought by the authors to be just as important as the spectral analysis. Almost any aspect of the motion of the ship can be dealt with in statistical terms once the connection between the energy spectrum and the statistics has been established.

The determination of damping by auto-correlation following Tukey deserves attention, and a proof is given by the authors that the auto-correlogram under special conditions coincides with the extinction curve.

6. *Seaworthiness of the Hydrodynamic Class of Vessels*

So far we have considered displacement ships only, because of the overwhelming importance of this class of vessels. However, from the viewpoint of future development, this attitude is not correct. A consistent theory should be able to furnish information on the inherent seaworthiness qualities of all existing classes of ships. We are still far from this goal.

While in the field of aircraft building there is a strong correlation between research and development, the hydrodynamic class of vessels—planing and hydrofoil boats—has for a long time been developed widely by a trial and error procedure. This applies especially to gliding craft; but even in the case of the hydrofoil boat, the success of which depends to a large extent on its seaworthiness qualities, the rate of investment of scientific work did not correspond to the importance of the task.

We review briefly the status of our knowledge of the behavior of hydrofoil systems in a seaway.

Even accepting the most drastic simplifications as to hydrodynamic effects involved (quasi-steady conditions) the problem is tedious because of the large number of significant variations: wholly submerged and piercing hydrofoils, number of foils and distribution of lift amongst them, the air gap between the bottom of the hull and the free surface in planing conditions, elastic cushioning etc. Model experiments yielded a decisive superiority of hydrofoil craft in a head sea over high-speed displacement and

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* After completion of this report an important paper has been presented by Jasper before the SNAME [55].

semi-gliding and gliding boats. Because of difficulties in experimenting they were seldom conducted in a following sea.

We mention first an elementary investigation on the behavior of hydrofoil systems in heave and pitch motion [57]. Assuming that we have at least two foil systems (at the bow and at the stern) we easily see that the coupling of heave and pitch is an essential feature of the problem involved. Expressions for the natural periods and the damping are readily obtained; the latter can be made much stronger than with displacement ships. This has to be considered an advantage of the hydrofoil principle. Conditions are in general less favorable in a following sea, the main reason being the direction of the orbital velocities.

Transverse stability of piercing foil systems so far has not caused much trouble. Experience has shown that it is easy to cope with the problem of roll; so little has been done in this direction.

At present a thesis is being prepared which deals with all six degrees of freedom, the hydrodynamic part of the investigation being kept as elementary as possible.

One can expect that such theories may serve at least as guide for planning experiments. Investigations of this character may be linked with those on displacement vessels with fins, and may yield a valuable extension of our knowledge on future lines of development of high-speed seaworthy vessels. Another important sideline is the connection with seaplane research.

Quite recently an important step forward in the field of hydrofoil theory has been made by P. Kaplan [58]. The theory developed by him refers to unsteady motions of a completely submerged foil of infinite span near a free surface. Explicit results are given for the lift force and mean wave drag for two important special cases, assuming a constant speed of advance:

1. foil performing harmonic heaving oscillations in calm water.
2. foil advancing rectilinearly, head-on under sinusoidal waves.

The amplitude of lift force is rather frequency dependent. Values obtained by quasi-steady considerations grossly overestimate the actual conditions even at moderate Strouhal numbers.

It is to be expected that this theory, notwithstanding its limitations, will prove extremely useful in promoting hydrofoil boat development.

By far the largest part of our scientific knowledge concerning planing vessels (hydrogliders) is due to investigations on seaplane performance.

So far no theory exists of the behavior of hydrogliders in a seaway and literature on experiments is extremely meager also. It is imaginable that useful results can be developed from the impact theory due to Wagner, and such a theory supported by experiments should enable us to reach conclusions as to advisable dead rise angles, L/B ratios etc.

The present writer does not consider this task especially important since it is obvious that planing vessels must remain much inferior to hydrofoils with respect to seaworthiness. It is recommended, however, that the hydroglider problem be treated as a byproduct of research on hydrofoil and Archimedean vessels.

II. THE SIGNIFICANCE OF RESEARCH RESULTS FOR DESIGN

1. *General Remarks*

Recently in a technical journal engineers were described as people toiling over meager problems left over by physicists and mathematicians and frequently suffering from an inferiority complex.

Because physics is developing with increased speed in its "central" part, many classical problems like hydrodynamics and theory of elasticity, are left aside and taken over by engineering sciences. In addition, however, engineers have to fulfill other tasks, for example, to consider and coordinate the multitude of problems arising in a technical field and to evaluate and interpret results in such a way that they can be used in design. The extensive algebraic, numerical and experimental work needed to establish quantitative relations and to appraise the importance of various parameters is a necessary prerequisite for making suggestions which may lead to an increasing safety and seakindliness of ships. There should be no inferiority complex about such kind of endeavours.

Lack of systematic evaluations is one reason for the wide discrepancy between scientific activities and the limited amount of their application, and contributes to the fact that the determination of seagoing qualities, except for roll, rested more on opinion than on knowledge.

As pointed out already, International Safety Regulations for passenger ships are restricted to elementary considerations only on longitudinal and transverse stability, especially in damaged condition—an insufficient approach.

It is utterly futile to search for coherent scientific ideas underlying present cargo vessel *freeboard regulations,* upon which the vessel's safety depends to a large extent. *Faute de mieux,* one would expect that there exists at least proportionality between freeboard f and length L of similar ships; but actually the freeboard ratio f/L for smaller ships, following tables, can be lower than for bigger vessels, although the former are much more imperilled by short waves which possess higher steepness ratio than longer ones.

Worse than that, safety considerations were sacrificed to arbitrary requirements presented by tonnage regulations. Open spaces with tonnage openings (and in earlier times scuttles) were an affront to common sense.

Under such circumstances it becomes understandable that the distinguished work of experimenters like R. E. Froude, [59] Kent, and Kempf, although aimed at immediate application, did not find the deserved response in practice, especially commercial practice. At the VII International Towing Tank Conference even a loss of experience in the experimental field was stated.

The lack of interest in theoretical findings is clearly demonstrated by the fact that apparently nobody objected over a long time to the inconsistency of period formulas for heave and pitch calculated without the added mass effect.

The narrow concern with the calm water resistance once led to the development of extremely U-shaped forebody sections with flat bottom parts; a design which was disproved by continuous damages due to slamming.

We have here purposely assumed an aggressive tone when dealing with the conditions in a not too distant past, because in our opinion an appeasing attitude towards irrational regulations has seriously hampered progress.

Obviously, there are inherent difficulties in dealing with our problem from the designer's point of view. It is already a task to appraise the importance of seakindly performance as compared with other postulates in design. The viewpoint of *enlightened practice* has been presented in discussions to Ref. 5. Researchers should consult a paper by Kent [7] which gives an interesting aspect of the problems.

In what follows, frequent reference will be made to work by E. Lewis [5], [60], [61]. We can slightly amplify a list of topics enumerated by him, some of which may be considered as criteria of danger:

1. Shipping green water,
2. Large displacements, especially angular displacements, due amongst other reasons to loss of stability in waves,
3. Impacts, especially slamming,
4. Large accelerations,
5. Conditions leading to high stresses, especially girder stresses,
6. Resistance increase,
7. Loss of steering properties.

To determine ship characteristics which guarantee a good behavior in a seaway, we need a complete survey of all ship motions. This exceeds by far the scope of the present paper. Our aim is rather to indicate simple methods which, duly extended, will enable us to meet requirements of present and future practice. We shall restrict ourselves to some remarks on roll, heave and pitch. Future extension in knowledge will modify the procedure and results here indicated.

2. *Transverse Stability and Roll*

Froude's work on roll has been widely used in design. The importance of the tuning factor Λ and of the factor of magnification μ with its dependency upon damping has been clearly understood. However, because of limitations of the linear theory more advanced considerations must be introduced to cope with the safety problem. A most urgent task is to evaluate the influence of the shape of Reed's diagram on the behavior of a vessel. So far this question has been discussed on a hydrostatic basis only.

Even such an elementary approach shows that there may be an appreciable loss of "stability" (restoring moment in roll) in waves under certain conditions [62]. Thus *minimum* requirements for the metacentric height and the curve of righting arms (Reed's diagram) derived from calm water conditions and from some statistical information must be raised, especially in the case of smaller cargo ships.

A standardization of the minimum values of stability parameters will rest on future research dealing with the actual pressure distribution around a rolling ship and the non-linear character of roll prevailing at large angles.

Valuable information is now being collected on damping as well as exciting forces. There is a tendency at present to underestimate the bearing of such scientific activities on the design of ship hulls because of the application of antirolling devices. It should not be overlooked, however, that an adequate understanding of the hydrodynamic phenomena involved may be a prerequisite for a successful development of stabilization. Reference is made to various effects mentioned before, especially the sway-roll effect; earlier lack of knowledge in this field has caused serious setbacks.

The present state of roll stabilization can be described by quotations from a paper by Chadwick [17]:

1. "the technical feasibility of stabilization is an established fact"
2. "the control system no longer should prove a limitation on system performance." Ideas are being developed at present to recover some of the seaway energy for stabilizing purposes.
3. "At least some feedback control should always be used. Arguments for feedahead control, predictors, etc. have largely been negated by advances in control technology." This statement, if corroborated, would dispose of the attempts of a school of thought which preached the superiority of feedahead control.
4. "For stabilization at speeds of 15 knots and above activated fins provide the most efficient system. Tanks and gyros are still worthy of consideration in low speed application." This assertion again practically means the victory of fins since there is not too much interest in low speed application.

We refer further to two principles of stabilization which we consider as important notwithstanding some doubts expressed [Ref. 17, discussion]:

1. with respect to the true horizon,
2. with respect to the effective wave surface;

the first one being the natural solution for men of war, the second presenting advantages for passenger vessels. Recently these ideas have been generalized [63].

3. *Heave and Pitch*

After a brighter outlook has been gained in the case of roll the primary interest is now concentrated on obtaining favorable "symmetric" motions (pitch and heave).

3.1. *Basic Consideration*

It is much to the credit of E. Lewis [61] that he had the courage to recommend rules for design derived from elementary theoretical findings including considerations yielded by the modern irregular seaway theory. His paper contributed numerous results of immediate value for practice.

