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The Present State of Ship Theory

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INTRODUCTION

"The ship is a vehicle whose weight is supported by forces created in water." This definition is no more exhaustive after the hovercraft (GEM) has appeared; frequently (as will be done here), the latter is excluded from the family of ships, which, unfortunately, does not settle all the scientific questions involved.

"The investigation of properties of the ship which are fundamental from the standpoint of mechanics is the subject of Ship Theory." (In a narrower sense, however, only those problems belong to ship theory in which the hull can be considered as a rigid body.) While we were earlier satisfied by this approximate statement, we must now answer first the question put recently by a prominent colleague: "Is there such a science as ship theory?" The increasing weight of general disciplines, primarily hydrodynamics, seems to displace the usefulness of particular problems posed by the engineering profession as yardsticks of our subject. Thus, for example, the concept "Ship (or Naval) Hydrodynamics" has slightly obscured our dignified term "Ship Theory." Actually, the latter being more general, retains its full meaning. The presentation used in most books is advisable; here a section on ship hydrodynamics is included.

Ship hydrodynamics is displacing aerodynamics as the principal inspiration in the field of research on ideal, as well as viscous, incompressible flow.

A new comprehensive concept — hydroelasticity — tends to eliminate the borderline between ship theory and "strength of ships," which already was bridged by the theory of ship vibrations.

In general, an increasing number of problems in ship design (and operation) now become susceptible to scientific treatment, thus widening the scope of our subject.

There are perhaps few fields in the engineering sciences where the wide use of computers has been so decisive. Complicated solutions, characteristic of our subject, are now readily evaluated, and there is no longer a psychological barrier against developing and applying more exact or comprehensive methods which more closely approximate "reality." This is a necessary prerequisite for a general use of scientific methods in naval architecture.

Since most ships in present use belong to the displacement class our survey will be devoted primarily to problems connected with such vessels. Scientific work dealing with hydrodynamic craft will be referred to when necessary.

Advanced ideas concerning new types of ships are currently suggested by economic and still more by military considerations. The application of atomic power has stimulated research in many fields of ship theory.

The close relations between oceanography and ship theory will be intensified by a new scientific and technological activity—ocean engineering, of which research submarines are representative.

Finally, without going into detail, we emphasize the importance of *ship aerodynamics* as a branch of our subject which includes the theory of sailing and general problems caused by wind forces. Although a classic topic in ship theory, it is treated as a side issue here.

SHIP GEOMETRY AND HYDROSTATICS; BUOYANCY AND STABILITY

The determination of the hull form is increasingly based upon analytical (and numerical) methods,

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rather than graphical procedures. This development is promoted by

1. theoretical considerations and
2. by practical requirements, i.e. the desire to eliminate the mold loft and to compute the hull ordinates with the accuracy needed for construction.

In theoretical considerations, "exact" representations of ship forms are especially useful in research on wave resistance and ship oscillations in a seaway; pertinent methods are based on (*a*) a synthetic construction of formulas for the surface from given characteristic form parameters, or (*b*) on approximating empirical lines by the least squares method. Polynomials are most suitable for these methods since (via spline curves) they are a language understood by ship artisans.

As far as practical requirements go, practice so far prefers procedures which depart from a given empirical set of lines and uses interpolation formulas in a specially adapted form (again based on spline curves).

Our subject is now an important phase of ship theory — *ship geometry*, a designation used earlier for special investigations on static stability. We have criticized the peculiar use of nomenclature in the field discussed and have proposed the term "righting couple" of roll and trim (reserving the concept of stability for our investigation of the state of equilibrium). The study of extraneous forces causing ships to heel (wind, centrifugal forces, etc.) is now intensified—a necessary prerequisite for standardizing minimum values of the transverse stability parameter. Obviously, the static concept is in many respects inadequate and is being supplemented by considerations based on ship behavior at sea. Nonetheless, recent systematic evaluations of static stability in a damaged state are a valuable contribution. Progress has been achieved in the field of ship subdivision by applying probability theory to problems of ship damage.

