An Appraisal of Hydrofoil Supported Craft[1]

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TOPICAL OUTLINE

SUMMARY

The purpose of this paper is to arouse the interest of the naval architectural profession in the potentialities of hydrofoil supported craft and to enlist its aid in solving the problems which stand in the way of fully achieving these potentialities. The paper is essentially expository in nature. The only claims to originality lie in the manner of presentation of known fundamentals and in certain conclusions drawn from them regarding advantages gained and limitations imposed by the use of hydrofoils.

The hydrofoil is described as a hull supported clear of the water surface while under way by the dynamic lift of underwater wings, or hydrofoils. For certain speed-length ratios, it offers a substantial reduction in resistance and a marked improve-

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The statements in this paper represent the personal opinions of the authors and should therefore not be construed as reflecting the views of the organizations with which the authors are affiliated.

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From 1951 to 1953 he served as Technical Officer, Mathematical Sciences Division, Office of Naval Research, Washington, D. C. He is presently on duty at the David Taylor Model Basin, Washington, D. C.

[4] Formerly project officer for hydrofoils in the Design Division of the Bureau of Ships, Navy Department, Washington, D. C.

Commander Stilwell received his degree of Bachelor of Science in Electrical Engineering at the United States Naval Academy in 1938. Following sea duty aboard the U.S.S. *California*, he received a Master of Science in Naval Architecture and Marine Engineering from Massachusetts Institute of Technology in 1943. Subsequently he has served as docking officer at Pearl Harbor Naval Shipyard, chief engineer of the cruiser U.S.S. *Topeka* in the Pacific and has had various duties in Boston Naval Shipyard. He recently acted as project officer for the hydrofoil project in the Bureau of Ships and is currently on duty in the Hull Design Branch of the Bureau of Ships, Washington, D. C.

ment in seakeeping capability over a comparable displacement or planing craft. The efforts of various inventors and shipbuilders to produce hydrofoil supported surface craft and seaplanes during the past half-century are reviewed. The early sporadic efforts have been followed by government supported programs in Germany during World War II and subsequently in this country. The feasibility of hydrofoil craft is considered as well demonstrated, at least for smaller sizes.

To indicate the present state of the art, the most important elements of hydrofoil design are considered in some detail. The methods for determining the principal components of hydrofoil resistance, or drag, are outlined. In a fashion analogous to aerodynamic practice, hydrofoil drag may be separated into profile, parasitic, induced, and wave-making components. A characteristic feature of hydrofoil craft is that the wave drag coefficient decreases rapidly with increasing speed. The "take-off" speed, where the hull first clears the water, is shown to play an important role in determining the over-all relationships between speed, drag, and power required. Configurations embodying fully submerged foil systems are shown to have "hump" power requirements at take-off speed.

The question of stabilizing hydrofoil craft in a seaway is dealt with in a qualitative fashion. The forces acting on a foil in both ahead and following seas are described and certain tentative conclusions are drawn regarding the ability of various configurations to negotiate these seas.

While it is considered that a detailed consideration of the design and construction of hydrofoil craft lies beyond the scope of this paper, a brief discussion is given of certain points where hydrofoil craft depart from more conventional ship design practice.

In evaluating the practicality of hydrofoil craft, comparisons are made of specific hydrofoil and conventional designs both in ranges where the hydrofoil shows a clear advantage and in ranges where the application of foils is obviously absurd. From this, a general study is made to determine where the proper field for hydrofoil applications lies. It is concluded that upper limits on size, together with lower limits on speed, fix the maximum size of hydrofoil craft, consistent with available powering, in the 1,500 to 3,500 ton range, and set the lower limit of Froude number based on over-all length between 0.6 and 0.7. Within these bounds, the prospect is considered favorable for application of hydrofoils to high-speed passenger ferries, small premium cargo carriers, military patrol craft, and pleasure craft.

INTRODUCTION

There is a world-wide resurgence of interest in a novel means of reducing the resistance of high-speed boats called the hydrofoil which well merits the attention of naval architects and marine engineers. It is the purpose of the authors in this paper to trace the developments that have taken place in this field, to evaluate the promise of the device, and to outline the problems inherent in development of these vessels with the hope that interest created in this Society may lead to better solutions to some of the problems.

Anyone who has faced the problem of increasing speed of small to moderate sized ships or boats is well aware of the price that must be paid, particularly in craft which depend on the water surface for support. While in most vehicles such as aircraft, autos, or trains the power required varies roughly as the cube of the speed or less, in ships and boats at higher speeds the power is proportional to about the fifth power of the speed. This physical fact has brought some criticism to the naval architects from certain lay circles which judge progress in terms of speed. A brief reflection shows that wave making at the water surface is the principal contributor to this disparity between ships and other forms of transportation. When it is seen that in a destroyer type in the 30 to 40 knot range, more than half the required power goes into wave making, and when it is realized that there has been no means developed so far to stop a ship from making waves, the prospects for large increases in speed without large compensating increases in power and size look bleak indeed.

Since about the turn of the century various inventors have attempted to overcome this barrier to higher speeds by lifting the hull of a boat out of the water and supporting its weight by the lift produced by hydrofoils operating in the water. In the course of these experiments, it was discovered that, in addition to substantial reductions of power required, the hydrofoil-equipped boat gave better riding qualities in rough water than a conventional boat of comparable size and speed.

Before proceeding to more detailed discussions of hydrofoils perhaps some description of hydrofoil-equipped boats might afford better visualization of the problems involved. While many different configurations of hydrofoils have been tried, four general types will suffice to illustrate ways of doing the job. Referring to Fig. 1 we have examples of craft fitted with the following systems:

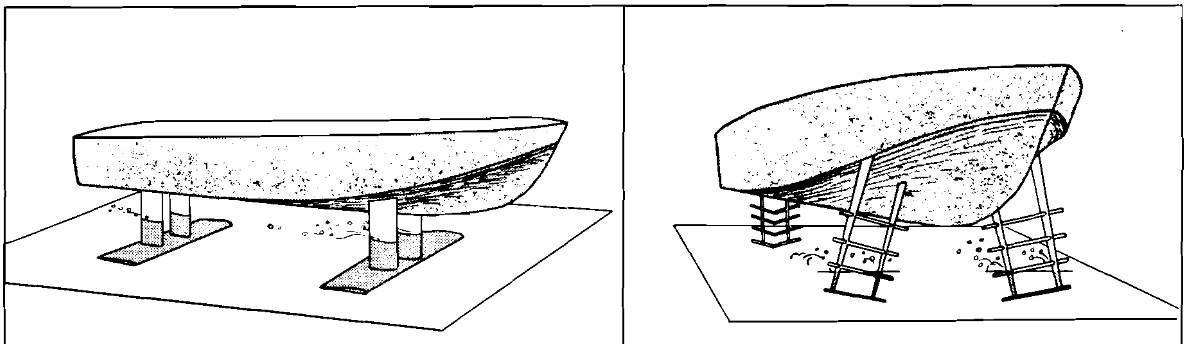
A. Tandem submerged foils
B. Surface-piercing ladder foils

C. Surface-piercing V-foils
D. Submerged after foil plus surface skids (Grunberg configuration)

All of these configurations, among others, have been successfully used on small to moderate size boats, and developments are continuing. Regardless of configuration, the lifting force required is generated by the motion of an airfoil section through the water. This hydrofoil is smaller than its sister airplane wing because of the difference in density of the fluids. Basic lift and drag properties for hydrofoils are directly available from existing published airfoil data. However these data must be corrected for certain effects peculiar to water and the presence of a free surface.

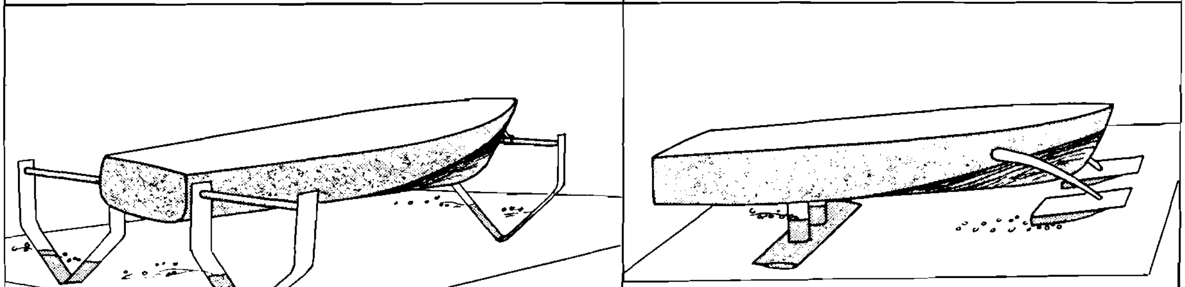
The inherent differences in the four configurations, illustrated in Fig. 1, lie in the methods of obtaining stability and controlling "altitude in flight." The first system requires electric, hydraulic, or mechanical controls which vary the angles of attack of the foils in response to an automatic signal which is a measure of the height of the hull from the water surface. The second scheme (surface-piercing ladder foils) achieves both stability and altitude control by maintaining equilibrium between the lift of the foils that are submerged and the weight of the boat. The third gets its stability and control from the equilibrium between weight and the lift of the portion of the foil remaining submerged. The fourth scheme (a totally submerged after foil and forward skids) is somewhat more subtle. Here, after speed is reached, the skids plane on the water surface and in effect make the boat pivot about this point. Then, the large foil is designed to respond to the trim of the boat, seeking an equilibrium trim where the lift corresponding to the angle of attack on the foil exactly equals the weight not carried by the skids.

In all these schemes, the boat starts from rest in a displacement condition and is accelerated to a "take-off" speed at which foil lift causes the hull to rise clear of the water leaving just the propulsion and foil systems in the water. Little imagination is required to recognize the kinship between this craft and an aircraft, but the presence of the free water surface introduces problems not met in conventional aircraft. Thus the foil boat may be said to fall between aircraft and ships.



(A) TANDEM-SUBMERGED FOILS

(B) SURFACE-PIERCING LADDER FOILS



(C) SURFACE-PIERCING V-FOILS

(D) GRUNBERG CONFIGURATION
SUBMERGED AFTER FOILS
PLUS SURFACE SKIDS

Fig. 1.—Typical Hydrofoil Configurations

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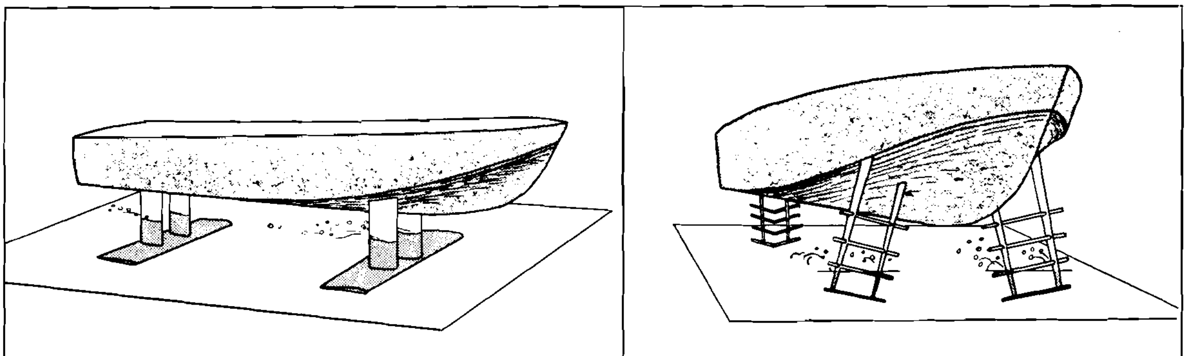

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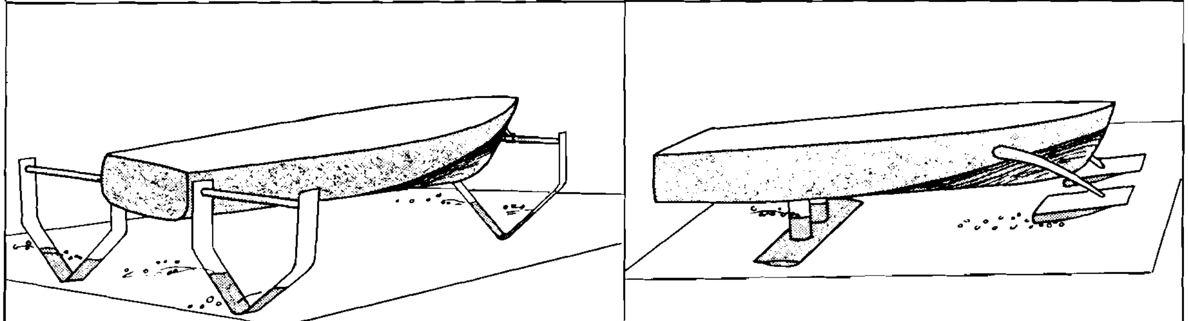

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HISTORICAL DEVELOPMENT

The history of hydrofoil development is a record of many failures italicized by a few notable successes. There is little evidence of a steady improvement in types and much evidence of haphazard approaches to the problems of flight in near proximity to the water surface. In fairness to the many inventors and scientists who turned their efforts to this intriguing problem (including the Wright brothers, Alexander Graham Bell, and Otto Tietjens) it should be stated that there were two fundamental reasons for their meager success. First, the problems of hydrofoil flight are inherently more complicated than those of subsonic aerodynamics. Second, the aircraft faced no real competitor during its formative years while the hydrofoil faced the prospect of comparison with surface transport from its inception. As a consequence, serious consideration of hydrofoil vessels has had to await the development of materials, power plants, and fundamental understanding of principles, fortunately, largely derived from the advances in aircraft and ship design over the past 50 years.

At the turn of the century, the men experimenting with the early aircraft and those developing the first successful planing hulls both considered the use of hydrofoils as an integral part of their experiments. As a result it is difficult to determine when the first true hydrofoil boat actually lifted its hull clear of the water by foil, and not planing lift. In France in 1897 the Comte de Lambert drove a catamaran fitted with four transverse "hydroplanes." The floats, or hulls, were raised clear of the water, but it is not clear whether this was accomplished by planing or hydrofoil lift. Perhaps the first true hydrofoil boat was developed in Italy by Forlanini between 1898 and 1905. This craft was supported by a complex system of flat ladder foils. There is little record of its performance other than evidence that it "flew." Also in Italy, and shortly thereafter, Crocco developed a craft supported by monoplane dihedral foils which attained a reported speed of 50 mph [1].[5]

In 1907 Wilbur and Orville Wright experimented with a foil-supported catamaran on the Miami River at Dayton, Ohio. Testing was abandoned following a river dam failure which resulted in insufficient water depth to permit operating the craft. In 1909 Captain H. C. Richardson, U.S.N., (Ret.) fitted tandem biplane foils to a canoe. When towed at 6 knots this craft flew on the lower set of foils. Later, in 1911, Richardson and White outfitted a dinghy with submerged foils employing manual angle of attack control for stabilization and maneuvering, Fig. 2.