Although we accept E. Lewis' work as basic, there are some reasons to reconsider the heave and pitch problem.

1. E. Lewis intentionally does not consider the influence of the longitudinal displacement distribution (more correctly, the shape of the load waterline) on the exciting forces for given main dimensions of the ship. This is, however, one of the few dependencies which can be investigated with some confidence within the range of validity of the Froude-Krylov hypothesis.

2. The present knowledge of damping properties admits of more definite statements although we are still far away from an exhaustive solution of the problem.

3. Objections have been raised against the choice of Taylor's displacement-length ratio by several writers including the present one. Let us consider the question once more.

The use of the parameter D/L^3, consecrated by resistance research, has undoubtedly led to a preliminary orientation in the new field, since for fixed displacement, this main form parameter successful shows the importance of length. For detailed work, however, one should avoid merging several characteristic form parameters into a single one.

The present survey is based on the simple Equations (1) and (2) and their solution for forced motions. Exciting terms can be corrected using the relative motion concept.

For our present discussion, which remains within the linear range, the wave length λ is the most interesting characteristic, although height (steepness or slope) obviously becomes equally important when limiting values or accelerations have to be considered.

Let us first collect some basic, useful formulae.

Frequencies of encounter:

$$\omega^* = \omega_0^*(1 - F\omega_0^* \cos\chi) \qquad (17)$$

Tuning factor:

$$\Lambda = \frac{\omega_0^*}{\nu^*}(1 - F\omega_0^* \cos\chi) \qquad (18)$$

Amplitude ratios:

$$z_m^* = \frac{z_m}{r_m} = E_z(\lambda^*, y^*)\mu_z(\kappa_z, \Lambda_z)$$

$$\psi_m^* = \frac{\psi_m}{\theta_m} = E_\psi(\lambda^*, y^*)\mu_\psi(\kappa_\psi, \Lambda_\psi) \qquad (19)$$

Phase lag:

$$\tan\xi = \frac{\kappa\Lambda}{1 - \Lambda^2} \qquad (20)$$

Damping:

$$\kappa_z = \frac{N_z}{\rho\sqrt{V'_z A_w g}} \qquad (21)$$

Magnification factor:

$$\mu = \frac{1}{\sqrt{(1 - \Lambda^2)^2 + \kappa^2\Lambda^2}} \qquad (22)$$

In what follows $\cos \chi$ will be put equal to -1, since the essential procedures can be demonstrated by considering the ship heading directly into waves.

Following traditions in naval architecture wide use use can be made of graphical representation.

As first item we consider the tuning factor. Although the discussion of the latter represents a large part of the "theory" of roll, quite a bit remains to be done in the present case. There is occasionally some confusion about the supercritical range of ship operation due to the fact that for a given T the tuning factor can become greater than unity either because

$$\omega_0/\nu > 1$$

or because (23)

$$1 + \frac{\mu}{c}\left(= 1 + F_{\omega_0}{}^{*} \right) \text{is large.}$$

Obviously, when advancing in short waves the supercritical condition is the natural one for larger ships. This case is, however, in general not interesting because of the insignificant effects involved. The supercritical state becomes a problem in long waves only.

To answer our problems we need:

1. The equation of the hull $y(x, z)$, L, B, H, and the mass distribution. Call $y^* = y/L$.

2. Natural periods T_z, T_ψ or frequencies. For simplicity we neglect here the dependence of T upon ω^* (and a fortiori upon F), so that $T = \text{const}$. However, when exploring new conditions (high speeds) it may become necessary to consider $T(\omega^*)$ as variable. In any case reasonable data are available to calculate T by a strip method and applying corrections.

An experimental determination of period and damping is recommended in model research as a necessary prerequisite, notwithstanding the difficulty due to the evaluation of pertinent extinction curves.

3. Curves of damping in heave and pitch.

We can assume $\kappa = \kappa(\omega^*, y^*)$ neglecting the dependency upon F. κ is best calculated by a strip method introducing corrections when ω^* is small. As in the case of period calculations the appropriate frequency parameter in general is $\omega_B{}^* = \omega\sqrt{B/g}$. The conversion to $\omega^* = \omega\sqrt{L/g}$ requires care. For the present purpose we use curves in Fig. 1 and some averaged results. It appears fortunate that in the range of resonance $\omega^* = \nu^* = 2.5 \rightarrow 5^{(5)}$ we are not too far from the peak of the damping curve when the lower values of ν^* apply. This may be the case, for example, when large mass moments of inertia (in the supercritical range) are admitted. For large ν^* ($\nu_B{}^*$) the decline in damping can become noteworthy.

To avoid confusion the *dimensionless* coefficient κ should be used for discussions of this kind.

The interval in which damping represents a *decisive* factor, say

$$0.6 \leqslant \Lambda \leqslant 1.2 \qquad 1.5 \leqslant \omega^* \leqslant 6 \qquad 0.5 \leqslant \omega_B{}^* \leqslant 2$$

is large but nonetheless not excessive. There has been, naturally, a concern about a possible loss of damping power when one departs strongly from present practice. It turns out now that this loss can be safely estimated and does not become prohibitive when ν^* is properly chosen.

Particularly, the range of frequencies where three-dimensional effects are pronounced, $\omega^* \leqslant 2.5$ for heave and $\omega^* \leqslant 3$ for pitch, lies normally at the border or outside of the synchronism zone. The most important task at present appears to be to obtain consistent functions $\kappa(\omega^*, y^*)$ which allow us to calculate the influence of all important form variations.

4. We assume the curves of exciting force coefficients E_z, E_ψ as known, although explicit data for the diffraction effect are not yet available. For the present purpose the Smith effect and the relative motion correction can be included; in principle the second correction requires the use of Equation (2).

The functions E allow us to deal with any wave component constituting the irregular seaway, hence by superposition with the total seaway.

The curves E_z, E_ψ show that it is possible to consider $\lambda^* = 1$ as a significant point for determining the *character* of heave and pitch for two reasons:

1. firstly, the point $\lambda^* = 1$ lies in the final region of large wave effects;
2. secondly, the maximum steepness of the E_ψ curve occurs actually in the range $0.9 \leqslant \lambda^* \leqslant 2 \rightarrow 2.5$, although magnitude and slope strongly depend upon the shape of the waterline (the coefficient α). However, *quantitative* data so obtained cannot be widely generalized.

The analysis of ship motions can be conducted as follows [51, 5]:

We start with the relation $\Lambda = \frac{\omega_o^*}{\nu^*}(1 + F\omega_o^*)$ and plot a diagram of the function $\omega_o^* + F\omega_o^{*2}$.

Resonance conditions are found from

$$\nu^* = \omega_0^* + F\omega_0^{*2}, \tag{24}$$

yielding the critical value for ω_0^* or

$$\lambda^*_R(F) = \frac{2\pi}{\omega_0^{*2}}. \tag{25}$$

For $F = 0$

$$\nu^* = \omega_0^*, \tag{26}$$

so that

$$\lambda^*_R(0) = \frac{2\pi}{\nu^{*2}} = \frac{T^{*2}}{2\pi}. \tag{27}$$

$\lambda^* R\ (0) = \lambda^*_R$ is a characteristic value for a given ship, $\nu^* =$ constant, indicating the wave length ratio at which synchronism occurs in the hove-to condition [51].

Assuming

$$1.2 \leq T^* \leq 2.5, \quad \text{or} \quad 5.2 \geq \nu^* \geq 2.5, \tag{28}$$

one obtains

$$0.23 \leq \lambda_R^* \leq 1. \tag{29}$$

The reasoning can be easily extended to cope with the general case. Resolving (21) with respect to F one obtains the critical Froude number

$$F_R = \frac{\nu^*\lambda^*}{2\pi} - \sqrt{\frac{\lambda^*}{2\pi}} \tag{30}$$

Curves can be drafted to show the dependence of the critical Froude number F_R upon λ^* with ν^* as parameter. The strong variability of F_R with ν^* is obvious.

The curves $F_R\ (\lambda^*, \nu^*)$ divide the subcritical from the supercritical range.

To investigate the behavior of a *given* ship, one proceeds as follows:

1. $\kappa(\omega^*)$ and μ can be plotted versus ω^* and Λ.
2. Exciting functions E_z and E_ψ are calculated and represented ,in the form $E\{\gamma\} = E\ (\lambda^*) = E\ [\omega^*]$.

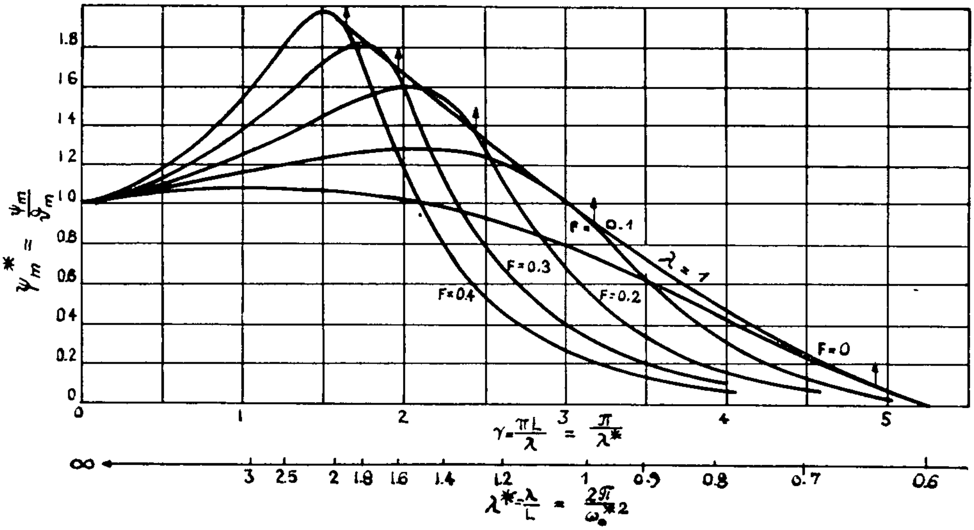


Figure 3. Schematic diagram. Dimensionless pitching amplitude $\psi_m{}^* = \psi_m{}^*(\lambda^*; F; \Lambda)$, $\nu^* = \pi$.