SHIP HYDRODYNAMICS

A great and increasing inheritance from classical hydrodynamics and aerodynamics belongs to this chapter; the more specific problems only can be touched upon. From scientific as well as practical considerations we begin with the study of bodies moving in an unbounded medium ("deeply submerged" bodies). More general body forms have been generated by singularities located in a uniform stream by distributing them over the center *plane* or skeleton surfaces. Still more conspicuous is the progress of the inverse method—the determination of generating singularities for a given body fixed in a uniform or nonuniform flow field. A routine computer procedure has been developed for solutions of the integral equation which determines surface singularities distributed over the hull. The potential flow has been calculated for several "double models" of actual ship forms (the "double model technique" gains in value as a research tool). Similar efforts have been made in the field of real fluids (although still more effort has been made outside this field), and promising results attained in three-dimensional boundary-layer theory. Turbulence is as before a stumbling block. Refined experimental methods have been introduced. Nonetheless, important information on forces experienced by bodies moving in real fluid is lacking.

Obviously, the study of free surface effects is the most essential and conspicuous part of ship hydrodynamics. There is a comprehensive and creative synopsis of the general theory of water waves by Stoker (22) and Wehausen (23). Theories of the irregular seaway have been developed and have exerted a decisive influence on the treatment of seaworthiness and ship behavior problems. The theory of body motions close to (or at) an interface has progressed. So far linearized theories dominate the field but attempts are being made to handle second order approximations. Only tentative results so far have been obtained by considering the influence of viscosity on free surface effects.

The study of hydrodynamic impacts experienced by bodies hitting the free surface was originated by narrow applications in seaplane design; it now gains momentum in various fields of applied hydrodynamics. Although fundamental results have been reached earlier, two new solutions of basic character may be quoted:

1. the case of impinging free jets and
2. the consideration of elastic properties of the striking body.

We may pass briefly over the progress made in cavitation studies, especially investigations on the supercavitating state which has led to fundamental new auspices in applications, since we assume that this important subject will be adequately dealt with elsewhere in this volume.

RESISTANCE

Resistance is at present perhaps the most popular subject in ship theory both for scientific and practical reasons. From resistance studies come the strongest scientific impulses for developing new hull shapes. Of the three phases of scientific development (empiricism, similitude mechanics, theory) we may be said to be still in the second phase—characterized mainly by the prevalence of model research. But theory is developing faster than before and is having more of an impact on experimental research and to some extent on design.

Routine experimenting and systematic series work still dominate the model field (1, 9). Painstaking investigations are performed to guarantee consistency and *reproducibility* of resistance experiments. Recently new methods of measuring resistance came into being—determination of wave drag from the wave pattern behind the model, and of viscous drag by the impulse (traverse) method suggested by Tulin. The determination of normal resistance by pressure measurements has been revived. Notwithstanding serious efforts the two main problems in "tankery" remain:

1. conversion of model data to the full-scale ship (data extrapolation, scale and roughness effects) and
2. development of favorable hull forms; these are far from a satisfactory solution.

Point 1 requires much more full-scale work. But so far even resistance data derived from model families (geosims) are far from agreement.

Wave resistance theory (ideal fluid) and boundary layer-theory are the scientific backbones of our subject. The problem of "splitting" the total resistance into components is still fundamental. Attempts are being made to improve the classical Froude method by physical reasoning based on wave and viscous drag concepts. In formal presentations an additional interference term, dependent upon Froude's and Reynolds' numbers, is useful.

There are difficulties of a conceptual character that may result in definitions of components based on measuring procedures.

Scientific progress, however, results from a determination of the interdependence of wave and viscous effects based on wave and boundary-layer theories, and possibly pertinent experiments (6).

In the meantime wave resistance theory (based on the ideal fluid concept) is developing successfully. The scope of application of linearized theory is continuously increasing: general (including unorthodox) forms of bodies are investigated; the development of hulls of least (low) wave resistance has become a central problem, leading to the use of various competing methods which bear fruit and even open up interesting mathematical areas. Practical results have been reached, especially with respect to the bulbous bow.

Quite general solutions have been obtained for wave resistance in channels, and formulas obtained earlier are being widely evaluated as tank corrections. Second-order approximations are being developed, which, aside from being valuable in themselves, will in addition enable us to analyze more reliably experimental results. To promote the ship resistance problem the investigation of the *viscous* drag of deeply submerged bodies is extremely helpful.

Since our knowledge of the "viscous form effects" is very modest even for this case, large-scale experimenting as well as theoretical research must be speeded up. Solutions for the three-dimensional laminar boundary layer may lead to further progress in the turbulence region. The application of results to surface ships requires additional serious work as indicated above.