About 1911, Richardson and Curtiss in this country and Guidoni in Italy began using hydrofoils on seaplane floats to assist in take-off. Guidoni's work, in particular, was quite extensive. Over a period of 15 years he designed and flew various hydrofoil-fitted seaplanes ranging in weight from 1,400 to 55,000 lb. Float sizes were reduced through use of hydrofoils, resulting in a substantial reduction in take-off resistance [1]. However, as seaplane take-off speeds increased, the problems of foil cavitation and stability multiplied. Italian efforts in this direction apparently were at an end by 1925.

Dr. Alexander Graham Bell's spectacular boat, the HD-4, entered the picture in 1918, Fig. 3. Together with Mr. Casey Baldwin, Dr. Bell produced a craft of outlandish design coupled with a performance which must be considered remarkable even in the light of present knowledge. With a gross weight of 11,000 lb, the craft reportedly attained a top speed of 60 knots powered by two Liberty aircraft engines of 350 hp each [2]. The foils were of ladder type with dihedral and, despite the complexity of foil and strut intersections, they attained a maximum lift-drag ratio of 8.5 at 30 knots. During the years between the two World Wars, Mr. Baldwin made repeated unsuccessful efforts to interest the Navy Department in the military potentialities of the Bell-Baldwin design. Whether it was the tendency of the HD-4 to porpoise in a seaway or whether it was simply the sheer cumbersomeness of the design which caused these efforts to fail, one may only conjecture. Suffice it to say that there is no evidence of government support of hydrofoil development in any country for some 15 years after World War I.

During the 1930's there was a renewal of interest in the application of hydrofoils to both seaplanes and surface craft. Dr. Otto Tietjens tested his first hydrofoil speed boat at Philadelphia in 1932, and built and tested a second larger boat near Berlin in 1936. Both craft were supported by a configuration embodying a single large dihedral main foil located somewhat forward of the center of gravity and stabilized by a smaller elevator foil at the stern. H. F. von Schertel tested his first successful craft in Germany in 1936. The Schertel design differed from that of Tietjens in that two V-foils in tandem were used, each carrying approximately one-half the weight of the craft. During this period Guidoni's earlier work on seaplane applications was re-evaluated by the British [3]; and, at the request of the United

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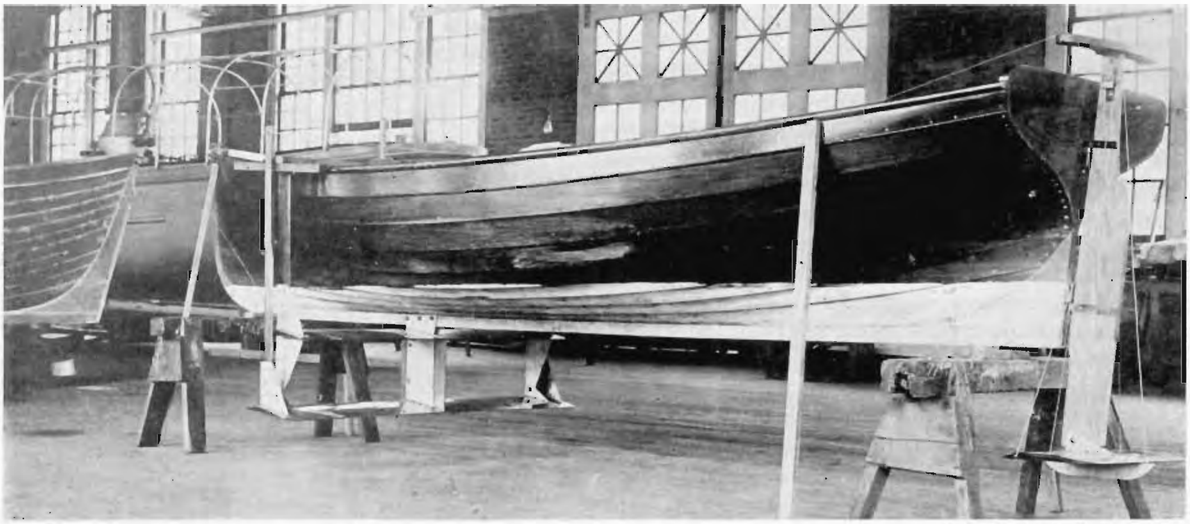
[5] Numbers in brackets indicate references listed at the end of this paper.



Official photograph, U. S. Navy

FIG. 2.—DINGHY FITTED WITH CONTROLLABLE SUBMERGED FOILS

States Navy Bureau of Aeronautics, the National Advisory Committee for Aeronautics undertook a model test program in 1936 initially aimed at testing various configurations originally proposed by Guidoni. In Germany, W. Sottorf reported on extensive experiments with various foil sections for high-speed use aimed at possible seaplane applications [4].

The first really practical configuration employing angle of attack stabilization was conceived in France by V. Grunberg in 1935. This system is shown schematically in Fig. 1(D), and its action in a seaway will be described later. The feasibility of this system was demonstrated at that time by model tests in the towing tank of the Institute Aerotechnique de Saint-Cyr [5]. In subsequent years, his idea has been studied by various investigators—attracted by its simplicity and reasonable margin of stabilization.

The first contributions to the understanding of the wave drag of hydrofoils were made by Russian theoreticians Keldysch, Lavrentiev, and Kotchin beginning in 1934 [6] [7]. While parallel experimental work in Russia was reported by Vladimirov [8], one finds no serious effort in that country to develop either hydrofoil vessels or hydrofoil-supported seaplanes prior to World War II.

With the advent of World War II, German hydrofoil development, already very active, received substantial support from both the Navy and the Army. At the Sachsenberg Shipyard, Rosslau, a number of craft were designed and constructed along the lines of the basic Schertel concept. The Schertel-Sachsenberg affiliation produced craft up to 80 tons displacement with speeds up to 60 knots. The 17-ton patrol boat VS-6, Fig. 4, and the 80-ton tank transport VS-8, Fig. 6, typify this work. At the same time, a 17-ton craft after the Tietjens design was built at the Vertens Yacht Yard in Schleswig and designated VS-7, Fig. 5.

None of the German craft was placed in operational use, despite the concentrated development effort. Various reasons have been given for the

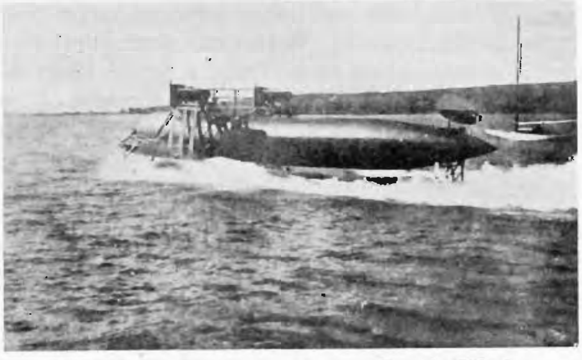


FIG. 3.—ALEXANDER GRAHAM BELL'S HD-4

FIG. 4.—SCHERTEL'S VS-6 ON TRIALS

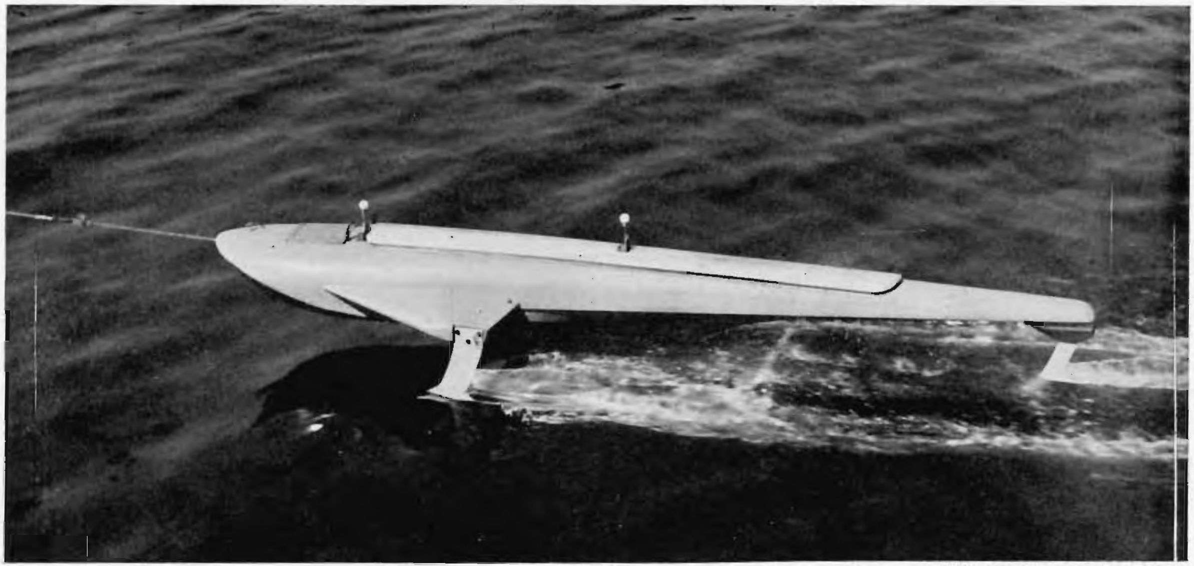
FIG. 5.—THE VS-7, TIETJEN'S COUNTERPART TO THE VS-6

FIG. 6.—THE TANK TRANSPORT VS-8, BY SCHERTEL-SACHSENBERG

failure of the program, chief among which were the insistence of the German high command for quick results and the lack of suitable materials and trained engineers. Allied bombing of the building yards destroyed most of the craft under construction and the deteriorating condition of the German war effort brought an end to the program in 1945. Tests of VS-6 and VS-7 furnished inconclusive results. VS-7 was the faster boat, but was much poorer than VS-6 from the point of view of stability and maneuverability. The ambitious VS-8 was apparently underpowered. During one series of tests she failed to remain foilborne in a following sea and was subsequently beached and abandoned. Some of this work is reported in Refs. [9] and [10].

In this country, the National Advisory Committee for Aeronautics has continued a modest program of hydrofoil investigations primarily aimed at seaplane applications [11] [12]. Various individuals have developed hydrofoil craft since World War II both here and in Europe. A novel extension of the Grunberg concept was devised by Christopher Hook of Cowes, Isle of Wight. The Hook boat, Fig. 7, uses two surface skids on long jockey arms ahead of the craft to stabilize inde-

FIG. 7.—CHRISTOPHER HOOK'S HYDROFIN



Official photograph, U. S. Navy

FIG. 8.—TWELVE-FOOT OPEN WATER MODEL FITTED WITH BIPLANE V-FOILS

pendently two forward submerged foils, each bearing one-third the load of the craft. An after foil, integral with the propulsion system at the stern, carries the remaining load and requires only craft trim to achieve adequate stabilization. Two Swedish engineers, Almquist and Elgstrom, built several craft basically of the Grunberg configuration, but with curved main foils to obtain area stabilization as well.

A number of small speed boats employing three retractable V-foils have been developed and constructed by J. G. Baker, of Evansville, Wis. An important feature of his design is the absence of immersed supporting struts. All underwater surfaces, except for the outboard propulsion unit, are lifting surfaces with consequent minimization of parasitic drag. Schertel has resumed activities in the field. His new passenger ferry, PT-30, is similar to VS-6 in appearance. It has been operating recently on Lake Lucerne, Switzerland. Ref. [9] indicates that this craft displaces 9.5 tons and achieves 40 knots with 450 hp.

Since 1947, the Navy Department has supported a program for hydrofoil research and development involving the cooperative efforts of ship designers and government and university laboratories. An intensive effort has been made to overcome problems of foil design and stabilization which thwarted many early investigators. Studies have been made to determine the limits of practical size and speed, consistent with feasible powering, within which the hydrofoil possesses inherent advantages over other surface craft. In the course of this work, certain small test craft were developed to permit open water evaluation of performance in a seaway.

Fig. 8 shows a 12-ft open-water model employing a pair of biplane V-foils forward with a small V-foil elevator aft. Two basically different test craft of about 20 ft in length are shown in Figs. 9 and 10. The former has four V-foils arranged in tandem providing inherent stabilization. The latter employs an automatic surface-sensitive incidence control system acting on a tandem submerged foil configuration. Other systems of hydrofoil support are also under active consideration.

In retrospect, it appears that the hardy persistence of the hydrofoil concept for over a half-century testifies both to its basic soundness and to its difficulty in execution.

STATE OF THE ART

The present state of knowledge of hydrofoils may be said to lie somewhere between research and development and practical design, depending on the size of the craft. To best illustrate this status, there follows a discussion of the design problems encountered in these boats and their methods of solution.

The same problem exists in design hydrofoil craft that is involved in conventional ship design, namely the proper balance of the major variables so as to best achieve the required function. For proper consideration of the important factors, a hydrofoil craft should be considered as a carefully designed foil system with an integrated propulsion unit supporting and propelling the necessary mass at a given speed, subject to external conditions.

Official photograph, U. S. Navy

FIG. 9.—UNITED STATES NAVY TEST CRAFT EMPLOYING TANDEM V-FOILS

The estimation of power required depends on reasonably accurate determination of resistance under flying and take-off conditions. Since much of the data required in this estimate is derived from tests of airfoils and aircraft components, aeronautical terminology is used for convenience. Thus resistance is described as drag.

Official photograph, U. S. Navy

FIG. 10.—AUTOMATIC INCIDENCE CONTROL STABILIZATION ON A 20-FOOT UNITED STATES NAVY TEST CRAFT

Hydrofoil Drag

Since the weight of the craft is supported by dynamic lift of the foils, we equate displacement to lift and write

$$\Delta = L = C_L \cdot \rho/2 \cdot S \cdot V^2$$

where S is the projected foil area.[6] The selection of the foil section and operating lift coefficient C_L is a careful compromise between conflicting requirements for high foil strength, minimum total drag, and avoidance of foil cavitation at maximum craft speed and flow separation at take-off speed. The method of stabilization and the sea state which the craft must be capable of negotiating on foils play important roles in this determination. Generally speaking, the selection of a foil section with a flat suction-side pressure distribution, a thickness ratio in the order of 10%, and a design lift coefficient of about 0.25 affords a reasonable starting point for a preliminary drag estimate.

Lift coefficients obtained from aerodynamic data should properly be modified for the effect of foil submergence. However, while a hydrofoil tends to lose lift as it approaches the water surface, the effect on lift coefficient is not particularly significant for submergences of one chord or greater and may reasonably be ignored in preliminary calculations.

The total drag of a hydrofoil craft may be expressed as

$$D = C_D \cdot \rho/2 \cdot S \cdot V^2$$

where the dimensionless total drag coefficient C_D is the sum of profile, parasitic, induced, and wave drag coefficients:

$$C_D = C_{D_0} + C_{D_p} + C_{D_i} + C_{D_w}$$

each expressed in terms of the projected foil area. The induced and wave drags are entirely residual in nature, while the profile and parasitic drags have both frictional and form components.

The free surface does not appear to have an important effect upon the profile drags of struts and foils, hence these coefficients may be obtained from known aerodynamic data such as in [13]. For a lifting surface, the profile drag coefficient is

$$C_{D_0} = (C_{D_0})_{\min} + KC_L^2$$

expressed as where $(C_{D_0})_{\min}$ and K are dependent upon the section used and are functions of Reynolds number.