3. Three forms of amplitude ratio diagrams can be derived.

a. $z_m{}^* = z_m{}^*(\lambda^*; F, \Lambda)$,

i.e., $z_m{}^*$ (or $\psi_m{}^*$) as *function* of the wave length with F and Λ as parameters [51] (see Fig. 3),

b. $z_m{}^* = z^*(\Lambda; F, \lambda^*)$.

Such a complete diagram has been first established by Gawn using experimental results [51]. See Fig. 4.

c. $z_m{}^* = z_m{}^*(F; \Lambda, \lambda^*)$. See Fig. 5.

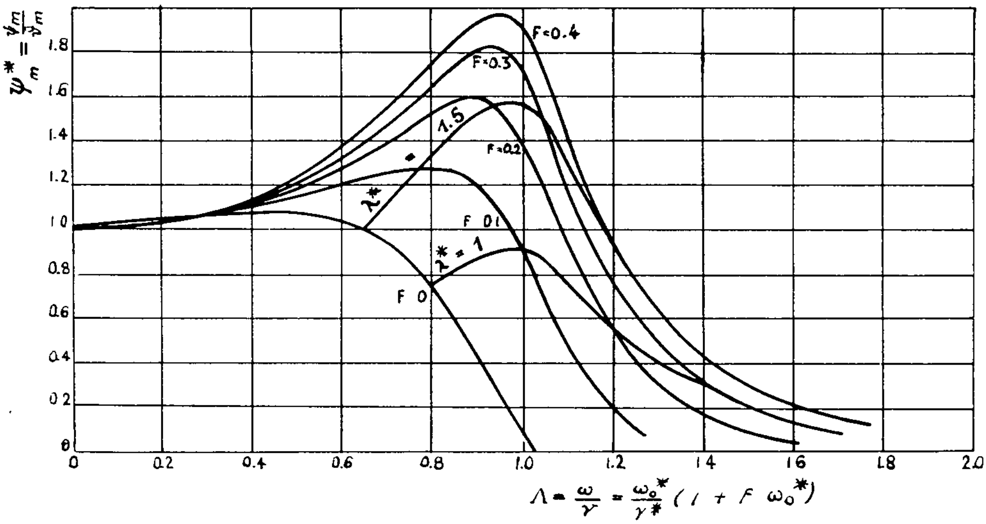


Figure 4. Schematic diagram. Dimensionless pitching amplitude $\psi_m{}^* = \psi_m{}^*(\Lambda; F; \lambda^*)$, $\nu^* = \pi$.

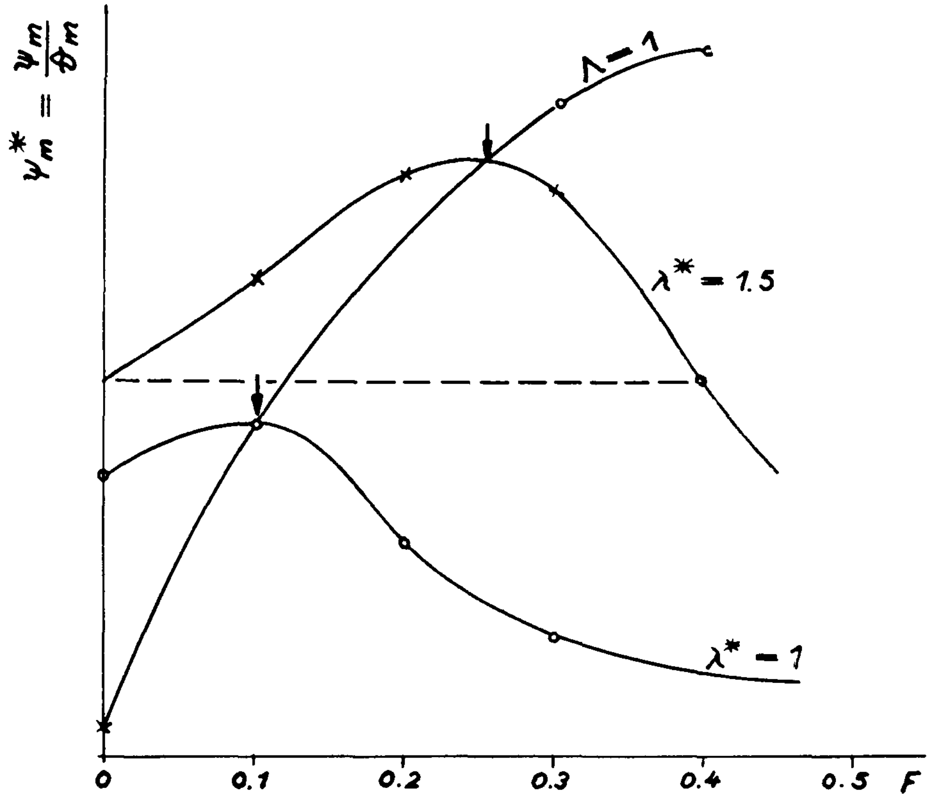


Figure 5. Schematic diagram. Dimensionless pitching amplitude $\psi_m^* = \psi_m^* (F; \lambda^*; \Lambda)$, $\nu^* = \pi$.

It is now customary to plot model results in the form

$$z_m^*(\Lambda; \lambda^*) \text{ or } z_m^*(F; \lambda^*),$$

i.e., to investigate the ship motion in a given seaway λ^*, as function of Λ or F.

This settles the question for a given ship.

4. Using such diagrams, the influence of variations in mass distribution and form can be investigated.

In particular, if the hull form is kept constant, the influence of changing mass distribution is seen in these diagrams as the result of changing ν^*.

The chosen dimensionless form of representation lends itself when L remains constant. Another approach is more advantageous when L is varied.

3.2. *Inflence of Form Variations*

As example we discuss shortly the influence of variation of some basic ship parameters on heave and pitch motions. The procedure is similar to that used in an investigation on ship resistance [64]. It has the advantage of showing the need for systematic experimental information in this field notwithstanding the large amount of model work completed. Only large values of λ^* are considered. We treat several cases:

1. *Principal dimensions constant.* $J_y \simeq$ const. "V" versus "U" sections (increase of α).

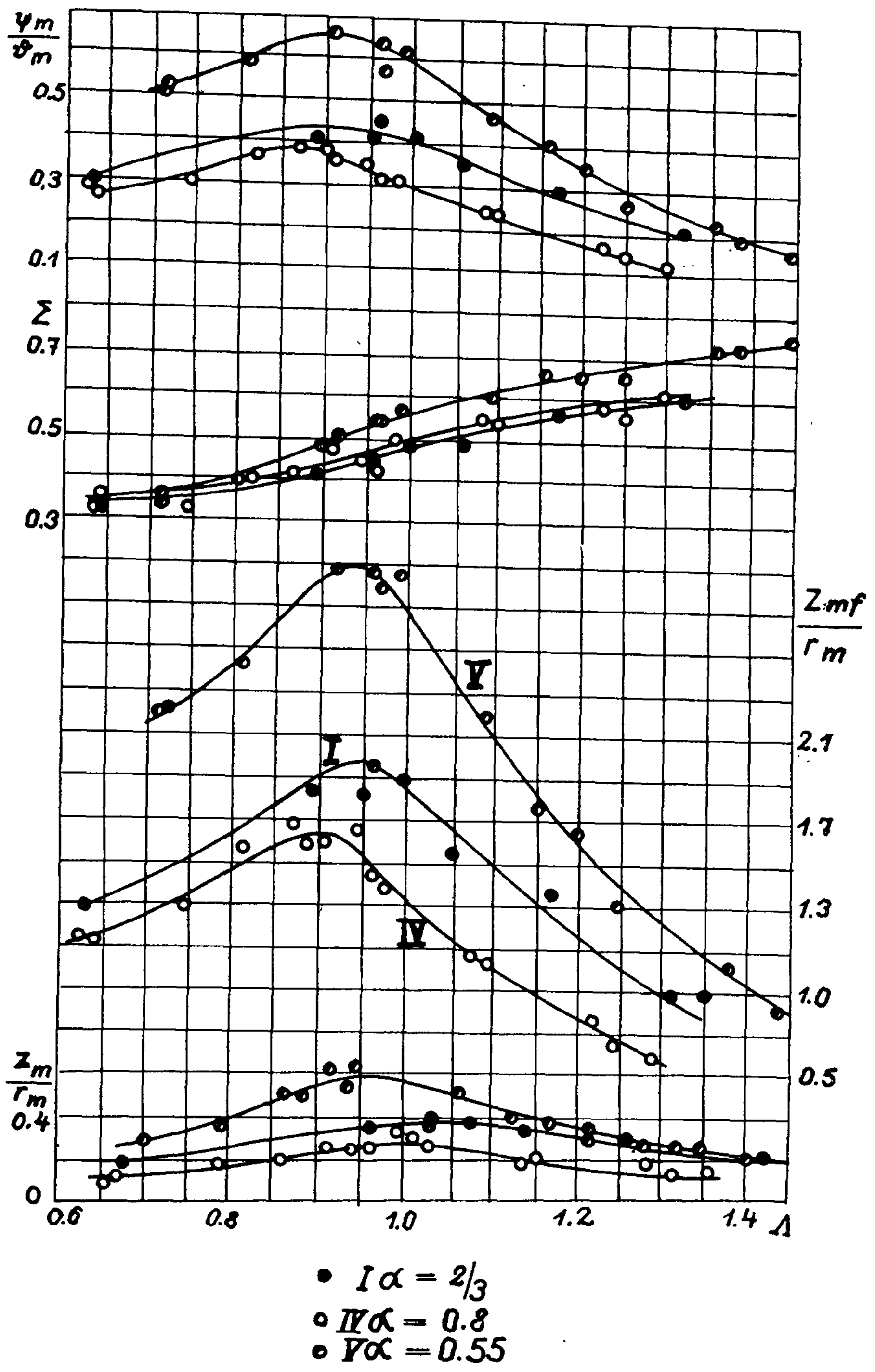


Figure 6. Dimensionless amplitude of pitch, heave, and motion of the stem, z_{mf}/r_m, for models with differing α. αH = constant, V constant, $\lambda^* = 0.815$.

