Marine Hydrodynamics

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Preface

The applications of hydrodynamics to naval architecture and ocean engineering have expanded dramatically in recent years. Ship design has been related increasingly to the results of scientific research, and a new field of ocean engineering has emerged from the utilization of offshore resources. The number of technical symposia and journals has increased in proportion to this expansion, but the publication of textbooks has not kept pace.

This volume has been prepared to satisfy the need for a textbook on the applications of hydrodynamics to marine problems. These pages have evolved from lecture notes prepared for a first-year graduate subject in the Department of Ocean Engineering at MIT, and used subsequently for undergraduate and graduate courses at several other universities. Most of the students involved have taken an introductory course in fluid mechanics, but the necessary fundamentals are presented in a self-contained manner. A knowledge of advanced calculus is assumed, including vector analysis and complex-variable theory.

The subject matter has been chosen primarily for its practical importance, tempered by the limitations of space and complexity that can be tolerated in a textbook. Notably absent are topics from the field of numerical hydrodynamics such as three-dimensional boundary-layer computations, lifting-surface techniques including propeller theory, and various numerical solutions of wave-body problems. A textbook on these subjects would be a valuable companion to this volume.

Since most countries of the world have adopted the rationalized metric *Système International d'Unités* (SI), this is used here except for occasional references to the "knot" as a unit of speed. Conversion factors for English units of measure are given in the appendix, together with short tables of the relevant physical properties for water and air. A unified notation has been adopted, despite the specialized conventions of some fields. Cartesian coordinates are chosen with the y-axis directed upward. Forces, moments, and body velocities are defined by an indicial notation that differs from the standard convention of ship maneuvering. The symbol L is reserved for the lift force, and D for drag. Thus length is denoted by l and diameter by d. Vessels with a preferred direction of forward motion are oriented toward the positive x-axis, following the practice of naval architecture but contrary to the usual convention of aerodynamics; a fortunate consequence is that a hydrofoil with upward lift force will possess a positive circulation as defined in the counterclockwise sense.

This text was initiated with the enthusiastic encouragement of Alfred H. Keil, Dean of Engineering at MIT, and Ira Dyer, Head of the Department of Ocean Engineering. Financial support has been provided by the Office of Naval Research Fluid Mechanics Program, which for the past thirty years has fulfilled an invaluable role in the development of this field. Additional thanks are due to the National Science Foundation and the David Taylor Naval Ship Research and Development Center for their support of the research activities that have filtered down into these pages.

Many colleagues and former students have helped significantly with encouragement, advice, and assistance. John V. Wehausen of the University of California, Berkeley, pioneered in applying the discipline of contemporary fluid mechanics on a broad front to the teaching of naval architecture; he has been generous with his advice as well as his own extensive lecture notes. Justin E. Kerwin of MIT shared in developing the course from which this text has evolved, and he has been particularly helpful in discussing a broad range of topics. Other colleagues to whom I am indebted include Chryssostomos Chryssostomidis, Edward C. Kern, Patrick Leehey, Chiang C. Mei, Jerome H. Milgram, Owen H. Oakley, Jr., and Ronald W. Yeung of MIT; Keith P. Kerney, Choung M. Lee, and Nils Salvesen of the David Taylor Naval Ship Research and Development Center; Robert F. Beck and

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Introduction

The applications of hydrodynamics to naval architecture and ocean engineering cover many separate topics and range over a broad level of sophistication. The topics are as diverse as the propulsion and steering of ships and the behavior in waves of a moored buoy or oil-drilling platform. The former are classical problems of naval architecture, predated only by Archimedean hydrostatics. The buoy and platform problems are more recent from the standpoint of scientific and engineering analyses. The degree of sophistication varies from empirical design methodology to theoretical research activities whose justification is based on long-range hopes of application.

The fields of technology are also diverse, and to solve these problems requires a knowledge not only of fluid mechanics but also of solid mechanics (to describe the mooring system especially), control theory (to represent the mechanical and human systems involved), as well as statistics and random processes (to deal with the highly irregular environment of the ocean). Here we shall focus our attention specifically on the hydrodynamic aspects, emphasizing those unique to this field as opposed to the other engineering disciplines where fluid mechanics is applicable.