The principal sources of parasitic drag are:

A. Hull windage
B. Surface interference drag of struts (spray drag)
C. Interference drags of foil-strut intersections
D. Drag of underwater appendages such as propulsion nacelles, control rods, and hinge joints

Where intersections of one or more lifting surfaces occur, the corresponding interference drag coefficients are functions of the C_L^2 for the lifting surfaces. No detailed treatment of the various parasitic drags will be attempted here as their determination for hydrofoil configurations follows from the many experimental and theoretical results obtained in aerodynamic and naval architectural work [14].

One parasitic drag, however, is peculiarly important to hydrofoil craft. This is the surface interference drag, or spray drag, occurring at the point where struts or foils pierce the water surface. It results from a complex combination of effects involving air entrainment and spray formation. The wave-making component of this drag is of little consequence because of the very high Froude numbers, based upon strut chord, c, at which most hydrofoil craft operate. A reasonable measure of this drag has been derived from tank tests as

$$R = C_{Dt} \cdot \rho/2 \cdot V^2 t^2$$

where t is the strut thickness and where an approximate value of the coefficient $C_{Dt} = 0.2$ may be assumed for $F_c = V/\sqrt{gc}$ greater than 10. For lower Froude numbers, C_{D_t} assumes much higher values which are roughly proportional to the thickness ratio t/c. The dependence of spray drag upon strut profile and rake angle make further generalization on its magnitude difficult.

An important assumption is made in the calculation of the remaining portions of the drag of hydrofoil craft; namely, that the induced and wave drag components may be treated separately. Considering a uniformly loaded submerged hydrofoil represented by a horseshoe vortex, this assumption amounts to an arbitrary separation of the bound and trailing vortex drags. The induced, or trailing vortex, drag may be calculated by use of classical biplane theory considering the image vortex system to have circulations of the same direction and magnitude as those representing the submerged hydrofoil. The separation between the hydrofoil and its image is, of course, twice the foil submergence. The induced drag of the hydrofoil is then the sum of the drag derived from the effect

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[6] All coefficients, such as C_L, appearing in this paper are dimensionless. Where units for physical quantities are not explicitly stated, they may be inferred from context.

of trailing vortices of the foil itself plus that derived from the effect of the image trailing vortices on the foil. This may be expressed in coefficient form as

$$C_{D_i} = \frac{C_L^2}{\pi \text{A.R.}} (1 + \sigma)(1 + \delta)$$

where σ is the Munk interference factor and δ is the planform correction [15]. This representation is consistent with the free surface conditions only for infinite craft velocity (or infinite Froude number $F_h = (V/\sqrt{gh})$). However, since the Froude numbers, F_h, of most hydrofoil craft at their designed speeds and foil submergences are usually quite large, and the corresponding wave drags are usually small, this formulation agrees reasonably well with experimental results.

A two-dimensional treatment of wave drag effect based upon bound vortex circulation appears adequate for estimating the wave drag coefficient. This result, obtained in 1934 by Keldysch and Lavrentiev [6], is here modified by the assumption that the effect of submergence upon lift may be neglected. The resulting expression in coefficient form is

$$C_{D_w} = 0.5 \frac{C_L^2}{F_c^2} \cdot e^{-2/F_h^2}$$

where $F_c = V\sqrt{gc}$ is the Froude number with respect to foil chord c and $F_h = V/\sqrt{gh}$ is the Froude number with respect to foil submergence h.

It is thus seen that the wave drag coefficient is a function, not only of C_L^2, but also of two distinct Froude numbers F_h and F_c. However, since practical considerations of strut drag and strength limit foil submergences to the order of one to three chords, a single Froude number F_c may be considered to govern the magnitude of the wave drag component for feasible hydrofoil designs. Here the "effective craft length," or characteristic dimension, is simply the chord of the lifting hydrofoil, consequently all hydrofoil craft operate in a regime where wave drag decreases with increasing speed. As may be seen in Fig. 11, very small, high-speed craft have almost negligible wave drag.

With the increase in size of hydrofoil craft, and corresponding decrease in their designed speeds to limits imposed by available powering, the wave drag becomes a very appreciable component of total drag. A possibility then arises for the elimination of a substantial portion of the wave effect by use of a tandem foil configuration with foil spacing so adjusted to the design speed that the wave created by the forward foil is partially annulled by the wave from the after foil. The two-dimensional treatment of Ref. [6] gives the disturbance of the free surface at a distance x in

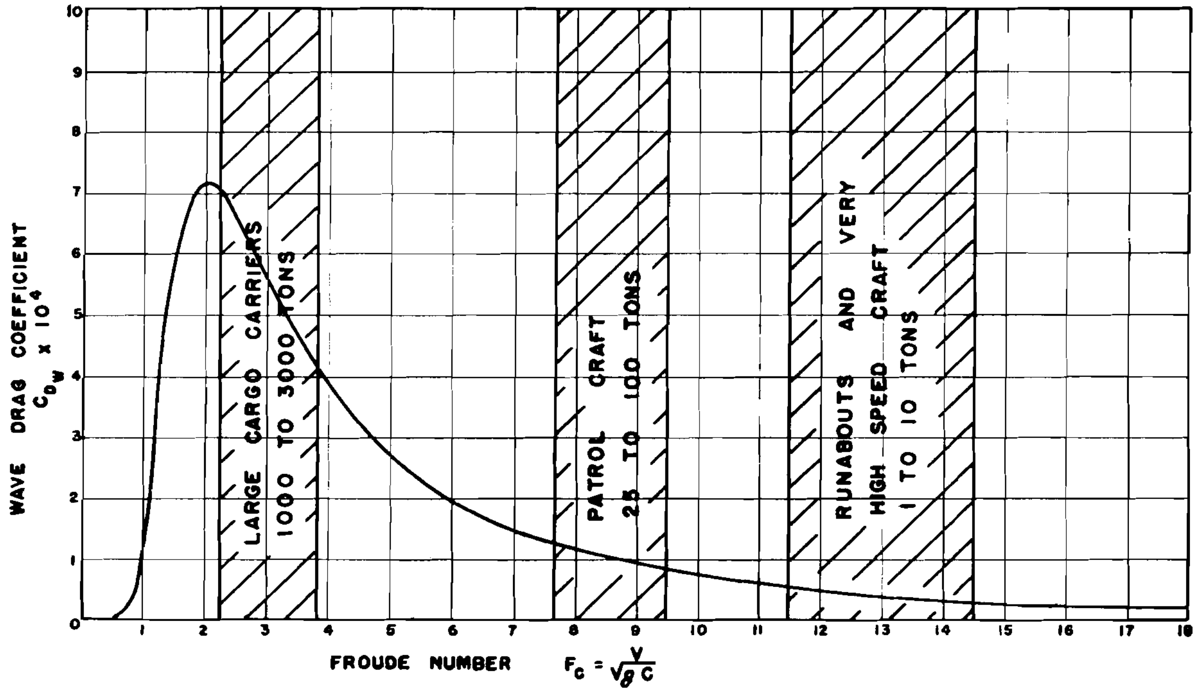

FIG. 11.—RELATIVE IMPORTANCE OF WAVE DRAG FOR VARIOUS HYDROFOIL TYPES

feet behind a bound vortex of strength Γ at a submergence h as

$$y = \frac{-2\Gamma}{V} e^{-1/F_h^2} \sin \frac{gx}{V^2}$$

where V is the free stream velocity in fps. Strictly speaking, this formula applies only for very large x. Practically, it is a good approximation to the surface for distances of one-quarter wave length or more behind the foil. The wave length of this disturbance is $2\pi V^2/g$, hence locating a second bound vortex of the same strength a distance $\pi V^2/g$ ft behind the vortex would result in a complete cancellation of the disturbance. For a hydrofoil ship with a designed speed of 30 knots, the required foil spacing would be about 250 ft. This must be regarded as approximate, for the formula is only asymptotically correct and does not consider the bound vortex and source distribution necessary to form a mathematical model of a foil whose chord/submergence ratio is of the order of unity. More importantly, the three-dimensional effect of the trailing vortices results in waves characterized by the appearance of a roach or "rooster-tail" in the wake of a single submerged foil. This non-uniformity in flow may well affect the foil spacing required for optimum recovery of wave drag.

Even a brief discussion of hydrofoil drag such as this one should not omit some consideration of the troublesome question of the effect of surface roughness and fouling upon the profile drags of foils and struts. It seems that the acceptance of drag coefficients, based upon standard roughness as defined by the NACA [13], leads to pessimistic conclusions regarding the performance attainable by hydrofoil craft. Such conclusions are probably unwarranted, especially in the case of smaller craft employing retractable foils. Here it appears quite feasible to construct and maintain foil surfaces with a degree of smoothness practically unattainable in aircraft wings (with due regard to proper scaling in this comparison). On the other hand, acceptance of very low profile drag coefficients obtained for "laminar flow" sections is equally unjustified in view of the turbulent nature of a seaway and the variable operating conditions required of the foil.

For large hydrofoil craft—where foil retraction becomes clearly impractical—fouling and corrosion will certainly take a heavy toll in increased drag. This situation will probably be only partially mitigated by the possibility of improving the relative smoothness of foils during construction because of the increased craft sizes. Little or no data exists which would permit a quantitative evaluation of these effects. There is, perhaps, some small comfort in the realization that the knowledge of the effects of surface roughness on the full scale resistance of conventional ships and aircraft is far from adequate, despite years of investigation.

TAKE-OFF

In the design, and particularly in the powering of hydrofoil craft, careful attention must be paid to the conditions of take-off. Take-off may be defined as the instant that the hull leaves the water, or the instant at which the hull ceases to contribute to either the lift or the water drag of the boat.

This discussion is limited to the "aircraft type" take-off which may be described as follows: At rest, the entire weight of the boat is supported by the hull buoyancy; as the craft accelerates, the foils increase their lift, unloading the hull, until at take-off speed the entire weight is on the foils and the buoyancy (or lift) of the hull is reduced to zero.[7]

The phenomenon that causes the most trouble in foil craft take-off is the drag hump. Characteristically, the thrust required to propel the hull and foils increases to a maximum as take-off is approached. Then, as the hull clears the water, thrust requirements drop to a minimum value at a speed slightly over take-off and then climb again, until with proper design, the full power is reached at maximum speed. Although the power available for full speed is usually considerably more than the maximum hump requirement at take-off, the normal characteristics of propellers, attempting to deliver high power at relatively low speed of advance, limit thrust available. Therefore, the maximum resistance at take-off rather than the power required is the controlling factor, Fig. 12. In addition, the margin of thrust available over resistance is the accelerating force, the amount of which determines the time and distance required for take-off. A good thrust margin is required because take-off may be necessary in rough seas and under other adverse conditions that increase resistance, particularly of the hull. Even in ideal conditions, a craft that can just get to a condition of equilibrium between thrust and resistance at take-off speed will not take off, as there must be a slight excess of lift over weight to provide for the vertical acceleration needed to lift the boat to its flying attitude.

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[7] An alternative "elevator type" take-off has, on occasion, been used with submerged foil craft. Here the craft accelerates to flying speed without lift on the foils, then, suddenly, lift is applied and the craft rapidly ascends to its flying attitude. The authors find no advantage in the elevator type take-off.

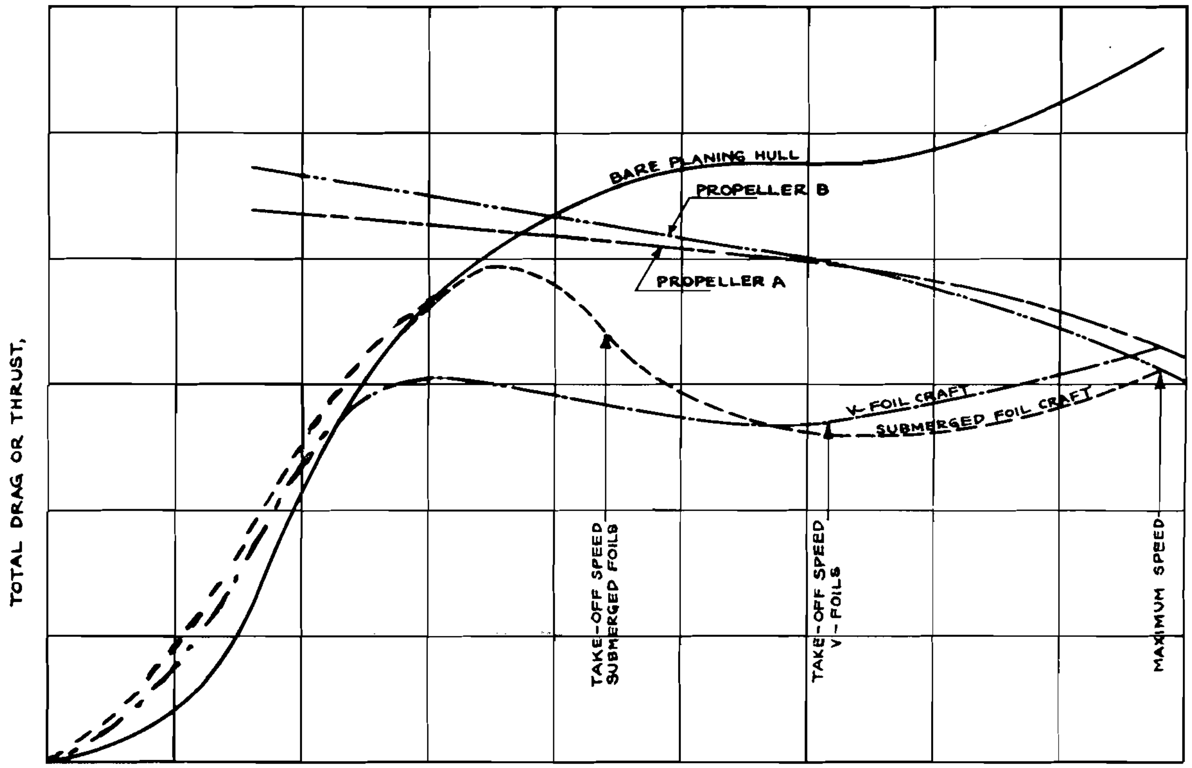

FIG. 12.—TYPICAL THRUST-DRAG CURVES FOR TWO HYDROFOIL CRAFT

The speed selected for take-off coupled with the foil lift coefficient that can be tolerated in this condition will determine the minimum foil area required for the craft and thus will affect the top speed, unless a surface piercing or ladder-type foil is used where some of the area required for take-off comes out of the water at top speed. In choosing take-off speeds and lift coefficients, it is convenient to use a relatively high value of lift coefficient and a relatively low take-off speed to avoid prolonged runs at full power and with objectionable wave encounter. It can be shown that take-off distance is a function of speed squared so that an increase of take-off speed causes a large increase in distance. However, since the induced drag of the foils increases as the square of the lift coefficient, this practice may induce unacceptable power humps requiring a compromise in top speed or the inclusion of variable pitch propellers in an already complicated propulsion problem.