The clear advantage of "V" sections established several times can be explained by 1) the *increase* of κ_z and κ_ψ which vary roughly as α following some approximate calculations, and by 2) the *decrease* of the *exciting functions* E_z, E_ψ. On the other hand, differences in natural periods T_z, T_ψ may be unimportant.

2. $L =$ const., $B =$ const., $J_y =$ const., $\alpha H =$ const.

We discuss this somewhat artificial assumption since it has been tested using 3 wall-sided, flat-bottomed models with $\alpha = 0.533$, ⅔, 0.8 to check Haskind's damping formulas [65]. See Fig. 6. Models with higher α (larger A_w and still larger I_y) experience much less motion at $\lambda^* = 0.815$ as well as $\lambda^* = 1.33$.

The explanation again is obvious, exciting functions and damping working in the same direction.

Natural periods disclose a somewhat erratic behavior which seems to be of no great moment; unfortunately, however, nothing has been said about the *wetness* of models.

Slamming, which will undoubtedly affect the very shallow full models, limits the practical applicability of results beyond the statements made with respect to damping and exciting forces.

3. Affine *distortions* of the *set* of *lines,* first so that $L =$ const.; $BH =$ const. An *increase* of B and, therefore, decrease in H leads to a slight reduction in natural periods, but the most important change is the strong *increase* in *damping* coefficients.

The exciting forces are slightly *increased* due to a smaller Smith effect, but *decreased* due to a larger relative-motion (diffraction) effect, the net balance probably being close to zero. Thus, motions are reduced; however, the advantage may be destroyed by adverse impact effects.

4. Affine distortions of lines, with variation of length, such that $LB =$ const., $H =$ const. Let us consider two cases for which L is *increased* by decrease in beam L/B being strongly increased:

4a. $J_y =$ constant.

Again, this artificial case is considered because systematic experiments have been made on damping properties of three affine models C_3, C_2, C_1 with L/B ratios 5, 7.5, 10.

Heaving periods T_z are not too much affected by the variations (decrease in added mass), pitching periods vary approximately as $\sqrt{I_y}$ where I_y is the moment of inertia of the waterline.

Keeping $\lambda =$ const such that $\lambda_3^* = 1.15$, $\lambda_2^* = 0.94$, $\lambda_1^* = 0.815$. z_m^* and ψ_m^* decrease heavily with increased length because of the decline of the exciting functions $E(\lambda^*)$. Beside, an increase in phase lag indicates stronger damping in pitch for C_2 and C_1. See Fig. 7a.

Fig. 7b shows a more interesting comparison at a constant $\lambda^* = 1.33$.

The reduction of pitching motion for the longer models is due to an *increase* in the *dimensionless* damping coefficient in agreement with theory.

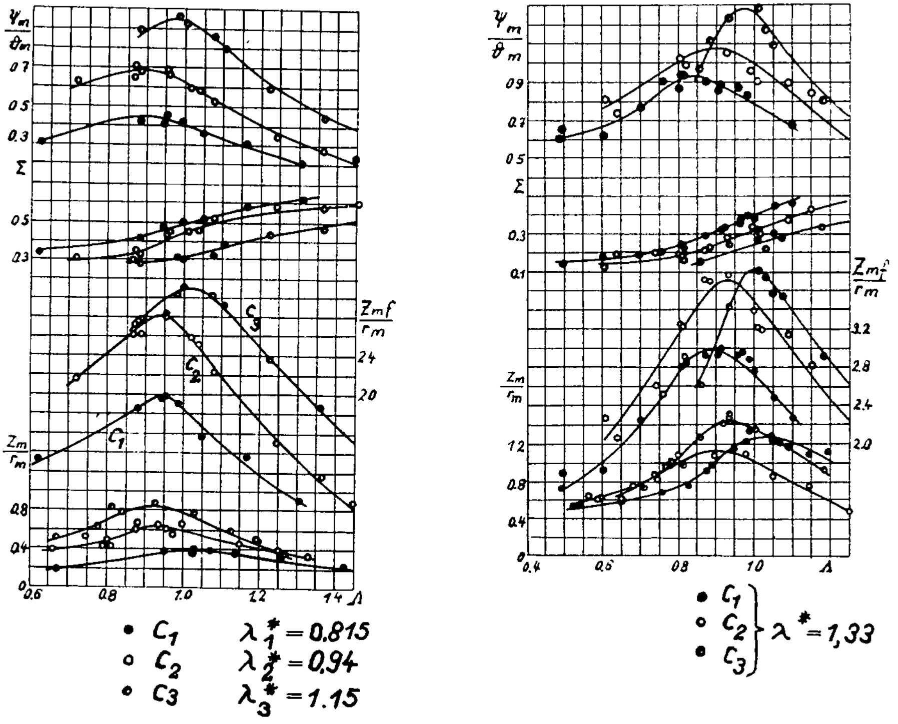
The heaving diagram cannot be satisfactorily explained by present theoretical reasoning.

4b. J_y variable, $\dfrac{J_y}{I_y} \approx$ constant.

Natural periods are slightly reduced.

As under 4a. the *dimensionless heave* damping may be reduced and the same applies now to *pitching* although the absolute damping coefficient increases strongly with length.

The advantage of the form variation under consideration consists in the fact that, keeping the speed of advance constant, resonance for a longer ship occurs almost in the same seaway since T_ψ remains almost constant. This means a reduction in λ_R^* and thus amplitude ratios z_m^*, ψ_m^*.



(a) (b)

Figure 7. **Dimensionless amplitude of pitch, heave, and motion of the stem for models of differing length and waterline moments of inertia. V = constant, J_y = constant.**

(a) λ = constant. (b) λ* = constant.

5. A length *increase* with LH = constant and low, B = const., while the longitudinal mass distribution remains affine, involves

1. a moderate decrease in T_z and T_ψ, and
2. a slight increase in dimensionless damping κ_z and κ_ψ.

Resonance occurs at somewhat lower wave length λ, and λ_R^* is still further decreased as compared with 4.

The discussion can be, obviously, conducted in such a way that the advantages of lengthening with respect to higher speeds of advance are demonstrated.

6. Finally, it can be considered as well established that the *bulb* has no detrimental effect on motion performance [66], [31], [61].

These findings throw some light on the merits of the analysis by E. Lewis based on the parameter D/L^3. Although effects are lumped together which follow different laws corresponding to B/L, H/L, α and δ variations, the overwhelming importance of the length dimension is clearly borne out by plotting results versus Taylor's parameter. To this extent, E. Lewis' synopsis, intended to cover the whole range of normal ship types, is justified. On the other hand, investigations on the sea performance of a given type require a more detailed approach.

We have seen that a ship with normal proportions and mass distribution will meet resonance in the hove-to conditions at λ_R^* well below unity.

At finite speeds the supercritical range is extended to larger λ_R^*. Theory and experiment show that absolute motions can be small in the supercritical range; phase relationship and accelerations require a special investigation. When sufficient power is available to cross the resonance barrier in waves of larger $\lambda_R{}^*$, it can be advantageous to extend the supercritical range as far as possible by increasing natural periods. The means leading to this goal are large $\frac{H}{L}$, large $\sigma = \frac{\delta}{\alpha}$, large mass factors. The penalty which one has to pay consists in a pronounced deterioration of qualities in the resonance condition [10].

3.3. Wetness

Relative motions of the ship with respect to the water surface rather than the absolute motions, determine wetness. Naturally, the corresponding equations should be used, although this so far has not been done in general.

A lot of experimenting has been carried out on wetness. Using the standard steepness ratio $\frac{h}{\lambda} = \frac{1}{20}$, very unfavorable conditions are obtained in larger waves in the neighborhood of synchronism.

For a better understanding of the matter it is advisable to test models at lower steepness ratios where the assumption of linearity still holds and comparison with the existing theory is justified.

Again, only a small amount of *systematic* work based on such comparison has been performed. Szebehely [52] found that the present theory yields a useful guide for slamming investigations but that quantitative agreement between results of measurements and calculations is frequently lacking. Vladimirov [67] improved the prediction of wetness phenomena by adding wave effects, calculated for the speed of advance in calm water, to the surface of the sea. The theoretical determination of *phase angles* which is decisive in this kind of research is not too reliable. Further, the distortion of waves caused by the advancing and oscillating ship cannot yet be calculated by our present elementary approach. Earlier inspiring attempts by Kreitner, are based on rather arbitrary assumptions.

In the subcritical range the relative motion of the ship with respect to the corrugated water surface improves at large λ^*. The question arises as to what criteria should be used for activated pitch stabilization—a problem which becomes urgent at present after reasonable suggestions have been made some twenty-five years ago to use fins.

An increase in damping tends to tie up the ship with the wave surface in larger waves which appears to be a reasonable answer in the subcritical zone. In fact, for a phase angle $\varepsilon < 90°$ it can be shown that the most favorable results with respect to wetness can be obtained at the bow when the linear motion amplitude $Z_{mbow} \overset{.}{\approx} r_m \cos \varepsilon$. When $\varepsilon > 90°$ the best answer is "horizontalization" i.e., $\psi_m = O$. This seems to settle the question.

4. Hydrodynamic Impacts

At present, this topic has been so frequently discussed [4], [5], [52] that we can restrict ourselves to few remarks only.

The following form characteristics appear desirable to avoid hydrodynamic impacts:

1. high rise of floor at the ends, especially at the bow,
2. sufficient draft, again primarily at the bow,
3. moderate angles of entrance at and above the waterline,
4. moderate, not excessive, flare in the forebody (St. Vincent),
5. to combine conditions 3. and 4. a clipper stern is advantageous,
6. high freeboard and sheer, including a forecastle to keep the deck free from impacts by green water. The forecastle should be designed with respect to horizontal impacts (for example, whale-back).

The difficulties due to slamming experienced in ballast condition have been emphasized by several writers; Akita has pointed out at the detrimental influence of a flat stern in this case [53].

Heavily raked stems appear advantageous only if the wedge angle of the sections at the centre plane is not too high.

The proper design of superstructures, hatches, wave breakers etc. in the forebody must be kept in mind.