Faced with the choice between empirical design information and esoteric theory, we will follow a middle course to provide the necessary background for an intelligent evaluation and application of empirical procedures and also serve as an introduction to more specialized study on the research end of the spectrum. This approach has the advantage of being a compromise between two viewpoints, which sometimes appear to conflict; it also unifies the seemingly diverse problems of marine hydrodynamics by examining them not as separate problems but instead as related applications of the general field of hydrodynamics. For example, propellers, rudders, antirolling fins, yacht keels, and sails are all fundamentally related to wings and hydrofoils, or *lifting surfaces*, and can be treated and understood together. Similarly, the unsteady ship, buoy, or platform motions in waves and the maneuvering of ships or submarines in nonstraight paths can be analyzed, to some extent, from the same basic equations of motion. In fact, however, the maneuvering problem generally involves separation and lifting effects, whereas the motions of bodies in waves are not as significantly affected by viscosity or vorticity.

The dynamics of fluid motions, like the dynamics of rigid bodies, are governed by the opposing actions of different forces, and moments, which are implied when not explicitly included. In fluid dynamics, these forces can no longer be considered as acting at a single point or discrete points of the system; instead they must be distributed in a relatively smooth or continuous manner throughout the mass of fluid particles. The force distribution and the kinematic description of the fluid motion are in fact continuous if and only if we assume that the discrete molecules of fluid can be analyzed as a *continuum*.

Typically, we can anticipate force mechanisms associated with the fluid inertia, its weight, viscous stresses, and secondary effects such as surface tension. In general, the three principal force mechanisms—inertial, gravitational, and viscous—are of comparable importance. With very few exceptions, it is not possible to analyze such a complicated situation, either theoretically or experimentally, and we can either give up or try to assess intelligently the role of each force mechanism, in the hope of subsequently treating them in pairs. As we shall see, this relatively simple state of affairs is still fraught with difficulties.

It is useful first to estimate the orders of magnitude of the inertial, gravitational, and viscous forces. We shall suppose that the problem at hand can be characterized by a physical length l, velocity U, fluid density ρ, gravitational acceleration g, and a coefficient of fluid viscosity μ. We then can estimate the three forces:

Type of Force	Order of Magnitude
Inertial	$\rho U^2 l^2$
Gravitational	$\rho g l^3$
Viscous	$\mu U l$

These estimates should not be interpreted too strictly. For example, it could be argued, from Bernoulli's equation, that a factor of $\frac{1}{2}$ should be associated with the magnitude of the inertial force. Nevertheless, the estimates are valid in the sense that changes in the magnitudes of any of the physical parameters l, U, ρ, g, or μ will affect the forces as indicated. Thus, suppose the length scale is doubled, as might follow from attempts to compare directly the forces acting on a 100 m ship and on a 200 m ship, moving with the same speed; then the corresponding changes in the inertial, gravitational, and viscous forces will be be multiplicative factors of 2^2, 2^3, and 2, respectively. Therefore, the fundamental balance among the three types of force will change as the length scale changes, and the effects will be more pronounced if we anticipate the relatively large changes of length scale (on the order of ten or one hundred) associated with a comparison of small-scale models and full-scale vessels.

To predict full-scale phenomena from tests with a scale-model, the absolute magnitude of any one force acting alone could be corrected by a suitable multiplicative factor. The principal concern is that all three forces act simultaneously and that their relative magnitudes be preserved so that the resulting flow is dynamically similar. For this reason, it is illuminating to form the ratios of the three forces, which yield a set of three nondimensional parameters to describe the fluid flow:

$$\frac{\text{Inertial Force}}{\text{Gravitational Force}} = \frac{\rho U^2 l^2}{\rho g l^3} = U^2/gl,$$

$$\frac{\text{Inertial Force}}{\text{Viscous Force}} = \frac{\rho U^2 l^2}{\mu U l} = \rho U l/\mu,$$

$$\frac{\text{Gravitational Force}}{\text{Viscous Force}} = \frac{\rho g l^3}{\mu U l} = \rho g l^2/\mu U.$$