The problem of designing a hull and estimating its performance under these conditions of unloading with increased speed is peculiar to the hydrofoil and seaplane fields. Since the amount of foil lift and drag imposed on the hull depends on the speed and the trim, and since the trim during take-off is a resultant between the natural trim of the hull at the given speed and the impressed trim from the action of the forward and after foils, the estimation of the total resistance at any pre-take-off speed is a complex job that is best handled by model experiments.

For the initial selection of the hull form for this service, certain guides can be set down. To reduce impact loading during inadvertent high-speed touch down or during momentary wave slap when flying, V- or U-shaped sections appear to be preferable to flat sections. As for the best form for take-off, the speed at take-off and the size of the craft must be considered. If the take-off speed is in the range of speed-length ratios for the craft that are favorable for displacement operation, then a displacement type hull should be used. If, however, the speed is such that in a normal craft of the size planing would be an advantage, then a planing type is indicated. In addition to these considerations of impact and minimum hull resistance, if the foil configuration is a surface-piercing, Grunberg, or ladder type, the trim of the hull under the speed and load conditions to be met must be investigated, since, in these cases, the ability of the foils to achieve a proper lift coefficient to lift the craft depends to a certain extent on the hull trim.

The surface-piercing and ladder type configurations generally have a smooth take-off with little drag hump as compared to the fully submerged foil types. On the other hand, the submerged types usually can take off at lower speed but with a sharper transition evidenced by a considerable drag hump, Fig. 12. This condition is brought on by the fact that the submerged foil uses the same amount of area at take-off as it does at top speed. Thus there must be a large lift coefficient at the low take-off speed to support the weight. This can only be achieved by increasing the angle of attack. Assuming a take-off at one-half of top speed, the submerged foil will require a lift coefficient equal to four times that at top speed, and since the induced drag varies as C_L^2, the induced drag at take-off will be about four times its value at top speed. With the surface-piercing type foil, on the other hand, it is common practice to use about one-half of the total area available for top speed operation, and almost all the available area at take-off. Therefore, the take-off lift coefficient can be about twice that for top speed and the induced drag, taking into account the effects of aspect ratio change, will be about the same for both conditions. The above effect is so marked that in actual operation it is often difficult to ascertain the exact take-off point with surface-piercing foils.

All of these factors affecting take-off assume added importance when it is realized that a hydrofoil is usually capable of flying through sea conditions which it would have difficulty negotiating as a displacement craft, and that unless it has excellent take-off capabilities, a landing in such a sea might become permanent.

STABILITY AND SEAKEEPING

A major advantage of hydrofoil craft is their ability to operate at full power in a seaway, i.e., they are capable of maintaining higher sustained speed in a seaway than displacement or planing craft of comparable size and power. This is accomplished by keeping the hull above the wave surface resulting in a large reduction of wave impact forces. The seakeeping advantage is most beneficial to small vessels (below 1,000 tons) since sea states experienced are frequently large by comparison. While the reality of this advantage has been amply demonstrated by small craft presently in operation, the full potentialities of hydrofoil stabilization have not been attained. Some of the troublesome (and challenging) problems involved are indicated.

Most hydrofoil craft can be stabilized in calm water and the requirements are clear. However, with few exceptions hydrofoil craft are required to operate in waves, and the combined requirements of stability and wave response are not fully understood. Speaking in general terms the flying characteristics of a hydrofoil should be a compromise between two requirements. From the point of view of comfort and minimum acceleration, the craft should fly in a straight path with the irregular water surface positioned within the gap between the hull and foils. This implies no wave response and is indeed the most satisfactory means of flying in small waves. However, from the point of view of maintaining the hull above the water surface the craft should closely follow the wave pattern as the waves get larger. Since these are limiting conditions, a compromise between the two is strived for in most hydrofoil designs.

Surface-piercing V-foils have been used extensively since they serve as stabilizing members as well as lifting surfaces. Lateral stability is inherent if the center of gravity is not too high, since heel provides increased foil area on the low side, and the increased lift produces a righting moment. Longitudinal trim is maintained in a similar manner since when a foil sinks below the equilibrium position it adds more foil area producing a restoring force. It should be noted that as speed increases a craft with a constant chord V-foil configuration tends to rise in the water. If this proves undesirable, the rates of change of lift with submergence for the forward and after foils can be physically altered so that the trim of the craft and resultant angle of attack of the foils is reduced as the speed is increased. This prevents the craft from rising too high.

Where permissible foil dimensions unduly limit the rate of change of lift with submergence of V-foils, or where an increased range of flying speeds is desired, ladder foils can be used. Dihedral is usually incorporated in the ladders making the stabilizing action much the same as that of V-foils. However, the operation of a ladder configuration in a seaway produces complex spray and interaction effects characterized by erratic variations in hydrodynamics forces on the system.

The Grunberg configuration has one main submerged foil aft with surface stabilizers forward and lateral and longitudinal stability are achieved by the forward planing surfaces. These surfaces, or "skids," have strong depth stability and poor lift/angle of attack curve slopes. Since these are no better than conventional planing hulls, they are not used for main lifting surfaces, and normally carry only 10 to 20% of the weight of the craft. The remaining weight is carried on the main foil placed aft of the center of gravity. However, the "skids" are quite satisfactory as stabilizing surfaces, providing a positive force to locate the craft in the proper relation to the water surface. The craft trims about the planing surfaces. Consequently if the main foil tends to rise, it automatically decreases its angle of attack and lift as the hull trims, thus the craft returns to the original position. The dynamics of such a craft can be investigated by making the assumption that the skids follow the wave contour. In practice it has been shown that is true for low frequencies of wave encounter but is not realistic for high frequencies. Therefore, such calculations must be properly weighed, and since they are tedious, model tests are probably more desirable. The tendency of the "skids" to skip and the light damping of disturbance motions are disadvantages.

With fully submerged foils the situation is somewhat different. Since the foils must remain submerged at all times, they are not affected by their depth of submersion. Essentially, no inherent stability or control is present and some type of stabilization must be provided.[8] The possible configurations are a large foil under the center of gravity supporting most of the weight of the craft with a small tail foil aft for balance purposes and the tandem foil arrangement where the two foil areas are approximately equal. There has also been some use of the "Canard" configuration with the small foil forward. All of these must be artificially stabilized.

Submerged foil configurations can be provided with incidence or flap control for the foil sections. The angle on the foils or flaps is governed either by a very lightly loaded planing surface and mechanical linkage or by a water surface detector providing a signal to an autopilot which in turn motivates an actuator to position the angle of attack of the foil. With a configuration of this type it can be assumed that the foils are completely submerged at all times and the stability may be investigated satisfactorily by theoretical means, namely the traditional aircraft approach to dynamic stability and servo mechanisms, modified by the hydrodynamic surface effects.

The ability of the hydrofoil craft to fly in waves of various heights depends upon the relation of strut to craft length, the frequency of encounter with succeeding wave crests, and the effects of orbital velocities. The relation of strut to craft length determines what vertical displacement the craft must make to keep the hull clear of the wave profile. The choice of strut length governs the maximum craft motion normal to the wave profile as well as the admissible normal accelerations equivalent to limiting column loading of the struts.

The frequency of encounter with wave crests is a function of craft velocity relative to the sea and of the wave length. It governs the time in which corrective actions at the foils must act, and conversely, the time in which orbital velocities may affect the foil lift. The higher the frequency of encounter with waves, the less time there is for variations in lift to act, and the smaller the vertical displacement. For the same boat speed the frequency of encounter is lower while running with the waves than when going into them. Hence the need for changing the attitude of the foil or foil area is not as great in the case of head seas as in following seas.

The orbital velocity of the water, added vectorially to the craft velocity and to the instantaneous velocities due to pitch and heave of the craft, determines effective change in the angles of attack of the foils from their steady state values. These effects on foil lift must be coupled with the stabilizing effects of the configuration (area change for V-foils or angle change for controlled submerged foils) in relation to the instantaneous position of the craft in a wave train.

In the head sea condition as a foil system approaches the face of a wave either more foil area is added or in the case of a controlled submerged foil a signal developed indicating a depth error in a direction that causes the foil to increase its angle of attack thus causing the foil to rise. Also as the foil enters this portion of the wave it enters an area of upward water particle motion which further increases the effective angle of attack of the foil relative to the water flow, hence causing an additional upward force on the foil.

There are two basic differences between head and following seas which affect the behavior of hydrofoil craft. The frequency of encounter in following seas is greatly reduced giving the craft more time to respond and the orbital motions are in a detrimental rather than favorable direction. The orbital motion of the water particles in the back slope of a wave is downward which, when vectorially added to the horizontal velocity of the water past the foil due to the forward velocity of the craft, has the effect of decreasing the angle of incidence of the foil relative to the water flow. If the geometric foil angle is not changed or if the slope of the lift/angle of attack curve is not altered by other means, the foil experiences a reduced lift force at the very time that lift should be increased in order for the foil to rise and track the wave it is approaching and overtaking. The re-

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[8] A small stabilizing force exists due to a decrease in lift as a foil approaches the surface. It is possible in model scale to produce a configuration with fixed submerged foils which is stable for small disturbances. This is of little practical importance in full scale operation in a seaway.

verse and equally detrimental condition occurs under the forward face of the wave. There, the orbital velocities tend to raise the foil as it approaches a trough. The above is premised on the practical assumption that the craft velocity is higher than that of the waves. In the unusual case, where the following sea overtakes the craft from astern (very large fast waves), the orbital velocities aid the craft response as in a head sea.

The actions of submerged and surface-piercing foils in response to these dynamic conditions are quite different. For V-foils the principal restoring forces are provided by changes in foil area. At design speed these foils operate about half submerged, hence the maximum restoring force is approximately equal to the steady state lift. Submerged foils, on the other hand, operate with a constant lifting area and meet changing flow conditions by changes in angle of attack as signaled by some surface sensing device. At low flying speeds, restoring forces in the order of 3 to 4 times steady state lift are obtainable without stalling. However, at high speeds in a seaway, the permissible variations in lift coefficient, and the restoring forces available, must be severely limited if cavitation is to be avoided.[9]

One cannot make generalizations about the relative seakeeping capabilities of various configurations without considering the foils in their relation to the motion of the entire craft. Certainly trim, for example, plays an important role.

Despite the many variables involved, a few qualities appear inherent in each system operating in specific sea states. From the foregoing discussion one may conclude that an automatically controlled submerged foil craft will be superior to a V-foil craft in a following sea where relatively large, slow changes of flow occur. Conversely, a V-foil craft should perform better in head seas where high frequency of wave encounter is present. Ladders offer one possibility of improving the following sea operation of area stabilized craft, if the added drag penalties can be accepted, since the higher foils of the ladder system can be placed at greater angles of attack. The relative insensitivity of planing skids to orbital velocities indicates why a Grunberg configuration shows better ability to fly at low frequencies of encounter than a V-foil craft.

It is perhaps too much to expect that the future will see the development of a single method of stabilization which is optimum for all operating conditions. Yet the state of hydrofoil art, as demonstrated by the various radically different configurations presently in use, is curiously akin to that of aircraft just prior to the first World War. The underlying cause is the problem of stabilization, now as then. It is here, more than in any other particular, that emphasis on research and development must be placed if the hydrofoil is to realize its full potentialities. Modern techniques of analysis, model studies, and full scale evaluations developed in allied fields are certainly applicable—although the problem is severely complicated by the seaway. Even a cursory examination of the reported effects of sea state on sustained speed for conventional ships, however, shows that the speed losses incurred by them are great. It is felt that the prospect of alleviating this situation, for certain size-speed ranges, by use of the hydrofoil is great enough to warrant further serious consideration.

MISCELLANEOUS DESIGN CONSIDERATIONS

Sufficient information on hydrofoils is available to enable the designer to select the foil-strut combination to satisfy the design conditions. In most cases, however, it is difficult to rule out all but one possibility and two or more approaches may necessarily be developed in preliminary design form before the choice becomes apparent.

Generally, for small high-speed craft, the surface-piercing systems such as V or ladder configurations are preferred for simplicity and reliability.

As the size of the craft increases, geometry usually dictates that the main lifting surfaces be placed under the hull indicating submerged foil configurations. The size at which the complication of automatic control of submerged foils is required has not yet been definitely set but it appears to be in the 25–50 ton range. Even below this size, submerged foils with surface sensing such as the "Hook" configuration may be worth the extra complications if extreme seaways are anticipated and good riding qualities are required. The ladder foil system will also give excellent seakeeping but inherently gives a rougher ride. The V foil system while not as good in a seaway as some of the others, has proved to be one of the lowest drag configurations and should be considered wherever speed and simplicity are important.

Once the configuration has been indicated it becomes necessary to decide on a distribution of the foil area. Here the location of the center of gravity is of prime concern. The single foil with the main lifting surface under the center of gravity is practical in some instances, but may involve an added drag penalty due to the necessity of a non-

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[9] One may fairly ask if it is really necessary to avoid cavitation. Ref. [11], for example, presents test data indicating that the inception of cavitation is not accompanied by catastrophic effects on lift and drag. From the point of view of stability, however, there is little doubt that it introduces a significant, and relatively unknown, factor into an already complex problem. Here such danger as control reversal must be considered.

lifting stabilizing surface. Also placing all the area in one foil increases the span and this becomes a disadvantage in the larger sizes. Foil areas can be distributed fore and aft, in a "tandem" arrangement with two nearly equal foils. This has advantages but in quartering seas produces asymmetrical loading and subsequent racking. The third possibility of main area aft is not as common as the others, but works satisfactorily in some configurations. Generally, if the idea of a mail foil supporting most of the weight is used, the closer the center of gravity of the boat is to this foil, the better the seakeeping qualities of the boat.

Foil areas must be carefully selected after due consideration of the effect of various foil loadings. Foil area contributes greatly to the parasite drag and should be kept to reasonable proportions. In order to respond to sea conditions and the variation in speed from take-off to full speed, a lift of 3 to 4 times the weight of the craft should be possible without loss of lift. The stall lift coefficient equals 0.9 or 1.0; so, in practice, the design lift coefficient at operating speeds cannot vary greatly from about 0.2 to 0.3 except for very high speeds where lower values may increase cavitation free speed.

A great variety of foil sections have been utilized for hydrofoil craft. Although most of them have been standard aircraft sections there has been no indication of a universal preference. The thickness ratio ranges from 4 to 18% with the thinner sections being necessary for higher speed craft. To delay the inception of cavitation, and to reduce drag, sections should be thin as possible consistent with strength.

Various standard aeronautical devices such as sweep back, taper, dihedral, and careful intersection and tip design can be employed with equal success in hydrofoils to improve the drag and "flying" qualities of the configuration selected. It is, of course, important to keep all the immersed portions of the configuration hydrodynamically clean by the elimination of unnecessary intersections, sharp corners, or unfaired protuberances.

The primary requirement for strut design is adequate strength with minimum drag but consideration must also be given to providing sufficient lateral area for turning. The maximum lift coefficient obtainable for a strut piercing the surface at 90° is about 0.3. The optimum strut shape varies from the submerged portion to the point of surface penetration. However, most struts are made uniform in section and simple ogival (arc form) sections have proved satisfactory in service.