Skin friction is in general the largest part of ship resistance. So far the strongest scientific impulses for its reduction have come from aerodynamics. Recent ideas—"elastic" hide, introduction of non-Newtonian fluids—if up to now without concrete practical success, indicate that there is a new spirit of adventure after a long period of resignation.

The orthodox means of reducing friction by a smooth hull surface and its conservation remain decisive practical tasks. In addition to resistance due to uniform motion in calm water and its components, accelerated motion has been studied. Application of these results to evaluation of inertial runs may prove to be interesting. Of special significance are theoretical and experimental studies of resistance experienced in a regular and irregular seaway (16).

PROPULSION AND SHIP PROPELLER INTERACTION

As in resistance research, experimental and theoretical work is going on in the closely related field of propulsion. Similar difficulties due to scale effect are encountered. The self-propelled model experiments are the closest approximation to the full-size ship performance. The theory of the vortex-line at the screw propeller has been successfully improved (e.g. Weissinger's method). Nonetheless, efforts tend to concentrate on the lifting surface theory (27) as the only satisfactory solution for broad bladed propellers. Attempts are made in considering nonsteady effects. Much experimenting is devoted to models of *reversible* propellers. The *contra-rotating* propeller is gaining attention both in theory and practice.

Progress is noted in the theory of heavily loaded propellers. Adequate solutions have been found for the shrouded screw.

The serious difficulties caused by cavitation on high-speed vessels has found a fundamental and promising solution in the development of the supercavitating propeller (7), although a really satisfactory theoretical representation has not yet been given.

As before, water jet propulsion is much discussed; it has found a limited application in small craft. Although a theory of the paddle wheel has recently been developed, and experimental findings have demonstrated that good efficiency can be attained with this device, interest in this field has practically disappeared. Theoretical and experimental work has been devoted to the cycloidal (or vertical) propeller; its application remains limited to cases where high maneuverability is required.

Equally successful investigations have been made recently of ship propeller interaction based on the study of wake and thrust deduction. Essentially, Dickmann's earlier ideas have been corroborated—the prevalence of the displacement (potential) wake on thrust deduction, and the low value for the frictional and wave thrust deduction "components."

The characteristic integral equation which determines the singularities distributed over the surface in the presence of a sink system picturing the propeller, has been solved for the deeply immersed body (double model) and the results have yielded the desired information on the effective wake, potential thrust deduction, etc. Further effects must be studied, however, to explain the influence of the direction of propeller rotations or propulsion data on twin- or multiple-screw ships. Experiments show the influence of the working propeller on the separation of flow at the after body.

For the reasons mentioned, we merely touch upon cavitation research. As a new type of facility, tanks or channels have been proposed for self-propelled model experiments at pertinent cavitation numbers.

SHIP BEHAVIOR AT SEA AND SEAWORTHINESS

This most interesting subject can be dealt with briefly, since we possess, fortunately, an excellent synopsis by Ogilvie (13). The concept of the statistical nature of the sea and the assumption that the response of the ship is the sum of its responses to the various components of the sea enable us ultimately to supply useful information to the designer and to link modern research with classical investigations. Attempts are being made to base safety regulations, such as freeboard rules, on scientific reasoning. Although more general methods are available, the equations of motion are still the most evident means of studying phenomena in calm water and in waves. Decisive progress has been reached in determining added masses, and damping and coupling coefficients valid under free surface conditions. On the other hand, a form of equations has been formulated such that terms defined as added masses remain independent of a frequency parameter. Experimental research work keeps pace with theory, Valuable systematical investigations on resistance and motions in a regular seaway have been conducted by varying characteristic form parameters of models. The application of results of ship motions obtained in regular waves to the study of those in a random sea, and vice versa, has been well established analytically and experimentally. Rheolinear and nonlinear differential equations are indispensable tools for analyzing various phenomena of simple and coupled rolling motions. Important general relations have been found which connect the computation of added masses with damping, and forces experienced in a seaway with forced oscillations in calm water.

As indicated before, research on "slamming" (more generally on hydrodynamic impacts) is becoman important sector in research on sea behavior of ships. Here we mention the model investigations on conditions under which impacts occur in a regular and irregular seaway and the determination of (maximum) pressures.

One important application is the determination of load factors for strength calculation based on the computation of pressure distributions. Ample model testing has been devoted to collection of statistical data on maximum bending moments in irregular seaways.