To investigate impact properties of the hull above the waterline at high sustained sea speeds, especially in unfavorable phase conditions, it is suggested to develop a model, the lines and superstructures of which are designed primarily from impact considerations, and to compare such a model with a normal form. A similar proposal intended to reduce the excessive air resistance of ship superstructures have been made some thirty years ago. All big "roughnesses" were stripped off the deck and the superstructures "streamlined". This exaggerated simplification inspired the designer of the "Bremen" to try a new look which was successful. The grave error committed by dropping the forecastle has not been suggested by the designer.

5. *Conclusions*

Since considerable efforts are being made at present (contrary to the earlier state) to elucidate our problems, it is appropriate to try to answer in a summary way the question: what will come out of present and future scientific endeavors in our field for shipbuilding and shipping practice?

1. It can be claimed that an understanding of general phenomena has been reached already by the applications of the extended Froude-Krylov theory. The overwhelming importance of the ratio $\lambda^* = \lambda/L$ is established.

2. The influence of principal variations of hull (dimensions, proportions and form), and of mass distribution on motions in regular waves can be investigated to a first approximation by such elementary means. A lot of actual work remains to be done.

3. The introduction of the modern irregular seaway concept has an important bearing on application in practice. Because of the presence of long waves in a fully developed heavy irregular seaway the appraisal of the length dimension undergoes some changes. Earlier suggestions to increase the length of our largest ships in such a way that the ratio $\lambda_{\max}{}^* = \dfrac{\lambda_{\max}}{L}$ remains noticeably smaller than unity are superseded. In general, the advantage of long ships as compared with shorter ones established by the regular seaway concept may be slightly reduced; however, this problem can be settled only when a satisfactory standard representation of irregular seaways will have been reached. There is no need, however, to prove the truism than on the average larger ships are more seaworthy than smaller ones and that from our present point of view lengthening constitutes an important means to improve motions and speed qualities.

4. Conditions are similar to those in ship resistance research. By trial and error good or reasonable solutions to numerous problems have been found. It is, therefore, probable that work directed to improve normal ship types will yield slow progress. It should be different when new solutions which depart from the established routine are sought for, as shown by E. Lewis when investigating effects of lengthening ships.

5. The Froude-Krylov theory is an inadequate tool to reconsider the problem of ship behavior from principle, with the purpose to develop ship types possessing optimum qualities, though its possibilities as a guide for design were not exhausted as shown recently by the discussion on the supercritical range of ship operation.

The present state of knowledge admits, however, the definite hope that the problem of optimization may become reasonable within the near future and may yield new basic results for design, though a damped optimism is the appropriate attitude when speculating in the field of an old profession such as ours. The fact that rather awkward phenomena have been explained and found by more advanced theories is promising.

The paper by Kent [7] indicates some practical problems which should be investigated. It will be quite a task to prove or to disprove his assertions as to optimum form parameters and characteristics, and to extend the research to similar problems suggested by practice.

6. It is expected that the present freeboard regulations will crumble under the impact of the present research impetus and that ship theory will contribute its share in shaping more reasonable ones. This alone will have a most beneficial effect by increasing the safety of small ships, the freeboard being a most decisive parameter. In the same way, it is hoped that the safety regulations for passenger ships will profit from results of research.

7. By the introduction of the irregular seaway concept reliable information will be obtained on the average performance of ships with respect to motions and resistance.

The development of new instruments for measuring the seaway promises to increase decisively the value of statistical investigations.

The problem of service speed can be brought nearer to a solution, and the possibility of appraising ship behavior in relation to other fundamental properties will be promoted. For example, data will become available which permit one to decide when stabilization is desirable.

Statistics will furnish data on permissible acceleration and contribute to a better understanding of safety limits, though, as mentioned earlier, knowledge from other sources is indispensable to solve this problem.

8. The overwhelming importance of damping has been frequently emphasized. Already the present solution of the problem enables the designer to act on a rational base when assigning proportions and forms, and further development will help us avoid presently unknown pitfalls similar to those indicated by Ursell. There is not too much hope for unexpected favorable solutions.

9. We made the same statement earlier, especially with respect to exciting forces. However, in the case of the roll motion where small changes in the decisive ship parameters can have large consequences, conditions may be different. Reference is made to Grim's finding on the possibility of reducing the exciting roll moment by reasonable form variations in the range of synchronism.

10. The feasibility and efficiency of fins having been established, a wide field is opened for their applications as means of control around all three axes.

11. A better understanding of conditions leading to improved maneuverability in a seaway will furnish design data to reach this goal and to increase thereby the safety of ships.

12. Although roll stabilization is developing successfully, the danger of capsizing, or rather of reaching large angles of heel, still requires further investigations. Proposals in this direction have been made over a considerable time but the work so far invested does not correspond in any way to the importance of the task.

13. The study of hydrodynamic impacts has now reached the degree of intensity which corresponds to its fundamental importance. The continuation of research on slamming and its extension to phenomena in a horizontal plane may decisively influence the design of high-speed vessels; it may lead to considerable progress in designing important details like the forebody, superstructures, rudders, etc.

14. Means to reduce motions will frequently lead to a reduction of resistance and improvement of propulsion conditions. Furthermore, when reflection effects are better understood suitable changes of form for influencing resistance directly may be found. Old dreams of inventors to influence ship wave generation by fins at the bow appear to be substantiated by recent investigations on performance in a seaway.

15. Although possibly a refined determination of extraneous forces (pressures) acting on the ship will not change basically the assumptions underlying the contemporary strength calculations dealing with the ship as a girder the whole problem will be

put on a safer foundation. The importance of the recent model work aimed at the determination of bending moments and shearing force cannot be overestimated from a point of view of practice.

More basic and revolutionary can be the contribution of ship theory when a large increase in ship speed is postulated. It is difficult to predict how strong a pressure will be exerted in this direction by navies, shipping and shipbuilding practice. It is, however, the obligation of science to appraise the possibilities and to prepare the necessary solutions.

16. The future of the development of hydrofoil vessels depends upon their seaworthiness. Much more work must be invested in this field. Beside its immediate significance it may have a considerable stimulating effect on advanced design of displacement ships especially with respect to fin action.

III FUTURE RESEARCH

1. Facilities

When describing a new large wind tunnel Betz denounced some twenty years ago the trend to increase the size of facilities as uninspiring, and asked (without success) for suggestions to stop this race. The development did not bring any relief in aerodynamics, and, generally speaking, in ship research.

After Havelock had disclosed that wave effects are the principal source of damping in heave and pitch the use of small models for seaway research, notable after the war, appeared justified. Minimum size models become especially desirable when arbitrary courses in a seaway are investigated. Unfortunately, the situation is less simple with self-propelled models which obviously present definite advantages.

It is the author's contention that the establishment of large wave tanks is justified provided the number (and stature!) of scientists connected with such a tank work corresponds to the size of these facilities. If only a limited amount of funds is available it is preferable to invest the money in researchers rather than in facilities.

Beside large tanks, however, there will be an increasing need for facilities intended to tackle special problems.

The scientific foundation of methods used in "General Wave Tank Work" will require a large number of special investigations.

From the synopsis presented it seems at first easy to make proposals for the future research by analytical methods, model experiments and full scale investigations. Certainly it is a more pleasant task to speculate about things which should be done by others than to do the work oneself; nonetheless the task presents difficulties.

Roughly speaking, research in our field is proceeding following two lines:

1. Development of ship mechanics.
2. "Rigorous" solution of the boundary problem.

The first way leads to a program of research. Problems presented in such a way can be solved experimentally as well as analytically, whereby more rigorous methods become more and more popular.

We enumerate now a list of concrete tasks which are being tackled or should be attacked; they embrace surface and submerged displacement vessels as well as hydrodynamic craft.

1. The establishment of general equations of motion of displacement ships in a seaway.

    1.1. Complete equations.
    1.2. Linearized equations.

As mentioned above this work constitutes a necessary prerequisite for systematic work in our field yielding a comprehensive program of research. Simplified problems which can be treated with success can be derived from this general task.

2. Determination of forces experienced by an oscillating body moving in calm water as substitute for the actual seaway problem, one and several degress of freedom.

Added masses, damping, coupling terms and resistance as functions of the frequency parameter and the Froude number.

3. Forces experienced by wholly submerged bodies moving arbitrarily in a non-uniform and non-steady field (Cummins' problem).

4. Rectilinear motions of bodies moving at or beneath the corrugated water surface. Pressure distributions. Diffraction effects. Exciting forces.

5. The two-dimensional problem of a ship moving in a regular seaway.

6. Ship moving on a straight course in a regular seaway.
Transverse stability in waves.
Directional stability in waves.
Appraisal of the method mentioned under 2.

7. Theory of resistance augmentation of a ship moving as under 6.
Appraisal of the method mentioned under 2.

8. Propulsion in a regular seaway.

9. Interaction between propeller and ship.

10. Nonlinear problems of roll.

11. Other nonlinear problems.

12. Study of severe transient conditions.

13. Irregular seaway. Correlation of model and ocean waves.

14. Full-scale investigations (tests) on ships. Limiting data for accelerations etc.

15. Reductions of motion by artificial means. Roll and pitch stabilization.

16. The general problem of speed increase in a seaway. Cavitation.

17. Manoeuverability in a seaway.

18. Development of ship forms with high damping qualities.
The influence of viscosity upon motions.

19. Development of ship forms which experience low exciting forces in a seaway. The investigation and appraisal of nonlinear effects.

20. Development of the theory of impacts following various assumptions. Horizontal impacts.

21. Development of ship forms under water, above the surface, on deck with respect to impacts. Theory of the behavior of hydrofoil craft in a seaway.

ACKNOWLEDGMENT

It was my aim to indicate the satisfactory scientific progress in our field and to emphasize that application of its methods and results to problems presented by practice can be made nowadays with much more confidence than before. The scientific problems involved are both interesting and fruitful. Notwithstanding the age of our profession we have by no means come to a blank wall, and there is no danger of the status of diminishing return in research work which may decisively influence the future development of the ship.

A wide gap has been left in this report with respect to problems presented by *resistance* and *propulsion* in a seaway due to reasons mentioned in the text which are partly of an occasional, partly of a substantial character. It must be repeated that special efforts are needed to promote solutions of these problems, which recently have been somewhat neglected except by Japanese scientists. With respect to problems presented by the irregularity of the seaway, reference is made to numerous excellent papers published in this country.