Hull design is a straightforward naval architecture problem influenced strongly by such factors as take-off performance, wave impact, and the concentration of loads over the strut attachments. In smaller sizes, experience has shown that hulls designed for displacement or planing operation usually have sufficient strength for foil operation. In fact, in one case, a hull that was satisfactory with foils was found to fail when subjected to low speed planing operation.

POWER PLANT AND PROPULSION

The over-all design of hydrofoil boats is materially affected by the characteristics of available power plants. As in any boat or ship in the higher speed ranges, lower machinery weight and lower fuel consumption give a better design. In larger sizes of hydrofoils, the great growth of foil size with increased over-all weight places an added penalty on heavy machinery. Since, in general, machinery weight per horsepower increases with the capacity per unit, this process is magnified to the point where very large hydrofoil craft may well depend for their existence on the development of very light high-powered machinery. In small sizes, however, the hydrofoil can compete with other craft on an equal machinery basis. Fuel rate of course cannot be unduly sacrificed in the search for light machinery if reasonable range is to be kept.

Transmission and shafting design is unique in the hydrofoil case. Here, the power must be transmitted from the prime mover in the hull down to a propeller at about the deepest level of foil submergence, a distance in even a small boat of several feet. In addition, the propulsion supports, gearing, bearings, and associated equipment cannot present a bulky mass under the water or large drag penalties are incurred. Several solutions have been used, such as inclined shafting from a point well forward in the boat, double right-angled gearing permitting a vertical shaft, and outboard motors in small sizes. The maximum torque that can be transmitted through any of these schemes is, to date, lower than that which can be carried on conventional shafting thus establishing the number of shafts required in larger hydrofoil plants greater than in a conventional plant. For large sized hydrofoils, transmission development beyond presently available components is believed necessary.

In estimating propeller performance and propulsive coefficient, it is found that, unless the propeller is placed quite near foil structure or other sources of flow disturbance, the hydrofoil provides excellent flow conditions resulting in considerably higher values of propulsive coefficient than is normal for conventional craft of similar size and speed.

When considering very high speeds, the simplicity of air screw propulsion is most attractive and should be evaluated on an efficiency and weight basis against marine propulsion. To achieve reasonable ideal efficiency of air propulsion either very large diameters or speeds of advance that are exceptionally high in terms of marine practice are required. Thus, unless speeds well over 50 knots are desired, air propulsion is not desirable. In addition, the effects of wind on advance speed could be troublesome with air propulsion.

ARRANGEMENT AND FITTINGS

The tasks of locating machinery, shafting, and other components in the hull, and the determination of arrangements are generally controlled by the foil configuration and propulsion means selected, and by weight and moment considerations. However, good protection against spray for the pilot and excellent visibility should receive prime consideration in these high-speed vessels. Also, if passengers are to be carried, suitable means should be provided to prevent injury from high accelerations in the event of inadvertent high-speed landing. Likewise cargo-securing provisions should receive particular attention.

The ultimate use of the craft and the means for handling it in harbors or at piers should dictate the amount of complication and weight that can be afforded for retraction of foils and propulsion. Where size permits, some means of retracting foils is desirable on any hydrofoil craft for maintenance of foils without drydocking. In craft which may be required to operate alongside piers or other ships, a means of retracting the foils to positions within the over-all dimensions of the hull is nearly essential.

EVALUATION OF THE HYDROFOIL CONCEPT

Having examined the design problems of hydrofoils, it is apparent that the initial cost of such craft will undoubtedly be greater than that of conventional boats or ships of similar size. Therefore, it is important to compare hydrofoils with other surface craft to determine where this cost can be justified in terms of operating advantages.

Comparisons are first made of characteristics of specific types for the purpose of establishing the relationships of size and speed to power required. Following this, a study based upon suitable dimensionless parameters is presented to indicate to the limits of possible hydrofoil design.

SPEED AND POWER

To obtain a direct comparison with conventional ships, a brief analysis of resistance by ship standards seems in order. First, assuming identical weight, it may be found from a comparison of hydrofoils and planing boats in the higher speeds that the frictional resistance of the foil boat is approximately one-half that of a planing hull and the residual resistance is about one-half that of a planing hull.[10]

A typical example is as follows:

	Good planing boat	Comparable hydrofoil boat
Speed (knots)	44	44
Length, over-all (feet)	45	45
Displacement (pounds)	35,000	35,000
Wetted surface (square feet)	238	111
Frictional effective horsepower	367	200
Residual effective horsepower	402	245
Total effective horsepower	769	445
Lift/drag ratio	6.1	10.6
Propulsive coefficient	0.5	0.6
Total shaft horsepower	1,538	740

It should be noted that in addition to a saving in frictional resistance and in residual resistance, the hydrofoil has a slightly better propulsive coefficient since its propeller is operating in nearly open water unaffected by the proximity of hull and unequal flows. Thus the total shaft horsepower required is less than half of that required for the planing hull.

The above calculation could be refined by taking into account the net difference in weight between these boats due to inclusion of hydrofoils on one, and larger engine and fuel weights on the other. However, this weight balance can be varied by the designer by his power plant selection, type of transmission, endurance requirements, and materials used. With equal endurance and comparable power plants for the two boats in question, the following approximate weight comparison shows them to be equal. However, the foil boat would have about one-half the operating cost for smooth water operation, and in most sea conditions this margin would improve for the foil boat.

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[10] This breakdown of resistance, admittedly somewhat artificial for hydrofoil craft, can be made by first determining frictional resistance by the Schoenherr formulation applied to the wetted area of immersed foils and appendages. The frictional resistance is then extracted from the computed or trial full scale resistance, leaving a residual resistance composed of wave, induced, windage and interference drags as well as a form component of profile drag.

Weight Comparison (in pounds)

Component	Good planing boat	Comparable hydrofoil boat
Hull[a]	13,350	13,350
Pay load	6,500	6,500
Foil system	0	7,600
Power plant	12,300	5,950
Fuel	3,320	1,600
TOTAL	35,470	35,000

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[a] Hull weights are assumed equal, although a 10% variation in either is reasonable.

This so-called "typical" comparison was deliberately taken at an operating size—speed range that was reasonable for both the hydrofoil and its nearest high speed competitor, the planing boat. What happens to this comparison if it is extended to larger and smaller sizes and to much higher and lower speeds?

First, in the case of a large-sized, slow speed craft, consider these characteristics of a small merchant ship:

Speed	15 knots
Length over-all	320 ft
Displacement	6,200 tons
Payload and fuel	3,000 tons
Wetted surface	23,250 sq ft
Frictional effective horsepower	1,260
Residual effective horsepower	1,965
Total effective horsepower	3,025
Propulsive coefficient	0.6
Total shaft horsepower	4,200

An attempt to determine the characteristics of a comparable hydrofoil ship leads to immediate absurdities. Assuming a lift coefficient of 0.8 (which is well above a desirable value), one finds that about 27,000 sq ft of projected wing area would be required to lift the hull clear at 15 knots. Roughly, two hydrofoils of 30-ft chord and 450-ft span would be needed—and it would be utterly impractical to place them under anything resembling a reasonable hull. Moreover, the frictional resistance would be more than doubled, while the residual resistance would be increased fivefold over that of the conventional craft, with a resulting requirement in excess of 20,000 shp. Clearly, to get any possible hydrofoil either speed must increase, or size reduce, or both.

To make a more reasonable comparison, one may consider a displacement of 3,000 tons and a speed of 35 knots as a design point:

	Displacement ship	Comparable hydrofoil ship
Speed (knots)	35	35
Length over-all (feet)	400	400
Displacement (tons)	3,000	3,000
Wetted surface (square feet)	18,500	8,500
Frictional effective horsepower	12,000	7,000
Residual effective horsepower	25,500	34,300
Total effective horsepower	37,500	41,300
Lift/drag ratio	19.2	17.5
Propulsive coefficient[a]	0.625	0.625
Total shaft horsepower	60,000	66,000

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[a] No improvement in propulsive coefficient for the hydrofoil ship is given in this example. It is assumed that greater transmission losses will at least compensate for any improvement in propeller performance over that of the displacement ship.

Here we see the hydrofoil slightly worse than the conventional ship on a speed-power basis. Assuming nearly equal power plants, the extra weight required for foils and struts, transmission, and control would come out of pay load or range, leaving the hydrofoil inferior to the displacement ship on a smooth water basis. Rough water sustained operation might make the two nearly equal.

One must note, however, that this size and speed for the displacement ship is not one that could be considered economical in the normal concept of a ship and must be justified for other reasons such as military requirements.

If speed were held constant and size reduced, say by 50%, the above comparison would swing sharply to the favor of the hydrofoil ship. Thus a possible future for this type is indicated where there is need to retain speed on smaller size. A general discussion of the feasibility of foil boats in these sizes is contained in a following section of this paper.

At the other extreme of the size-speed range, it can be shown that the advantage for hydrofoils for very high speeds on small size is an increasing one. Although cavitation will undoubtedly affect the performance adversely, inspection of lift-drag ratios attainable for sections under full cavitation indicates that, even here, the hydrofoil should be able to surpass the ratios attainable with planing boats [11]. Although practical experience with fully cavitating foils is lacking, intuitively, it would seem that a hydrofoil under full cavitation would have a lift per unit area roughly equal to the difference between dynamic pressure on the bottom of the foil and vapor pressure on top, while a planing surface has dynamic pressure on the bottom and atmospheric pressure on top, thus giving the hydrofoil an advantage. However, many unknowns may affect this simplified picture. The possibility of stabilization difficulty has already been mentioned. Thus to stay within the bounds of reasonable experience, compare a displacement planing boat with a hydrofoil at 50 knots which is believed to be practically attainable by both. The characteristics are as follows:

Displacement	Planing hull	Hydrofoil
Weight (pounds)	50,000	50,000
Speed (knots)	50	50
Shaft horsepower	3,600+	1,200

Thus, even with a liberal allowance for foils and struts, a three-to-one advantage for the hydrofoil boat in power would result in a substantial increase in range or pay load.

This set of comparisons while bracketing the areas of advantage and disadvantage for hydrofoils, leaves considerable gaps to be filled to place the hydrofoil in a definite relation to other forms of water transportation. As an aid in this problem, an attempt has been made to compare ships, boats, planing boats, and hydrofoils on a fair non-dimensional basis. A "transport efficiency" expressed as maximum speed times pay load divided by shaft horsepower was selected as one parameter, and the ordinary Froude number based on maximum speed and over-all length was selected as the other. Plotting these values for various specific types caused these types to group themselves into definite patterns, Fig. 13. As would be expected, at very low Froude numbers characterized by slow ships or very large ships, extremely large values of "transport efficiency" appear. In the limit, of course, a non-propelled barge would have an infinite value on this plot.

As speeds increase and sizes moderate in the vicinity of Froude numbers between 0.6 and 0.7, the band for displacement ships has dropped sharply to relatively low values. Continuing this process the band for displacement types drops to near zero which indicates an upper limit of feasible Froude number since the useful load is calculated including fuel.

A second band originating around a Froude number of 0.6 is discovered for planing forms. This band drops at a slightly lesser slope indicating higher possible Froude numbers for this type of craft.

Further to the right (higher Froude number and higher efficiency) the family of hydrofoils appears, showing considerably less droop and much higher efficiency than other types in the higher Froude numbers. Thus from this form of limited analysis, the conclusion is indicated that from the standpoint of speed, power, size, and load capabilities, the hydrofoil is superior to other forms of water transportation above Froude numbers of 0.6 to 0.7, and that below this limit, if considered at all, a hydrofoil must be considered on other specialized grounds.

No very definite data were available to the authors on the design particulars of foil boats at supercavitating speeds. Therefore, the extreme end of the hydrofoil band and its slope at very high Froude numbers is questionable. However, it would appear that other considerations, such as stability, control, or structural integrity set the probable limits on the attainable Froude number with hydrofoils.

SIZE LIMITATIONS

From the previous discussion of speed and power, it is found that hydrofoil boats are uneconomical in comparison to other types below a Froude number of about 0.6 to 0.7. This fact indicates a minimum speed for each size of hydrofoil boat. By reference to Fig. 14 it may be seen that this relation indicates a minimum speed of about 40 knots for a 400-ft ship bearing in mind that length, as used herein, is merely a measure of size or bulk, assuming a hull of normal coefficients and weight loading for fast ships as shown in Fig. 15.

When discussing the maximum sizes and minimum speeds for successful large hydrofoil craft, low resistance or high lift to drag ratio is most important, since this feature controls the proportion of pay load and fuel that can be carried. These factors not only contribute to the economics of the craft but also determine whether it will have sufficient capability to be useful at all.

Even with high lift to drag ratios in the order of 15 to 20 in mind, other limitations appear. First, while cavitation can be tolerated in high-speed small craft, it would reduce the lift to drag ratio to unacceptable amounts in a larger cargo type craft. Therefore, assuming low lift coefficients for the foils at top speed, an approximate speed limit of about 45 to 50 knots can be established for these larger craft. The intersection of this speed limit with the zone of minimum speed for hydrofoil craft on Fig. 14 indicates a maximum size in the order of 5,000 tons. Whether even this limit can be reached in practice, or would be desirable if found practicable, is open to question.