Any two of these three ratios are sufficient to define the third and hence to determine the balance of forces in the fluid motion. Customarily, the first two are employed in the forms.

$$F = \text{Froude Number} = U/(gl)^{1/2},$$
$$R = \text{Reynolds Number} = \rho U l/\mu = U l/\nu,$$

where $\nu = \mu/\rho$ is the kinematic viscosity coefficient of the fluid. A short table of the density and viscosity coefficients for water and air is given in the appendix. Typical values for the kinematic viscosity ν are 10^{-6} m^2/s (10^{-5} ft^2/s) for water and 1.5×10^{-5} m^2/s (1.5×10^{-4} ft^2/s) for air. That this coefficient is small when expressed in terms of conventional units implies that the Reynolds number R will be large; hence viscous forces will be negligible relative to inertial forces. This is generally true, but one must be more cautious before concluding that viscosity can be completely ignored. In fact, viscosity can be neglected for the bulk of the fluid but must be included in singular regions such as the boundary layer very close to a body.

In this analysis we have tacitly assumed steady motion and hence constant characteristic velocity U. If instead the motion is oscillatory in time, as in the case of a buoy oscillating in a seaway, then the characteristic velocity U should be replaced by the combination ωl, where ω is the frequency of oscillations in radians per unit time. The counterpart of the Froude number for such motions is the nondimensional frequency parameter $\omega(l/g)^{1/2}$. Alternatively, we can use the ratio λ/l, where λ is the wavelength, or distance between successive wave crests, since λ can be explicitly related to ω ($\lambda = 2\pi g/\omega^2$ for waves in deep water).

Other important parameters arise when we examine the kinematic and thermodynamic aspects of the fluid. The most familiar of these is the Mach number of aerodynamics, which is the ratio between the velocity U and the speed of sound in the fluid medium; it arises from considerations of the elasticity or compressibility of the fluid. These effects are not important in the motions and behavior of ocean vehicles because water is not significantly compressible at the speeds of interest; in terms of the Mach number we note that the speed of sound in water is on the order of 1,500 m/s or 3,000 knots, which implies a negligibly small Mach number for water–based craft and thus insignificant compressibility effects. On the other hand we must consider in certain circumstances the possibility of cavitation, for when the pressure in the fluid is reduced below the *vapor pressure* p_v, the physical state of the fluid abruptly changes to that of a gas. Thus, while the fluid is extremely inelastic in compression, it cannot normally sustain significant tension. Dimensional considerations suggest the cavitation number

$$\sigma = \frac{p_0 - p_v}{\frac{1}{2}\rho U^2},$$

which is a measure of the likelihood of cavitation and parametrically describes the subsequent details. Here p_0 is a characteristic pressure level in the fluid, such as the hydrostatic pressure at the depth in question, and the vapor pressure p_v depends on the properties of the fluid and its temperature. If the cavitation number is large, cavitation will not occur, and the precise value of σ is immaterial to the description and analysis of the flow. If the cavitation number is sufficiently small so that cavitation occurs in the flow field, dynamic similarity between two flows will exist only if the corresponding cavitation numbers are equal. At normal temperatures p_v is substantially less than the atmospheric pressure, and thus cavitation is significant only at very high speeds.

Fluid motions that have similar geometries but different values of the relevant physical parameters are said to be dynamically similar if the relevant nondimensional parameters such as the Froude and Reynolds numbers are equal. It follows that the relative balance between the inertial, viscous, and gravitational forces is identical, and the resulting hydrodynamic effects, including fluid velocity, pressure, and forces acting on the boundaries of the fluid can all be analyzed by means of relationships between the two different flows. Dynamic similitude is clearly desirable if one is conducting small-scale model tests that can be used to design large-scale vessels. However, the simultaneous scaling of both Froude and Reynolds numbers is not possible, at least for reasonable changes of length scale with water as the full-scale fluid. To see this simply note that the ratio of the Reynolds and Froude numbers, $(g^{1/2}l^{3/2}/\nu)$, must stay constant. For a model length substantially smaller than the full-scale vessel, either the gravitational acceleration must be increased or the viscosity coefficient decreased, by an order of magnitude. The former suggests a centrifuge and the latter a superfluid, but neither is amenable to exploitation in this context.