It is my opinion that because of the ample scope of the subject and the fast rate of development, it is rather difficult for a single person to cope adequately with the problem. The kind support given by the initiators of this symposium and by colleagues especially from this country encouraged me to present this lecture. It is fortunate that thorough synopsis of the field is being prepared by Professor Korvin-

Kroukovsky which will serve as a source of references, and it is gratifying to state that the year 1957 has brought us many valuable publications part of which can be found in the Proceedings.

My special gratitude is due to the University of California, which gave me the opportunity to complete my report during a short stay at Berkeley as visiting professor.

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The present list contains only a selection of papers appropriate to the limited scope of this report.

The following abbreviations are used:

DTMB — David W. Taylor Model Basin, Washington 7, D. C.
JAN — Isvestiia, Akademiia Nauk SSSR, otdelenie teknicheskikh nauk.
JSTG — Jahrbuch der Schiffbautechnischen Gesellschaft, Hamburg.
PMM — Prikladnaja, Matematika i Mekhanika, Moscow and Leningrad.
QJMAM — Quarterly Journal of Mechanics and Applied Mathematics, Oxford.
SNAME — Transactions of the Society of Naval Architects and Marine Engineers, New York.
TINA — Transactions of the Institution of Naval Architects, London.
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SYMBOLS

A_w	load waterline area
B	beam
C	restoring coefficient in pitch (eq. [7])
D	displacement

E	exciting function, e.g., $E_z = E_{33}$, $E\psi = E_{55}$
F	Froude number
G	coupling coefficient in eq. [7]
H	draft
I	area moment of inertia
J	mass moment of inertia
K	inertia coefficients
K_z	function in eq. [3*b*]
L	length
M	moment
N	damping coefficient, e.f., $N_z = N_{33}$, $N\psi = N_{55}$
$N\ (\xi)$	damping coefficient per unit length.
$\overline{N}^{(d)}\ (\xi)$	diffractional damping per unit length
$\overline{N}^{(d)}$	diffractional damping coefficient
T	natural period, $T^* = T\sqrt{g/L}$
U	uniform speed of advance;
X Y Z	forces
V	volume
c	wave phase velocity; restoring coefficient in eq. [6]
f	freeboard
g	gravity acceleration; coupling coefficient in eq. [6]
h	wave height
i	$\sqrt{-1}$
m	mass; m_{ij} — inertia values; $m_z = m_{33}$; $J_{yy} = m_{55}$
r	wave surface elevation; r_m wave amplitude
t	time
x y z	coordinates, $y^* = y/L$
z_m	heaving amplitude, $z_m^* = z_m/r_m$
α	waterline area coefficient
β	midship section coefficient
$\gamma = \dfrac{\pi L}{\lambda} = \dfrac{\pi}{\lambda^*}$	
δ	block coefficient
ε	phase angle
θ	angle of yaw
κ	dimensionless damping coefficient
λ	wave length, $\lambda^* = \lambda/L$
μ	resonance factor, amplification factor
ν	natural frequency $\nu^* = \nu\sqrt{L/g}$
ρ	density

ϕ	rolling angle
χ	heading angle
ψ	pitching angle; ψ_m = pitching amplitude; $\psi_m^* = \frac{\psi_m}{\Theta_m}$
ω	exciting circular frequency (frequency of encounter)
$\omega_o =$	$\sqrt{\frac{2\ \pi g}{\lambda}}$ wave frequency $\omega^* = \omega_o \sqrt{L/g}$
$\sigma = \delta/\alpha$	vertical prismatic coefficient
Θ	wave slope, Θ_m = maximum wave slope
Λ	tuning ratio or factor
Φ	velocity potential

NOTES

1. To denote dimensionless values ample use is made of an asterisk. Where necessary the length of reference is indicated by subscripts, for example,

$$\omega^*_b = \omega\sqrt{B/g}.$$

The subscript L is omitted in expressions like

$$\omega^* = \omega\sqrt{L/g}.$$

2. Two subscript notations are used to designate values pertaining to motions:
   2.1 x, y, z, Φ, ψ, Θ, when a small number of motions is investigated;
   2.2 numbers 1, 2, 3, 4, 5, 6 in more general expressions.
3. In the latter case added moments of inertia are denoted by m_{ij}.
Virtual generalized masses are denoted by a prime, e.g.,

$$m'_{33} = m + m_{33}, \qquad m'_{44} = J_x + m_{44}, \text{ etc.}$$

4. Two-dimensional mass and damping values are distinguished by a bar, e.g. $\overline{m}_{33}$, $\overline{N}_{33}$.

DISCUSSION

Paul Kaplan

Since this talk was only a synopsis, and Dr. Weinblum expects the discussion to amplify and expand many of his statements, I will attempt to consider some of the work in hydrofoil craft and its extensions in greater detail.

With regard to the analysis of motions of hydrofoil craft in a seaway, many works of linearized theory exist with the use of quasi-steady forces in their derivation; among them, one due to Dr. Weinblum. Comparison of the theoretical motions with experiment, however, doesn't show good agreement, and presently, two alternate developments, making use of the forces determined from the theory of unsteady motions, are under investigation. Other work is being done on a study of scaling of the performance of hydrofoil craft in waves. This concerns the change in wave sizes that a hydrofoil craft can safely operate in when a change in size of the craft is made, with the speed maintained relatively constant. These studies may contribute to a better knowledge of the seaworthiness of hydrofoil craft, on which their future utilization greatly depends.

Another point about hydrofoil craft that makes them attractive for research purposes, is that, aside from the fact that they are a particular class of seagoing vehicles of importance, they are relatively simpler to analyze theoretically than a displacement ship. The forces are relatively localized and simple experiments can also be used to determine various coefficients in the motion equation. The techniques of aircraft motion analyses are easily applied to *this* case, and these may now be extended, in the broad sense, to the displacement ship problem.

The field of ship mechanics, as Dr. Weinblum refers to it, should develop along the lines of aircraft studies. The development of aircraft dynamics, from simple stability analyses to response to arbitrary gusts, even those of random nature, should be followed by the natural extension of ship maneuvering and directional stability studies in smooth water to studies of similar problems in waves. The general equations of ship motion can be easily constructed (in a rough, not too rigorous manner) and the evaluation of the pertinent coefficients is then the main problem. One of the techniques that may be used for this purpose is a relatively recent development in the aeronautical literature known as slender-body theory. This theory allows a greater fullness to the cross-sectional area of the body and may be more realistic than the classical Michell ship. Some work along these lines has been done by Dr. Cummins of DTMB for the case of wave resistance in smooth water, and has been indicated in a general way recently by Professor Fay of M.I.T., for the case of symmetric motions of a ship in waves, i.e. heave and pitch in pure head and following seas. The main difference between the aeronautical application of slender-body theory and application to the ship motion problem lies in the boundary condition for the potential, i.e., the free surface boundary condition, but alas, that is the core of the problem. These ideas should be taken up soon, in order to extend our meager knowledge of ship motions in the horizontal plane in oblique waves. More rigorous techniques may be developed in the future, but a working tool is now necessary and may be obtained in this manner.

I may have departed somewhat from my original discussion on hydrofoils, but I think I have maintained my general philosophy of applying the ideas of aircraft motion analysis to the seaworthiness problem.

R. W. L. Gawn

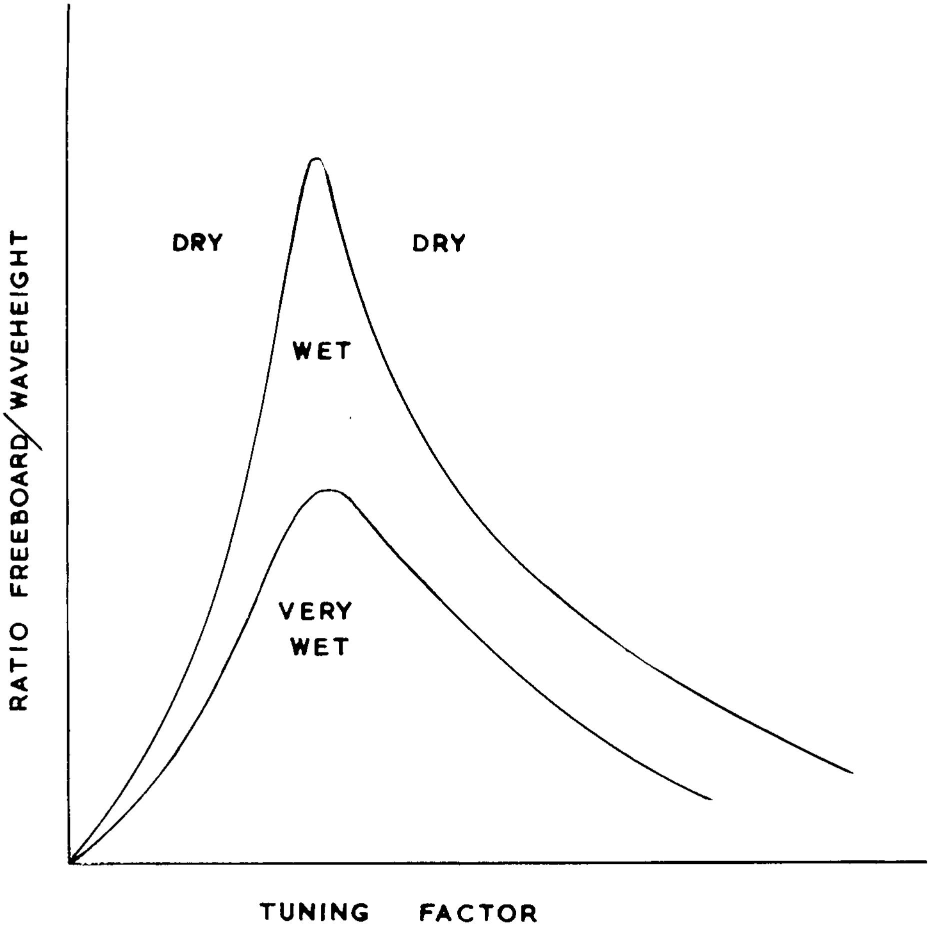
Prof. Weinblum's survey is admirable and comprehensive and his proposals for further research are in my view essential in all respects.