As pointed out before, the determination of the increase of ship resistance in a regular (or irregular) seaway is based primarily on pitching and, to a lesser degree, on heaving motions. Explicit formulas have been obtained, which, under reasonable simplifying assumptions, yield satisfactory results (16).

MANEUVERING OF SHIPS

Further efforts are being made in the field of rudder investigations, especially on the dependency of rudder forces upon profile and shape on the distance of the rudder from the ship hull and the free surface, and on the wake and propeller race. The theory of the maneuverability of ships in wholly (deeply) submerged conditions and at the calm water surface has been successfully developed, although the determination of hydrodynamic forces still presents problems. Second-order effects are essential in many cases. Maneuverability criteria and testing methods have been developed and analyzed. The equations of motions of a ship in a regular seaway have been established. No adequate treatment exists of the maneuvering problems under the influence of wind forces.

Maneuvering in shallow water and in restricted waterways (channels) has been studied experimentally. Only recently have adequate attempts been made to analyze theoretically the case of passing and overtaking ships.

To increase the steering qualities of ship bow rudders and vertical propellers have been introduced, and recently *bow thrust* propellers. The performances of the latter (dependence upon speed) have been frequently investigated experimentally.

HYDROELASTIC (VIBRATION) PROBLEMS

This subject has been treated for the first time on a broad scale at the 4th Symposium on Naval Hydrodynamics. Methods of handling free hull vibrations have been developed successfully to a large extent by borrowing general procedures based on matrix calculus. Earlier differences in results of added masses due to methods of calculation have been clarified. Shear deflection becomes dominant for high frequencies, and the shortcomings listed earlier have been reduced. Progress has also been made in treating forced oscillations (the damping problem). Coupling effects are important. While earlier the determination of natural frequencies and modes was the most popular problem, now special efforts are being made to determine the sources and the amplitudes of disturbing forces and to eliminate or reduce the latter, as indicated, for example, in the section on propulsion. Effects due to shocks are explored. Vibration measurements on board ship have been frequently made and the development of suitable instruments is progressing. In addition to vibrations of the hull as a whole, local vibrations have been successfully investigated.

"New" hydroelastic effects, which are studied by methods borrowed from aerodynamics, are divergence and flutter.

HYDRODYNAMIC VESSELS

Although basic problems are almost identical for displacement and hydrodynamic vessels, methods of dealing with them are frequently different, e.g. in the field of stability, resistance, motions in a seaway, maneuvering, etc. This difference is obviously more pronounced for hydrofoil craft than for planing vessels.

Because of its poor seaworthiness properties, the latter subclass is much less promising from a commercial or naval point of view (but not as a sporting craft!). After an approximate relation between planing and flying was established and the spray generation clarified, no more basic work was published on this subject. Systematic model investigations, however, have been conducted. Actual design is strongly influenced by empirical procedures. Only tentative endeavors have been made to explore scientifically the large family of fast vehicles with an intermediate character (V-shaped as well as round hulls) between floating and planing.

Serious efforts are being made to promote scientific investigation and application of the hydrofoil class. Pertinent progress in hydrofoil theory has been indicated. Interest centers around the sea behavior of this craft since it is superior to that of displacement vessels.

During the years since the publication of our first review, research in ship theory has advanced on a broad front. We may consider as revolutionary ideas devoted to skin friction reduction, also those to the application of full cavitation. While technical development is frequently comparatively slow, scientific progress, even in classified fields, is impressive. There is no doubt that these serious efforts will increase professional competence as well as the performance qualities, economy, and safety of ships. At the same time creative efforts are being made to enlarge the family of vehicles which we now call ships.

Although it is possible, by our definition, to exclude hovercraft (GEM) from this family, the fact remains that these vehicles in general operate close to the water surface and their properties are widely determined by hydrodynamic considerations. Model research on hovercraft is an interesting task for ship research institutes.

Since literature in our field is increasing like an avalanche, only a small number of references is listed here, to serve as a source for further information. The number of new textbooks is small; monographs become more popular. Scientific information is disseminated mainly by transactions of professional societies, by journals, and to an increasing extent by reports of research institutes. International conferences, especially those on Naval Hydrodynamics sponsored by the U.S. Navy's ONR, have contributed much to a worldwide exchange of ideas and thus to the disappearance of a certain provincialism, which still exists in our discipline. The ITTC (International Towing Tank Conferences) may play a similar role. Periodicals of a general character, like the publications of academies, should also be consulted. Ample lists of references are contained in the sources quoted beneath.

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