A typical ship of 500 ft will displace 15,000 to 19,000 tons while a lighter, slimmer design might go as low as 8,000 tons. Using 8,000 tons as an example, and choosing optimistic values for hydrofoil resistance and propulsive coefficient, the shaft horsepower required for 50 knots, on foils,

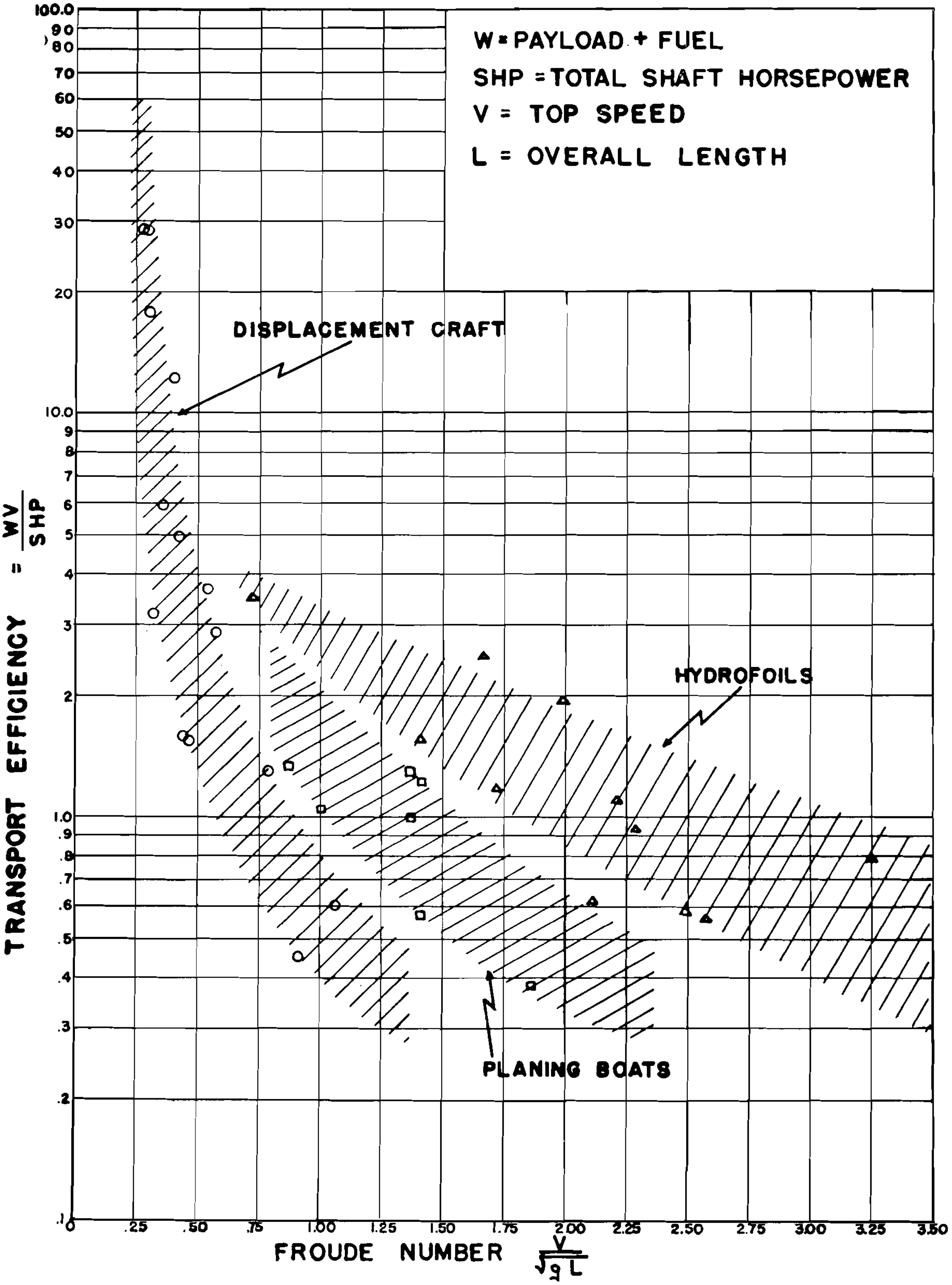

Fig. 13.—Transport Efficiencies of Surface Craft

would be over 300,000 hp. By very rough estimating, this would leave no allowance within 8,000 tons displacement for any fuel, let alone pay load. Thus, the percentage of weight which must be allocated to machinery places an additional limit on maximum craft size, unless very radical future developments make available large capacity power plants with specific weights (lb per hp) in the order of 25% of those of present units.

Still another factor in the speed-size problem is the possibility of wave drag recovery by use of tandem foils. Since the spacing between foils for maximum wave drag recovery is dependent only on speed, and since in large cargo type hydrofoils a savings in the order of 20 to 25% in resistance is involved, wave drag recovery controls, within limits, the relation of physical size to speed, calling for longer hydrofoil ships as speed increases. As may be seen from Fig. 14, the curve of maximum wave drag recovery falls slightly below the zone of minimum speed of economical hydrofoil craft, emphasizing the wisdom of designing to the minimum profitable speed for a cargo type hydrofoil ship.

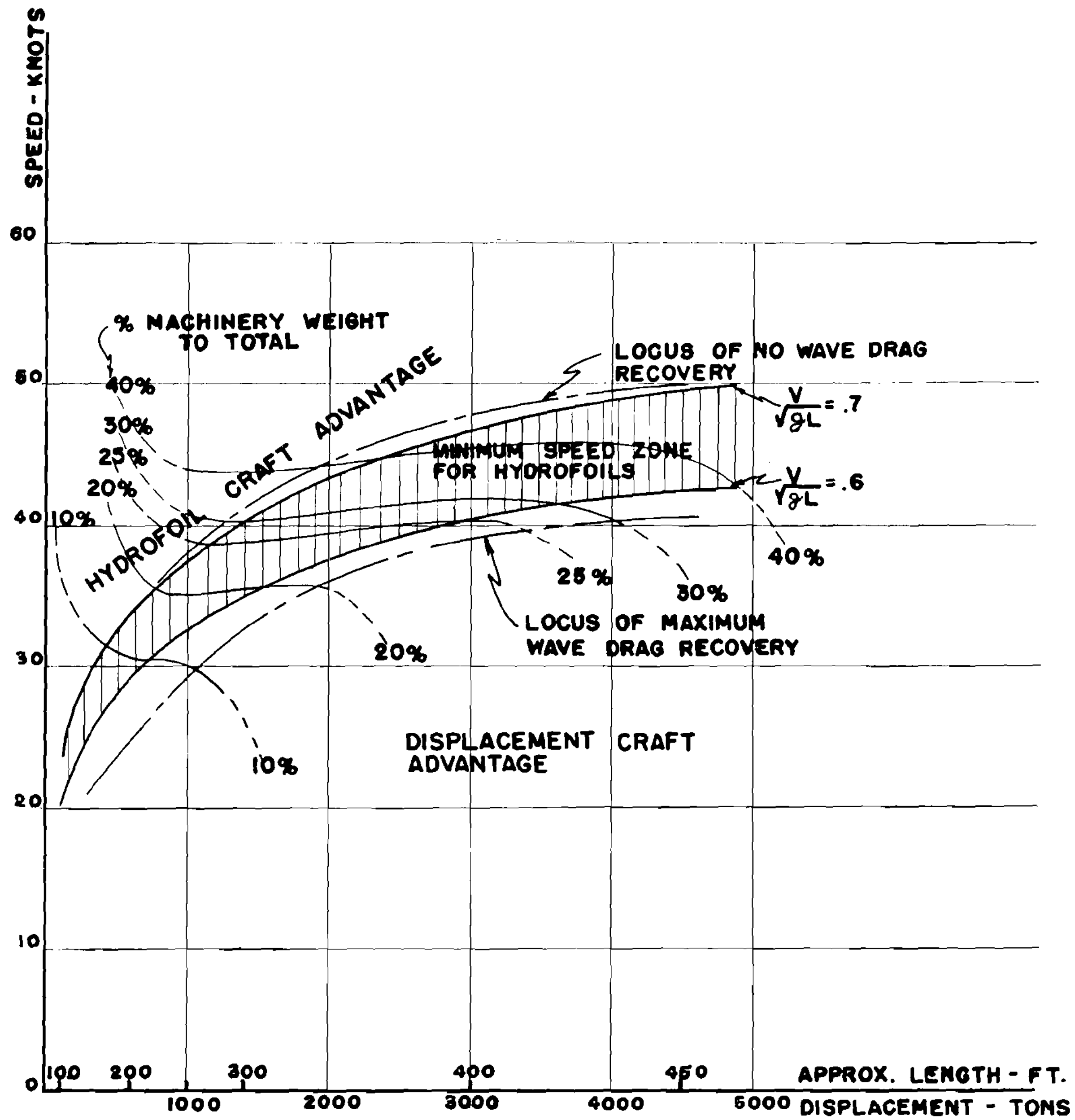

Fig. 14.—Possible Characteristics for Large Hydrofoils

If the best existing weight per horsepower ratios are used for plants in the 10,000 to 100,000 hp range, if the effects of wave drag recovery on attainable lift to drag ratios are considered, and if propulsive coefficients including shaft and gear losses in the order of 0.5 to 0.6 depending on speed are assumed, it is possible to estimate the power required and hence the machinery weight required for the larger sizes of foil craft at various speeds.

Fig. 14 also shows, in approximate terms, the relation of size to speed and to the percentage of total weight required for propulsion power. By reference to data on displacement ships at comparable speed—length ratios, about 30% allowance for machinery is the maximum that could be considered useful in a cargo type if any range is to be obtained. If this is so, Fig. 14 would indicate that the maximum size of useful hydrofoil ships would fall in the range of about 1,500 to 3,500 tons at a speed of about 40 knots, depending upon which portion of the minimum speed band is selected. Of course, special requirements that overshadow reasonable efficiency, or new developments resulting in lower plant weights, may produce hydrofoils outside this range. For the present, it is believed that these sizes may be considered at least qualitative limits—ones which may actually be difficult to obtain in practice.

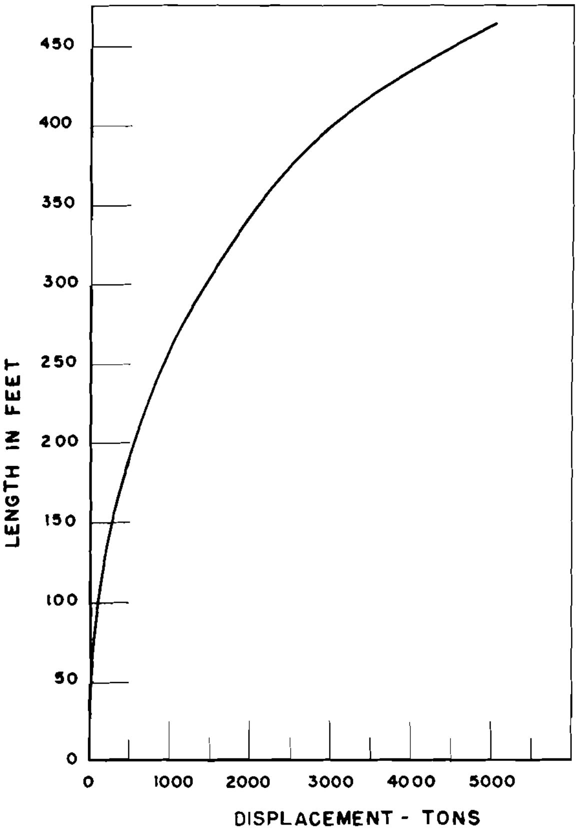

Fig. 15.—Typical Weight vs. Length Curve Derived from Fast Displacement and Planing Craft

Some of the difficulties in obtaining even these sizes are: (a) limitations on maximum torque that can be absorbed in a single transmission of the right-angled or V type; (b) the large foil size compared to hull size brought about by the fact that foil lift increases as the square of a linear dimension while weight increases as the cube of a dimension; and (c) the fact that strut thickness (or the number of struts) must increase with size out of proportion to other dimensions, even when Froude scaling can otherwise be maintained.

In favor of increased size are the opportunities for making foil configurations and propulsion devices relatively cleaner, the possibilities for the use of wave drag recovery to increase efficiency at higher speed, and the fact that as long as geometrical similarity of foil configuration can be maintained with constant speed and foil loading, the stresses in the foils themselves are independent of size, although this relation does not exist for the struts.

It should be noted, however, that in all of this appraisal of larger sizes of hydrofoil ships, further development of a reliable control device for submerged foils is a prerequisite since at large sizes (over about 100 tons) it does not appear feasible to provide sufficient lifting area or high enough lift-drag ratios with surface-piercing foils.

Special cargo handling, docking, and launching facilities would probably be required for large hydrofoil ships since at these sizes retraction of the foils would be most unattractive. Thus these ships would have an increased draft over conventional craft of the same size when not on the foils. Also, the foil span with relation to hull beam grows with size to the point that handling alongside would become infeasible. Other difficulties that appear with size increase include the need for the protection of the foils against fouling and the need for provisions to inspect and repair minor foil or strut damage without the opportunity to bring them out of the water except by a complicated docking procedure.

Conclusions

It may be concluded that hydrofoil supported craft are feasible and, within certain limitations of maximum size and minimum speed, are superior to displacement or planing craft on the basis of speed and power. While further development of stability and control features can improve the seakeeping qualities of hydrofoils, they generally provide a smoother ride and maintain speed in a seaway better than conventional craft.

What the future brings depends on the continued effort that is put on this problem. Certainly many applications present themselves. Fast, comfortable, point-to-point passenger service such as a commuter's ferry would provide could be operated at lower cost with hydrofoils; pleasure craft of high speed could be placed within the reach of the average sportsman if and when mass-produced foil systems are made available; and military applications for relatively small stable high-speed craft undoubtedly exist.

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DISCUSSION

Dr. K. S. M. Davidson, *Member:* A boat that tries to sprout wings and become a hydrofoil craft is evidently in something like the same fix as a caterpillar that tries to sprout wings and become a moth. A long period of incubation seems to be needed for both. But, just as the butterfly does eventually emerge from its cocoon, so, it would appear, the hydrofoil craft is now emerging into the light of day.

It is not that there have been no successful hydrofoil craft in past years. It is rather that the main engineering aspects of the design of hydrofoil craft have not been brought out for discussion nor have the main difficulties that stand in the way of further development been made clear. The present paper does much to remedy this state of affairs.

I have been especially interested in trying to get an idea of the long-range possibilities of hydrofoil craft in the broad picture of overseas transport vehicles. At this stage I suggest that one may allow himself a fair measure of latitude in thinking about this, and that it may be rather fun.

As matters stand, we now have two types of overseas transport vehicles in actual operation; ships and airplanes. In Fig. 16 of this discussion, showing speed versus gross weight, we see at once that spots for these types tend to form two islands which occupy very different regions of the chart, ships combining large weight with low speed and airplanes combining small weight with high speed. Further, if we add lines to the chart showing constant values of the speed-weight product, *WV*, which may be called "vehicle momentum" (in ton-knots), we see also that in going from the ship to the airplane the loss of weight is nothing like compensated for by the gain of speed, and that in consequence the airplane has much less momentum than the ship.

Now, it is an easy step from this picture to the suggestion that a third type of vehicle with speeds and weights more or less midway between those of ships and airplanes might have a useful place in the scheme of things, and it is natural enough to ask the question of whether hydrofoil craft might some day fill this role.

The question is a big one. The paper gives data for various hydrofoil craft. I have entered spots for these on the chart, and it will be seen that except for the hypothetical 3000 ton-35 knot combination, they fall far short of matching the vehicle momentums even of existing airplanes, let alone falling midway between ships and airplanes. The authors' contention that there is room for further development in hydrofoil craft is therefore, from the point of view I am discussing, putting the matter rather mildly.