One or two aspects may be usefully emphasized. The simple theory of rolling, now nearly a century old, has pointed the way in association with model experiments to the best arrangement of bilge keels to damp the motion. Much greater damping has been effected in recent years by activated fins. Theory played a full part in the development of this device although the engineering aspects are a major feature.

Increasing attention is being given to the development of the linear theory of pitch and of heave and in association with model experiments this has confirmed that the scope for increasing damping by passive fins or change of hull shape is very much greater than formerly supposed. This is therefore a real contribution from theory.

So far research both by theory and experiment has been largely pre-occupied with regular seas but there is a natural urge to extend the development to complex seas. The additional variables and complications involved are many and the resourses of staff and facilities will be overstrained and useful results unduly protracted unless the work is confined to essential channels. It is suggested to the Author that theory could help by defining a wave system of a standard complexity which would serve for most tests and so avoid, or at least considerably curtail, the multiplicity of experiments that would otherwise be necessary in different seas of random complexity.

The important contribution of adequate freeboard to the sea-keeping qualities of a ship cannot be too strongly stressed and it was a pleasure to hear Prof. Weinblum's insistence on this. This is a matter on which theory has drawn a blank and the designer must perforce rely on previous experience and model tests in order to arrive at a decision as to the amount of freeboard. My personal experience favours 6½ per cent of the length as a good standard, although it is realized that some ocean-going ships have a smaller ratio. Exceptional standards were aimed at for H. M. Yacht BRITANNIA and the freeboard coefficient was finally determined at about 8 per cent following a series of model tests. Perhaps the Author would comment on these figures and say whether he is aware of any theoretical or empirical rule to guide the designer in this vital problem. One empirical approach which has been attempted at Haslar is represented by the diagram herewith, which is self-explanatory. Experience to date indicates that curves as shown on the diagram fairly well differentiate between dry and wet ships. (See Fig. 1.)



P. Golovato

Dr. Weinblum has mentioned recent work at the Taylor Model Basin on the forces and moments on oscillating ship forms. I would like to elaborate on his remarks and summarize the principle results of this continuing investigation.

We at the model Basin are indebted to Dr. Weinblum for the foundations he laid for this work while he was with us several years ago. The very test facility and model we have utilized were originally built for Dr. Weinblum's use.

We have constrained a ship model with fore-and-aft symmetry to oscillate harmonically in heave in calm water and have measured the heaving forces and pitching moments. This enabled us to determine the frequency, amplitude and speed dependence of one-half of the coefficients in the commonly used pair of linear differential equations of motion. Subsequent pitching experiments later this year will determine the missing coefficients.

The principal results concerning the added mass and damping are as follows:

1. The added mass and damping coefficients are independent of the amplitude of motion.
2. The added mass in heave shows a strong frequency dependence which closely resembles in form the theoretical results of Ursell and Grim.
3. The added mass is essentially independent of forward speed.
4. The variation of damping coefficient with frequency shows the characteristic peak at the frequency predicted by the Distributed Source technique and the Grim solutions but the former greatly overestimates its magnitude while the Grim solutions are an improvement. The Haskind-Riman experiments at zero speed were re-analyzed and the same superiority of the Grim solutions was demonstrated.
5. The speed effects on damping are not very great. The maximum value is about the same for all speeds but the peak occurs at slightly different frequencies.
6. The existence of quadratic damping is indicated by harmonic content in the measured forces. It was then demonstrated that the neglect of these non-linear terms would lead to a serious overestimate of the motions in the vicinity of resonance.

In addition, significant cross-coupling moments were obtained for the symmetrical model which increased with increasing speed.

1. The pitching moment due to heave velocity showed a very strong frequency dependence that is not indicated by the theoretical work of Haskind and Havelock.
2. A moment due to heaving acceleration was obtained which is sharply peaked at low frequencies. This coupling moment is not indicated previously by theory or experiment for a symmetrical model.

E. V. Lewis

I have enjoyed Professor Weinblum's interesting survey on the seaworthiness problem very much, and appreciate the honor of being asked to comment on both it and some of our experimental work at Stevens.

It is of interest to note that Professor Weinblum now rates the importance of the irregular seaway concept very high. But I certainly agree with him that the study of the theory of motions in regular waves is no less important than before. In fact, it is probably even more so, and the many interesting graphs and data that Professor Weinblum has assembled from sources rather difficult to obtain in this country will be of great value to us in this work.

Professor Weinblum records definite progress in the overall problem of ships in a seaway, but he does not expect revolutionary improvements, within practical limits of ship form and proportions. My own feelings are somewhat more optimistic, because besides the possibile use of fins, it does seem that the possibility of gains in speed by careful consideration of ship proportions are quite large, even though perhaps not "revolutionary."

For example, within the scope of the Series 60 models that are now being extended by Dr. Todd, there is the likelihood of an appreciable increase of sea speed. In considering this matter, it is convenient to use the condition for synchronism with a wave of ship length as a rough criterion of relative speed attainable in rough irregular head seas. This is a useful reference because although the oceanographers feel that most seas have a very wide range of different frequencies present, motion studies show that wave components appreciably shorter than the ship's length are not serious, even if synchronous conditions exist. So if we consider the speed for synchronism with the shortest wave components that is apt to be significant, i.e. a wave of about the length of the ship, we have a relative measure of what we might expect to be the upper limit of speed in a rough head sea condition.

On this basis, it is found that a 500-foot ship built to the lines of the parent Series 60, 0.60 block model, might be expected to be in trouble in a particular sea at around 12 knots. Above this speed the motion would be too violent, and the ship would have to slow down. A ship of this same displacement, with the length over breadth increased from 7½ to 8½, and beam over draft increased from 2½ to 3, which is one of the new series, would be a 580-foot ship, and on the basis I have outlined we might expect it to run into storm difficulties at a speed of 17½ knots, instead of 12, on a comparative basis. This means a 15% increase in sea speed with a 15% increase in length.

This advantage of increasing length in irregular head seas has been shown by model tests to be more than theory. In a project at Stevens, sponsored by ONR, a wide variety of different models is now being studied. For example, a trawler model was tested in its original form, and then lengthened out and made more slender. When compared at the same displacement, the greater potentiality for speed for this lengthened ship could be clearly seen.

Unfortunately, length is, as we well know, the most difficult dimension to increase, not only from the point of view of cost, but from practical reasons, such as limitations of harbors and ports. Still, in many cases there may be a possibility of some increase, and whatever can be done will be to our advantage for speed in rough weather.

Finally, I should like to emphasize again Professor Weinblum's point about the need for ship data on permissible limits of motions and accelerations, both for comfort and for safety. Without more information of this sort new theoretical and experimental developments cannot be effectively applied. For example, even though model techniques, irregular-wave theory and new oceanographical data permit us to predict for a given condition the average or maximum amplitudes of motion, accelerations, etc. with some degree of confidence for a new design over a range of speeds, we still are unable to predict what would be the limiting speed for the actual ship.

This and the other problems outlined by Professor Weinblum will keep us all busy for some time to come.

V. G. Szebehely

It is a pleasure to make these few comments on Professor Weinblum's lecture at his request.

In order to save time, only a systematic listing of projects connected with the topics mentioned in the lecture will be given with a very few remarks.

1. In connection with Dr. Weinblum's reference to fins, attention is called to an investigation of the effect of anti-pitching bow fins on the motion of aircraft carriers and merchant vessels. Before the feasibility of applying fins was considered, the effects of bulbous bows on the motion were investigated by theoretical and experimental means. No significant motion reduction was found with normal size bulbs. Fixed fins at the bow have two beneficiary effects; firstly they reduce pitching, secondly they reduce speed losses in waves. Various planforms, profiles, area, combinations, speeds and waves were investigated and it was found that 40-60 percent pitch reduction can be obtained in certain practically important conditions with bow fins whose area was approximately 2 percent of the water plane area [ref. 1, 2].

2. A study of speed reduction in waves is given in ref. 3. The work evaluates the speed maintaining characteristics of a destroyer, of a fast and of a slow cargo ship. From simple theoretical consideration, formulas (which are very sensitive to phase relations) were derived and at the present time are being compared with the experimental findings.

3. Motion predictions were performed in connection with model tests. Phenomena in which phase relations play significant part, seem to be hard to predict. Con-

sequently, there is room for considerable improvement in connection with prediction of slamming, propeller emergence, speed reduction, water over the bow, pitching axis location, etc.

4. The effect of transients in irregular seas was investigated considering a trend of waves of constant length and variable height. The steady state response was compared, cycle by cycle with the measured response in ref. 1.

5. The influence of the block coefficient on the time and space dependence of the impact pressure was investigated and pressure mappings were computed [ref. 4]. The computed values are presently being compared with experimental results. Correlation between slamming pressure and acceleration are given in ref. 5.

6. It is felt that the new slamming model proposed by Dr. Weinblum has merits for so-called flat impacts. The practical importance and the usefulness of the "enclosed cavity" approach will have to be shown before this model can take over the presently established and practically useful methods based on Wagner's idea [ref. 6].

7. Head-on collision type impacts were observed and reported in ref. 7. Longitudinal accelerations amounting to 0.1 to 0.2g were recorded in heavy head seas on destroyers. Such values can be arrived at using Wagner's method to compute forces developed during water entry.

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J. F. Allan

I think it is interesting to note that since the classical analysis and presentation of Krylov, there has been very little real development of the subject until the last ten years or so. In that recent period the interest in the behavior of ships at sea, and the interest in the possibility of analyzing that against the mathematical theory has grown enormously.

I wish to pay a tribute to the enormous amount of work which has been done in this direction in the United States, both at the David Taylor Model Basin, and the Stevens Institute. This work has been presented in a number of papers, and it really places a very useful tool in our hands.

One should mention in passing, the work that Kent did at Teddington in the 1920's and 1930's, the chief point of which might be considered to be the indication of the importance of the relationship between the downward motion of the bow and the actual position of the bow wave. The recent work has shown how the theory explains a number of these characteristics, but, unfortunately, the accuracy of the theory and our knowledge of the characteristics is such that it is not reasonable to come to detailed conclusions on the comparisons. The broad picture is clear, but one cannot pursue it in too much detail.