This discussion of dynamic similitude demonstrates that assumptions or simplifications are often necessary to apply experimental methods with models to the hydrodynamics of ocean vessels. This is equally true, if not more so, if one wishes to pursue a strictly analytical prediction based on rational mechanics. Ultimately, therefore, we must expect both experiments and theory to be used and to be supplemented by full-scale observations to verify the original predictions.

In the theoretical approach the motion of the fluid is defined at each point in time and space by a kinematic description, usually of the vectorial velocity of the fluid particles or alternatively of the three scalar components of the velocity. This unknown velocity function is related by means of Newton's equations to the forces that act upon the fluid;

this yields a system of partial differential equations. For a fluid with conventional stress relations, the resulting system of governing equations is the Navier-Stokes equations, supplemented by the continuity equation expressing conservation of fluid mass. In principle, one can solve these equations, subject to boundary conditions on the boundary surfaces of the fluid. If this procedure could actually be carried out, it would be possible to calculate desired answers for arbitrary values of the Reynolds number and Froude number, and the scaling dilemma of model testing would be circumvented. In practice, however, it has not been possible to solve the Navier-Stokes equations exactly, except for a few cases involving very simple geometries that at first glance have no relation to the shape of marine vessels.

Considerably more analytical progress can be made if the viscous forces are ignored in the Navier-Stokes equations and the fluid is assumed to be inviscid or *ideal*. It is then feasible to construct mathematical solutions for the flow past bodies of realistic form and even to include the effects of wave motions on the free surface, albeit only after further idealizations. Clearly, however, neglecting viscosity will lead to results of only academic interest, unless the justification is more relevant than the mathematical desire to simplify a system of partial differential equations. For predictions of ship resistance, this justification was initially provided by Froude's hypothesis that the resistance could be composed of two separate components, frictional and residual. The frictional component is related to a much simpler geometry, a deeply submerged flat plate, and thus depends only on the Reynolds number. The residual component is assumed to depend only on the Froude number. This hypothesis was essentially an empirical one; its principal justification was that it led to a workable procedure for making model tests and obtaining full-scale predictions not totally at variance with the actual full-scale results. The neglect of viscosity in treating certain aspects of the flow, and Froude's assumption that the frictional resistance of a ship hull could be related to that of a flat plate of the same length and area, found a more rational justification after Prandtl developed the boundary-layer theory. Thus it became evident that at the relatively large Reynolds numbers of interest to naval architects and aerodynamicists, viscous stresses are significant only within the very thin layer of the fluid adjoining the rigid surfaces such as the ship's hull or the airplane. Outside this layer the fluid is essentially inviscid, not because its viscosity has suddenly changed but because viscous stresses are a consequence of large gradients in the fluid velocity and these large gradients are restricted to the immediate vicinity of the boundary. Moreover, the flow within the boundary layer is relatively insensitive to the form of the boundary, provided the body's radii of curvature are large compared to the thickness of the boundary layer. The consequences of Prandtl's boundary-layer theory would appear to be fundamental to Froude's hypothesis, and it is remarkable that Froude predated Prandtl by thirty years.

In the chapters to follow, model testing will be discussed first, with emphasis on the use of dimensional analysis to preserve dynamic similarity between the model and full-scale flows. This glimpse of the "real-world" will serve to introduce the theories that follow in subsequent chapters. The theoretical approach will commence with a study of viscous flows so that the importance of viscosity can be set in proper perspective.

Each chapter begins with a general treatment of the essentials and progresses to more specialized and advanced material. The order in which this is studied can be varied to suit one's interests and background. Readers anxious to proceed to their favorite subject, but lacking the prerequisites to do so directly, should find most of their needs met in sections 3.1 to 3.9 and 4.1 to 4.5. In the references listed at the end of each chapter, preference has been given to recent surveys and papers with comprehensive bibliographies where additional information on each topic may be sought.