It is of interest to note that if means should be found for increasing materially the sizes of presently existing hydrofoil-craft designs, at the

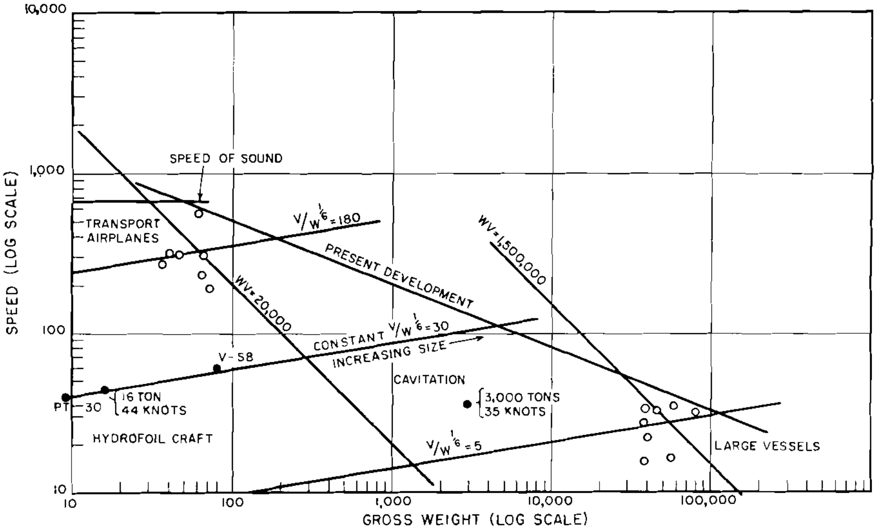

Fig. 16.—Speed-Weight Characteristics of Ships, Airplanes, and Hydrofoil Craft

same Froude number, craft eventually would be produced having characteristics about midway between those of ships and airplanes. Naval architects are accustomed to the concept of similar performance for geometrically similar ship forms moving at the same Froude number, and the same concept applies to hydrofoil craft if we let weight increase, as in ships, with the cube of the linear dimension. For present purposes it is sufficient to write the Froude number as $V/W^{1/6}$ (which is of course proportional to the British Ⓚ coefficient) and I have drawn several lines of constant Froude number on the chart. What I am saying is, then, that presently existing designs of hydrofoil craft have Froude numbers something like midway on a geometric scale between those of ships and airplanes. This means that they have something like the correct geometric configurations to meet the hypothetical requirement I am suggesting, because, again as in ships, the geometric configuration for best performance is a function of the Froude number.

But having the correct geometric configuration is a long way from being the whole story. Very large increases of size of presently existing hydrofoil craft, at constant Froude number, to bring them into general alignment between ships and airplanes, would carry us far into unexplored territory. This is true with respect to all three of the major categories of hydrodynamics, structures, and power plants. Very little thought is needed to convince oneself that it is certainly no easier, and may well be more difficult, to effect large increases of size in hydrofoil craft than in any other type of water-borne ship or boat. The combination of large size and high speed is hard to get, and that's that.

The 3000 ton-35 knot combination noted in the paper, the point for which is spotted in Fig. 16, herewith, is a much more realistic goal at the present time. Yet even this goal is far from simple to reach as matters stand today, particularly with respect to structures and powering. As a matter of fact, 3000 tons and 35 knots is about the combination one finds in conventional destroyers (which, incidentally, have very short ranges at full speed). The paper suggests that, for this combination of weight and speed, roughly the same characteristics may be expected for either a displacement ship or a hydrofoil craft. I myself came to this conclusion a year or two ago, at which time it occurred to me that one might summarize in some such way as this:

Starting with 3000 tons and 35 knots: (*a*) Any *increase* of weight and/or *decrease* of speed (lowering of Froude number) greatly simplifies the design of a displacement ship. (*b*) Any *decrease* of weight and/or *increase* of speed (raising of Froude number) greatly simplifies the design of a hydrofoil craft.

Thus, we come to the more or less inevitable conclusion noted in the paper that the "natural" area for hydrofoil craft is that of moderate weights in combination with relatively high speeds on the water. I think this must remain true unless we are prepared to enter into a major research and development program embracing hydrodynamics, structures and power plants.

The superior riding qualities of hydrofoil craft in head seas, although not yet very well documented in a technical sense, are nevertheless universally attested to by all who have had actual experience of them.

In my opinion, the authors have done a masterly job in co-ordinating and summarizing a complex subject. They have my congratulations.

MR. J. C. NIEDERMAIR, *Member:* The authors deserve a lot of credit for developing so clearly the present status of the hydrofoil craft. Much speculation has gone on over the long years since the early attempts were first made to raise a boat above the surface of the sea. I believe that much of the lack of practical success has been due to an overoptimistic approach to the problem. This paper should help in tempering down the excessive predictions which have been customary by those deeply interested in promoting research work on hydrofoil-supported craft.

The problem is largely a practical one. It simmers down to about three or four basic conditions:

(*a*) Hull design which is, as the authors state it, straightforward naval architecture.

(*b*) Hydrofoil design which is now principally a matter of selection for configuration and strength.

(*c*) Propulsion machinery which currently is only suitable for the propulsion of relatively small craft.

(*d*) A due recognition of the fact that the principal problem is control of craft in level flight.

Stems (*c*) and (*d*) are the real problems. Some progress is indicated in the solutions of (*d*), but in order to make any great strides with hydrofoil craft some radical change must be made in the propulsion-machinery weight-and-space requirements, as well as in the fuel rate per horsepower. The present limitations in propulsion machinery limit the hydrofoil craft strictly to small sizes. Hence I heartily agree with the authors' conclusions wherein they limit the craft to ferry service, pleasure boats, and some small military vessels.

I note that authors seem to feel that the propulsive coefficient probably will be more favorable in the hydrofoil craft. I doubt this to be the case. Another point which seems to be underrated, in the dreams concerning the use of hydrofoil craft, is the performance in high winds and confused seas which is the standard condition in the winter North Atlantic.

There appears to be a place for these craft but at the present time it is not in competition with large vessels such as the transatlantic liners. This is quite obvious if we take the results of the simple shaft-horsepower relationship for hydrofoil craft

$$\text{Shp} = \frac{11.5 \times \text{displt. in tons} \times \text{speed in knots}}{\text{lift over drag ratio}}$$

From this it will be seen that it would take about a million horsepower to drive a ship having a displacement of 50,000 tons and speed of 35 knots. This is roughly 5 times the power required for a well-designed displacement vessel.

Mr. R. B. Couch, *Member:* This paper is very timely in that it does much to dispel some of the mystery that has surrounded the hydrofoil craft. It is an excellent summary of the situation as it now exists. I hope that the paper will interest some others who previously have not worked on this type of craft and, perhaps, bring forth new ideas which will more rapidly advance the development of hydrofoil boats.

The authors have discussed hull form in connection with take-off and landing but have not stressed the importance of the hull form in relation to seaworthiness when hull borne. Since the hydrofoil system is somewhat vulnerable to damage, it is highly desirable that the basic hull be seaworthy when circumstances prevent foil-borne operation or when power is lost. Because of this consideration it appears necessary that the hull be somewhat conventional even though a simplified hull may be suitable for foil-borne operation.

The authors mention the probable loss of foil efficiency through fouling of the foils themselves. This is certainly an important point especially with regard to large craft with nonretractable foils. The performance of the foils may be compared to the performance of marine propeller blades. It is well known that propellers suffer appreciable loss in efficiency even with minor fouling in the form of slime accumulation. In the case of high-speed vessels with a low percentage of in-port time most hard growths may be washed from the propeller blades; however, the water speed of a foil on a high-speed boat is much lower than that of a propeller blade. Any roughness resulting from manufacture, antifouling coatings, or fouling growths definitely will affect hydrodynamic efficiency, including likelihood of earlier cavitation and, therefore, will be an important problem.

The authors state that the knowledge of the effect of surface roughness on resistance of conventional ships is far from adequate. While I agree it is not entirely satisfactory, a great deal is known about it and best of all we do know in general what to do about it.

The authors mention the maximum torque that can be transmitted through the type of drive system needed for a hydrofoil craft. It is not clear what is meant by this. Perhaps, the authors can clarify this point.

They also state that higher propulsive coefficients may be obtained with the hydrofoil boat as compared to conventional craft. This is not necessarily true; in fact the opposite is true in some cases. Higher hull efficiencies may obtain, as much as 1.3, where wake gain more than offsets thrust-deduction losses in certain single-screw conventional ships whereas in a hydrofoil craft, with a propeller operating in a comparatively free flow, the hull efficiency is likely to be about 1.0.

The authors point out the advantages of a submerged-foil system, especially for larger craft. Such a system, as they also state, requires development of a suitable automatic control system. High-speed craft, with whatever system is developed, operating into head seas will involve rapid and continuous reversals of motions of foils, linkages, and so on, so that wear and tear alone on equipment will impose extremely difficult engineering problems.

I have been associated with the authors in some of the hydrofoil work discussed in the paper and feel that they are to be complimented on their excellent presentation.

Mr. S. A. Vincent, *Member:* In the section, "Size Limitations," the authors delve into the possibilities of vessels up to several thousand tons displacement and speeds of 40 to 50 knots. Having observed the development of motor transportation, planes, radar and television I no longer believe in considering seemingly hopeless new ideas to be impossible of solution. My comments are not intended to be discouraging, but we should face the facts as we see them and endeavor to overcome the obstacles.

A great deal can be learned from model basin tests in waves, but not the whole story. Many valuable ship-model tests in waves have been made in our Newport News basin, but we do not overlook the fact that unlike the usual model basin uniform trochoidal waves, the seas that a ship encounters are neither regular in length or height and confused cross seas occur, wave crests are frequently very abrupt as distinguished from the mathematically smooth rounded crests of model-basin waves, and the surface of each major ocean wave is usually composed of a number of local smaller waves.

Seagoing vessels encounter waves of 10 to 20 ft in height from hollow to crest during fine weather and 30 to 40 ft, or even higher, during bad weather. By wave height I mean feet from hollow to crest. While at sea during a hurricane last winter my estimate of the wave heights was about double that of the experienced ship captain's estimate. It developed that his basis was that wave height is based on the height of the wave crest above mean sea level instead of above the wave hollow. This may explain partially the wide variance in estimated wave heights so often reported.

If a hydrofoil-supported ship followed the ocean wave-surface profile, using the Grunberg configuration shown in Figs. 1 and 7 of the paper, the vertical acceleration would be intolerably high even in fine weather. The passengers and crew would need stout seat belts and the structural stresses on both the ship and the hydrofoils would be enormous. This leads to the thought that a successful hydrofoil seagoing vessel should operate, as the authors indicate, with the hull continually above the highest wave crest and in my opinion with but little, if any, pitching or heaving motion. To this end it seems necessary that the supporting hydrofoils be continually below the lowest wave hollow. On such a basis the uppermost hydrofoil surface would have to be well over 50 ft below the keel for scheduled year-round ocean service. This may not be structurally impossible.

A practical hydrofoil vessel involves several totally new conditions that require consideration. Could such deeply submerged hydrofoils be retracted to permit entering 30- to 40-ft-depth harbors at slow speed and to permit dry-docking? What would happen if a whale or substantial submerged object seriously damaged the below keel units? How would the propulsion be arranged? Stability is involved, having in mind not only the wave effect but also the wind effect on the vessel.

Most normal seagoing ships can maintain their top service speed in fine weather. The lighter displacement high-speed vessels such as destroyers must reduce speed in only moderate head seas and even large vessels must slow down in heavy weather. We averaged 6 knots in a 24-knot vessel during the hurricane that I mentioned. In other words weather occasionally limits the top operating speed of "surface" ships regardless of the horsepower available. The three alternatives for high-speed transocean transportation seem to be:

(*a*) Nuclear-powered fast commercial service cargo-passenger submarines.

(*b*) Aeroplanes—these are not entirely independent of weather and depend upon seaborne shipping for return-passage fuel, and the like.

(*c*) The hydrofoil-supported ship suggested for study in this paper.

I have mentioned a few practical obstacles to be considered in the development of the latter for unlimited international operation. Serious as they may seem now, these obstacles may not be insurmountable. In my opinion it is well worth while occasionally to include such thought-stimulating papers in the Society's proceedings. The authors deserve our congratulations for their excellent paper.

MR. ROBERT R. STEELE, *Life Member:* The history of engineering indicates that dramatic developments like the hydrofoil are retarded not at all by our awareness that the development will reduce our life expectancy and further enslave us to the insurance companies. We prefer fun to sanity.

That said, we are able to thank the authors for a fascinating paper.

My comments concern submerged foils, only, because surface-piercing foils do not appear to hold promise of licking the classic problem of keeping small craft moving at speed in rough water.

Ignoring structural limitations for the moment, let us assume a strut length equal to the height of the highest wave likely to be encountered in a particular service plus the foot or two necessary to maintain circulation about the foil when it is below wave troughs. With this strut length the magic-carpet ideal could be realized if control were related to horizon rather than to the approaching water surface. The Grunberg and Hook trimming planes and other surface-following devices—no matter how gloriously electronic—provide the antithesis of this ideal.

Now, acknowledging structural limitations and the elusiveness of horizons, would not a compromise employment of a surface "averager" rather than a surface "follower" be an improvement? A partially immersed vertical strut-like member suspended so as to respond to changes in

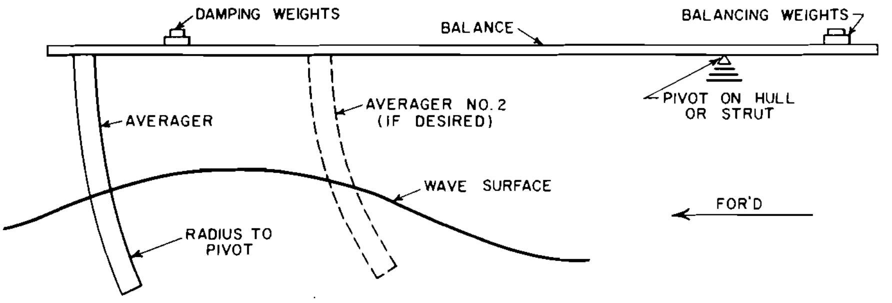

Fig. 17.—Partially Immersed Type of Surface "Average"

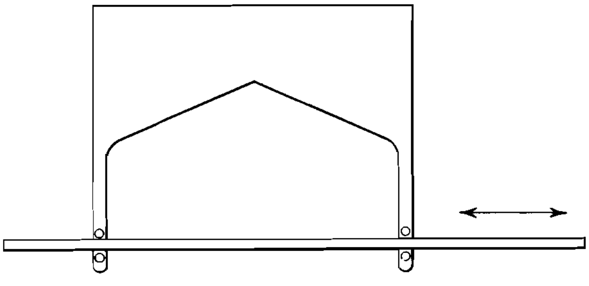

Fig. 18.—Typical Inverted-Vee Section Particularly Adaptable to Hydrofoil Use

buoyancy, when suitably dampened, could be such an averager, Fig. 17.

The "averager" is as small in section as satisfactory stabilizing action will permit, in order to minimize drag. It exerts no lift other than its buoyancy. When a system employing this device has been tuned for optimum inertia, the pitching of the craft will be no more than necessary to keep the hull bottom clear of the crests and the foils immersed in the troughs. In short waves where the system would tend to oscillate unnecessarily, one or more additional "averagers" can be employed, spaced so as to make their total lift remain almost constant. Thus, smooth sailing.

Of the many schemes employing the "averager" that come to mind perhaps the simplest is pivoting the balance so that it alters angle of attack of a stabilizer via a lift line.

It may be found desirable to put the stabilizer aft in order to gain a longer balance arm and consequent smaller amplitude of oscillation. In any case the balance arm is adjustable in length to suit varying courses and surface conditions. In slow-speed embodiments where the averaging need not be done ahead of the elevator, the averager can be the foil-shaped sheath of the strut itself, on which it is slidably mounted. This eliminates one element of drag. If just one averager is used, trim control only is obtained. If two are used, one to port and one to starboard, each actuating independent foils, or port and starboard ailerons on a single foil, both trim and list control are obtained. So much for the averager.