Probably the most significant indication, from the recent developments, is to show, or to suggest that the only really effective way of improving the seagoing quality of ships is to increase the damping factors.

Previous speakers have suggested that varying the proportions of the ship can achieve an improvement, but from the practical point of view the possibility of pursuing that line is distinctly limited.

As regards rolling, the natural damping factor is small, and while it would be possible to increase this factor greatly by giving the ship, for example, large bilge protuberances, from the practical point of view this has never been pursued, because it would interfere both with the propulsive characteristics and the handling of the ship.

The rolling problem has been substantially solved by the introduction in Great Britain of the controlled fin stabilizer, which increases the damping factor to such an extent that rolling is substantially eliminated.

Having successfully controlled rolling, one's ideas naturally turn to the question of pitch and heave reduction. It is an open question whether the shape of the ship can be so modified to increase the damping factor in pitch and heave, without paying a large penalty from the propulsion point of view.

If one applies controlled damping, in the form of controlled fins or other means, the question of the time element is of quite considerable significance. In other words, one must operate the control and produce the variation of the force on a time plan which matches the pitch frequency. As you are aware, this frequency is about twice that of roll and the problem is correspondingly more difficult.

A question, perhaps more properly discussed tomorrow morning, is that of driving ships very hard in bad weather conditions, which is of considerable interest in view of the possibility of largely increased driving power. If one equips a ship with a controlled mechanism which stops rolling and damps pitching, it is quite probable that one will be able to drive it successfully through very bad seas.

But there is a very serious practical point which arises, and that is, what happens if the control mechanism fails? The ship might meet catastrophe before the position could be rectified.

It may be of interest to note that the "Queen Elizabeth," which is equipped with roll stabilization, can be driven at full speed in conditions which would require a reduced speed if there was no stabilizer, but the captain is worried as to what would happen if the machine suddenly ceased to function in such circumstances. Reliability is of paramount importance.

M. C. Eames

Regarding Dr. Kaplan's amplification of Dr. Weinblum's reference to the study of the seaworthiness of hydrofoil craft, it is felt that one point should be clarified. Dr. Kaplan has quite rightly pointed out that a linearized quasi-steady theory of the pitching and heaving response of hydrofoil has proven inadequate for predicting the motions of such craft in regular seas.

The experimental work on which this conclusion is based, however, covered a necessarily limited range of wave conditions and craft speed. There is reason to believe that once the craft is well clear of conditions of resonant response, the linearized quasi-steady theory proposed by Dr. Weinblum suffices to give a very reasonable approximation to the true motion.

This in no way detracts from the remarks of Dr. Kaplan and his very fine work on the effects of unsteady motions. The most important case does, of course, correspond with resonant conditions and the correct prediction of the the motions resulting from such conditions is vital to the safe performance of hydrofoil craft. Unless the writer misunderstood the speaker, however, there was a hint that the more elementary approach should be discarded altogether, and it is felt that insufficient experimental evidence has been obtained to date to justify this.

Possibly this represents the wishful thinking of a simple-minded hydrofoil craft designer, but the feeling nevertheless remains.

B. V. Korvin-Kroukovsky

In this valuable paper, Dr. Weinblum has presented a very comprehensive review of the entire subject of the analysis of ship motions. It is not feasible to present a discussion of such a broad field; a discusser must single out a few aspects in his particular sphere of interest. This discusser appreciates the clear definition of two basic directions of ship theory development as given by the author: a. to state the practical conditions as completely as possible and to look for an approximate solution (the vigorous approach), and b. to simplify to the utmost the problem presented by practice (i.e., substitute a simple mechanical model), and to apply rigor in the mathematical solution.

The family tree of the first method is easily traced from the initial work of Kriloff (1896) through the work of Weinblum and St. Denis (1950) and St. Denis (1951) to Korvin-Kroukovsky (1955). During the past year it has received important additional development (as yet unpublished) by Prof. M. Abkowitz and Prof. Fay of M.I.T. and by Miss W. R. Jacobs (this discusser's associate). Valuable contributions for the elements of this theory appeared also in the more mathematical works of Havelock (1955, 1956). Were all these developments taken into account, the general tone of the author's outline would appear to be too reserved. The successful comparison of calculations with experimental data for several models in several wave lengths could well call for more enthusiasm. Unfortunately, a certain amount of time will have to elapse before these latest developments can be published.

The author points correctly to the fact that calculation of the exciting forces for a submerged body are simpler and appeared earlier than those for a surface ship. This discusser cannot agree with the author, however, that the calculation of the latter was made by "analogy". The technique was first developed for a submerged body, and then was applied to a surface ship, but this latter application was made independently without resort to analogy. The striving for simplicity required that the basic solution be developed for a semi-circular ship section; the results were subsequently generalized to apply to any form of cross section by introducing the coefficient of accession to inertia in view of the basic work of G. I. Taylor (1928) as well as Havelock's (1954) work on submerged spheroids. The word "analogy" is therefore partly applicable only to this final step. The computed exciting forces for a ship model were found to agree very well with the experimental data.

The cross-coupling damping terms which appear in the work of Haskind and Havelock (1955) deserve additional comments. It should be observed that these "damping" terms result from the calculations based on the inviscid fluid, and in Havelock's case, without wave formation. They do not involve, therefore, any energy dissipation, and can be termed "dynamic" damping, in distinction to the wavemaking damping defined by the works of Holstein, Havelock, Ursell and Grim. This wavemaking damping must be added as a separate step to any calculation in which the surface wave formation is not included in the initial setup of the problem, as, for instance, that of Korvin-Kroukovsky (1955).

"Dynamic" damping terms of the general form

$$Ak_2mV\dot{z} \quad \text{and} \quad Bk_2mV\dot{\theta} \tag{31}$$

appear in the work of Korvin-Kroukovsky (1955), as well as in the yet unpublished work of Prof. Abkowitz and Prof. Fay. It is gratifying to see that with regard to these terms the simplified work of these authors is in agreement with the more rigorous mathematical work of Haskind and Havelock. While there is an agreement in regard to the form, the coefficients *A* and *B* have different values with each author, and apparently depend on the assumptions made as to the nature of the free boundary and of the ship surface. In particular, comparison of the work of Korvin-Kroukovsky (1955) and of Fay (not yet published) brings out the difference between the assumptions of cylindrical or conical form for an element of ship length.

In connection with the significance of the cross coupling, the work of Prof. Fay brings out the fact that heaving motion is strongly affected by pitching, while pitching is relatively little affected by heaving. This explains why in the publications in which the pitching only is considered, as Cartwright and Rydill (1956) for example, the effect of cross coupling does not appear to be pronounced. This effect becomes immediately evident when the heaving is considered, and in particular it leads to a large increase of heaving motions. This is important in practice because large heaving motion of a ship leads to the occurrence of slamming.

G. P. Weinblum

As expected, the discussers have succeeded in supplementing my sketchy exposé in such a way that a more adequate representation of the ample subject has been reached. May I express my sincere thanks for their contributions. Obviously, it was a hard task for them to prepare their remarks without knowledge of my manuscript which I was able to make available in a very rudimentary state only to Prof. Korvin and Prof. Lewis. As mentioned at the beginning of the lecture, my wish to dwell at some length on foreign work less known to the audience and to assume other basic publications as familiar, has distorted the oral representation of the subject.

Dr. P. Kaplan is to be congratulated on behalf of his theory on non-steady hydrofoil performance. The present writer had earlier underestimated these effects. It is interesting to note, however, that Mr. Eames is supporting the rudimentary quasi-steady approach. I concur with him that it should not be wholly discarded for the time being. In fact, work is going on following these lines under the present writer's guidance dealing with the general case of hydrofoil motions on arbitrary courses in regular waves.

Mr. Golovato's contributions have clarified important problems and promise to promote knowledge in our field in the future. His success is especially gratifying to me after I was afraid to lose my reputation completely because of my responsibility for suggesting the oscillator used by him. There appears to exist a slight contradiction between point 1. and 6. of the discussion with respect to nonlinear effects.

Thanks to Dr. Szebehely for his competent remarks on a subject which he has successfully developed for several years. With respect to point 6. I wish to emphasize that in my opinion Bagnold's ideas on hydrodynamic impacts may lead to a better understanding of some pertinent effects but by no means can take over Wagner's theory.

In his oral reply Dr. Gawn has justly pointed out an understatement with respect to Froude's work on roll. I agree wholeheartedly with Dr. Gawn that theory has drawn a blank by neglecting severely the freeboard problem. The condensed experience contained in the figure presented by him should be used when freeboard regulation will be reconsiderd. Theory may contribute useful results to the determination of freeboard, sheer and size of superstructure especially as a guide to experimental work, provided extensive numerical evaluations will have been performed. The lack of the latter precludes at present to discuss the figures communicated by Dr. Gawn.

Dr. Allan refers to Kent's work to whom the profession should feel deeply indebted as well as to Kempf. Dr. Allan's remarks on damping and especially on controlled damping are highly appreciated as those of a pioneer in the latter field. The postulate "reliability is of paramount importance" is to the point especially at a meeting of the present character. Some doubts expressed as to the effectiveness of varying proportions lead to the discussion by Professor E. Lewis, the protagonist of the problem at stake.

To avoid any apparent disagreement with him, I have somewhat mitigated in my final text the slightly nebulous statement concerning revolutionary improvements within normal limits of ship form and proportions. It has been my aim for many years to emphasize an almost trivial fact—the importance of the ratio $\lambda^* = \lambda/L$

when dealing with most motions. Further, it has been pointed out, that synchronism loses its danger when occurring at low values of λ^*. Due acknowledgement to Prof. E. Lewis' achievements has been paid in the text and some hints have been given as to how to extend the pertinent analysis. A numerical investigation of conditions on arbitrary courses appears to be urgent especially in the case of supercritical running.

My earlier reserve with respect to the solution of the irregular seaway referred to the formal representation only. Some doubts still persist as to the final character of the Pierson-Neumann approach.

Professor Korvin-Kroukovsky points out quite justly that the word "analogy" is applicable to one part only of his research on the behavior of surface vessels—the investigation on exciting forces. His investigation on coupling terms is farther reaching. It is to be expected that further work in this direction will go beyond Haskind's bold attempts which by no means have so far led to final conclusions.