In the jockeying of ailerons or independent port and starboard foils, to obtain transverse stabilizing moment, it may be that we countenance unnecessary drag. Can we not obtain stabilizing moments by *traversing* the main foil along its axis (Fig. 18) to port to counteract port heeling moment, to starboard to counteract starboard heeling moment?

The traversing foil need never trade lift for control. There are no ailerons to disturb circulation; no inefficient angles of attack required for independent foils. Another advantage of the traversing foil is that the actuating force is not a function of the stabilizing moment. The actuating force is no more than that required to accelerate the foil athwartship, whether the corrective moment is 10 lb-ft or 1,000,000 lb-ft.

Incidentally, the traversing foil offers interesting possibilities for sailboats, both hydrofoil-supported and displacement types. In the latter the foil replaces ballast, permitting reduction in scantlings and easier lines, and consequently, higher speeds.

Regarding hulls for hydrofoils, it is surprising to learn that the inverted vee-bottom has not been used. (A typical inverted-vee section is indicated in Fig. 18.) Six advantages of the inverted vee over the hulls shown in the paper are: (*a*) The stresses at the moment connection of strut to hull are distributed to the skin panels with less concentration at the fillet. (*b*) The conical skin panels require less stiffening to absorb these stresses than do the warped skin of more usual hull types. (*c*) Struts may be shorter, thus reducing the stresses at the moment connections still more. (*d*) The take-off power hump will be lessened because the inverted-vee hull, when well designed, rises to planing without change of trim. It does not have to climb over a wave of

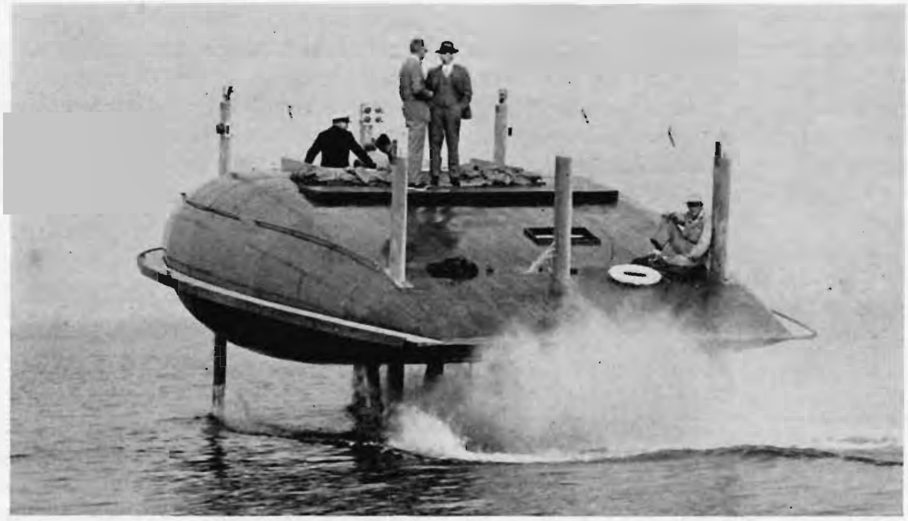

FIG. 19.—NAVY HYDROFOIL CRAFT OF TANDEM SUBMERGED-FOIL TYPE

its own making. (*e*) The take-off power hump will be lessened further because of the obtuse angle between strut and bottom; no "wire-drawing" of the water between strut and hull. (*f*) Untoward landings with an inverted-vee bottom are cushioned, when compared to those of more usual hull types.

One must have ridden an inverted-vee-bottom boat in rough weather to appreciate the validity of the last claim. There were thirteen of us aboard a 55-footer, last October 22nd, trying for size the 4 to 6-ft waves of a typical 25-mile northeaster. After having run down a quartering sea at better than 30 knots, without a trace of yaw, and around a 180-deg turn with no more than a 5-deg roll or list—call it what you will—we decided to take her upwind as fast as we could go without throwing her clear: Waves two points off port bow; average speed for 1 nautical mile, 33 knots. It would have been difficult to drink coffee on this run without soiling the saucer.

But it was just after this run, while still at speed, that we come to the main point of this story. A windward island, a shoal, and some thoughtless seamanship, collaborated to produce two oversize waves, dead ahead; perhaps 10 ft in height and steep. We—all 27 tons of us—left the water twice before the throttles were backed off.

The few people who have had an analogous experience in an orthodox planing boat know that the landing impact is an explosion, leg bones are fractured, and solid water comes aboard. In this instance, with an inverted-vee bottom under us, no bones were broken and no water came aboard—although it is admitted that if any of those hypothetical saucers were still unsoiled, it was only because they were no longer occupied by cups.

It would seem that the cushioning dynamics of the inverted-vee are particularly worthy of the scrutiny of hydrofoil designers, for at high speeds crash landings are sure to occur due to collision of foils with obstructions, and it is doubtful that we can make effective use of parachutes.

The authors devote much space to comparing vee-bottom planing boats to potential hydrofoils. But they do not emphasize that these comparisons hold good only in picnic weather, the only weather in which vee-bottom boats can plane. Such comparisons are unfair to the hydrofoil. Inverted vee-bottomers, on the other hand, put on a better show. They can plane in gale weather—reducing throttle, or tacking, only when necessary to forestall being thrown clear. And in smooth water they can carry 60 lb per hp at 35 mph, 45 lb per hp at 40 mph, 36 at 45, 31 at 50, and 27 at 55—much more than their vee-bottom rivals—but not enough to preempt the hydrofoil.

DR. VANNEVAR BUSH, *Honorary Member:* This paper is an exceedingly useful document. The authors are to be commended on many aspects of the paper, but I find especially helpful the treatment of the range of speeds and weights within which hydrofoil-supported craft offer interesting economic possibilities.

Yet the paper leaves out of consideration the most interesting form of such craft. This is not surprising; and no criticism of the authors is implied, for much information in this field is, or has been, classified for security purposes.

In Fig. 19 is shown a craft built for the Navy by The Hydrofoil Corporation. It is of tandem submerged-foil type, of 10 tons weight, 35 ft long, with 22 ft beam. It utilizes about 200 hp from a Chrysler marine engine. It is controlled by a Sperry autopilot.

An important feature of this craft is that it embodies the constant-lift principle in its foils. This greatly modifies performance and calls for elaboration of some of the statements in the paper.

For constant lift the foils are pivoted ahead of their center of lift. The control force, which holds them in position to exert lift, is applied through a resilient member. This member is made equivalent to a very long spring by a cam or lever arrangement. On a larger craft the same procedure may be applied to a flap. The result is a lift which is independent of a number of factors which otherwise would affect it, and equal, under equilibrium conditions, to the load carried by the foil. The load rides on an elastic cushion instead of on a rigid support.

A number of interesting results follow. A very important one is that the foils adjust automatically to the changes of angle of incidence due to orbital motions, within limits set by inertia of course. The lift is thus substantially constant on passing through waves. Hence, there is very little vertical acceleration, or departure from level flight, in a seaway which otherwise would produce a rough ride. The crest-to-trough height that can be negotiated depends of course upon the length of struts.

There is little or no alteration of lift with change of fore-and-aft trim. The old bugaboo of hydrofoil craft, a tendency to porpoise, is overcome by removing the cause. This will be especially important at high speeds, when the angle of attack of foils is very small, and when conditions are thus present such that a sudden perturbation in trim is capable of initiating porpoising, or a violent impact with the surface. Independence of lift from trim angle simplifies the control problem at all speeds.

Now, even with fixed submerged foils, there is a small inherent stabilizing tendency. Such foils lose lift and also drag, as they approach the surface. This becomes of importance only when the submergence is comparable to the chord as the paper points out. But with constant-lift foils the effect is much enhanced, owing to a shift of center of lift as the surface is approached.[11] There is thus a strong tendency to seek a fixed level of flight. The craft as shown is readily flown, in moderate weather and at various moderate depths of submergence, with the altitude control disconnected, in fact with no controls whatever except those for lateral stability.

The paper under discussion notes, but does not emphasize, the fact that craft with submerged foils operating in undisturbed water should have a higher value of L/D than craft with surface-piercing foils. The improvement may be substantial. In discussing this point and also that of rising on foils, the paper points out the limitations as to what can be accomplished due to variation in angle of attack of a fixed foil resulting from vector addition of the orbital velocity to the velocity of the craft. This is further discussed in connection with head and following seas. With the constant-lift principle applied to the foils these effects are substantially absent. A foil which is freely pivoted, and resiliently constrained, can follow the changes in angle of the resultant water velocity with respect to the foil. Such following is not perfect, for the foil has inertia; but it can be made close except at high frequencies of wave encounter, and at these high frequencies orbital velocities are small. The motion is highly damped. Thus, within limits, one may neglect the effects of orbital motion in connection with such matters as maximum utilizable lift coefficient and the like, and performance in rough water is made to approximate closely that in smooth water.

In a submerged-foil craft the active foil area is constant, whereas in a surface-piercing-foil craft it varies with speed. The paper points out the effect of this on the hump at takeoff, the necessity for ample power to override the hump, and the angle of attack at cruising speed. This is all sound comment. But there is no reason why a submerged-foil craft may not be supplied with auxiliary foils for use on takeoff, which may be retractable or set so close to the hull that they are in the clear during flight. The submerged-foil craft then becomes a variable-area craft, and conditions regarding the hump are decidedly altered. Whether such addition is desirable depends upon the design ratio of takeoff to cruising speed. The craft, illustrated in Fig. 19, takes off at about half of maximum cruising speed and does so in a few lengths. The process of taking off incidentally merely involves opening the throttle.

There is not the slightest doubt that hydrofoil craft will be used extensively in the future. The general idea of having a hull above the waves, and supporting means beneath, eventually will provide a new means of transport, intermediate between air-lift and displacement carriage. The

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[11] This effect has been measured in the tank at the University of California in Berkeley by J. S. Ausman.

FIG. 20.—HYDROFOIL-EQUIPPED CRUISER IN CONVENTIONAL OPERATION

FIG. 21.—CRUISER RUNNING AT SPEED, SHOWING HYDROFOILS IN ACTION

problem of control, which has held up the art for a long time, has been overcome; and we now have excellent theoretical treatments on which to base design.

The surface-piercing foil has an undoubted field, especially in small sizes, where simplicity is paramount. For larger sizes the submerged-foil craft is definitely indicated on account of its higher L/D ratio, and its greater freedom from wave action. In this connection the paper seems to me to be somewhat preoccupied with the need of a hydrofoil craft to follow the surface. I would prefer to reverse the emphasis for in the roughest ocean trade routes the maximum waves 85 per cent of the time are only 20 ft or less. Craft undoubtedly will be built for relatively fast sea transport, which will handle any seas to be encountered and proceed at full speed with a substantially level platform. As this occurs the principle of constant lift will be utilized, for it simplifies control and cancels out nearly the last vestige of the effect of wave action. A craft that can proceed through rough water, and ignore the waves, is on the way. In a few years there will be hydrofoil craft of many types and designs flying about the coasts. When that occurs progress will become automatic and irresistible, and one will wonder how there could ever have been so many skeptics.

MR. DAVID D. BEACH, *Associate Member:* This well-prepared paper no doubt has been received gratefully by the small number of naval architects who dabble in the design of high-speed pleasure craft. For those who eventually will be confronted with a hydrofoil-design commission, the paper will be eagerly studied as a complete exposé of the basic problems of the subject.

Speaking from personal experience, which goes back only 2 years to the time I included some pictures of a German three-point hydroplane fitted with hydrofoils in an article on racing craft in the *Rudder*, I have found a widespread interest in hydrofoil craft in this country. This

FIG. 22.—TOP SPEED OF CRUISER 40 MPH

FIG. 23.—GERMAN-BUILT HYDROFOIL RUNABOUT

interest has evolved into two design jobs which currently are continuing as developmental projects with the ultimate intention of production models.

It is of importance to note that there are at least three boat builders in this country who are engaged in serious and advanced work with hydrofoils independent of government subsidy. This does not include the West Coast catamaran builder who has fitted hydrofoils to his 30-ft sailing catamaran with no small success.

The writer recently received from Fritz Vertens a packet of photographs, prints, and technical information on the current products of the Vertens Yachtwerk, mentioned in the paper. Certain of the photographs can be shown.

Fig. 20 shows a conventional appearing sedan-type cruiser of 39 ft 9 in. length over-all. It has a beam of 8 ft 2 in. on deck and displaces a bit over 2½ metric tons or about 5100 lb. This is a light-displacement craft. It is powered with one Chrysler 165-hp Royal marine engine, driving direct.

Figs. 21 and 22 show the same boat at speed. In waves of about ¾ m, or about 2½ ft, a sustained cruising speed of 56 km per hr is reported. That is about 35 mph. Top speed in less rough seas is given as 65 km per hr; about 40 mph.

Fig. 23 shows a production runabout which bears a strong family resemblance to the two boats previously mentioned. This boat is of the type which was to be introduced to the American boating public at the 1954 National Motorboat Show. This boat is a 20-footer and the forward surface-piercing foil is about 8 ft in beam in the form of a flattened oval, not vee'd. The craft shown attains a speed of 32 mph with only 30 hp, with an "all-up" weight of about 1600 lb.

The American cousins of this craft, powered with Ford V-8 conversions of the standard type, but given the "full house" treatment of hopping-up run in the high forties with an "all up" weight of just under 2100 lb.

The writer wishes to concur wholeheartedly with the conclusions reached by the authors, especially that as to sea-keeping qualities of hydrofoil boats. The real thrill that comes from running at 40 mph through the waves from a lake freighter without the slamming and pounding usual in a conventionally planing craft must be experienced to be believed. A slow but steady advance and acceptance of hydrofoils by the boating public in the next several years may be expected.

MR. FRITZ VERTENS,[12] *Visitor:* In all important respects, the writer is in agreement with the re-

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[12] K. Vertens Yachtwerft, Winning bei Schleswig, Germany.

sults and explanations given in the paper. The writer's company has built hydrofoil boats since 1942. The experimental VS-7, Fig. 5 of the paper, was the first craft of this type which left our plant. The hydrofoils for these first boats were designed by Professor Tietjens himself. A number of boats also have been built according to our own plans, but in all cases we have held to the system of one forward main surface-piercing foil combined with an aft elevator with which we have had good results as regards speed and seaworthiness.

During the war, two smaller jet-powered hydrofoil boats of 2 tons' displacement were built and reached 120 km per hr (75 mph). These were remote-controlled.

The writer agrees with the opinion expressed in the paper, that probably boats with vee-foils (to which we should like to add those of semicircular shape) will be used in either main foil or tandem systems up to about 50 tons' displacement. Above this size, boats with submerged foils and electric autopilot foil control will prove more advantageous. Beginning with this 50-ton size, the price per boat will warrant inclusion of autopilot foil control

In sizes between 10 and 60 tons it is expected that there will be transitional types too; the hydrofoils of which will also pierce the surface, but will not extend thwartships.

DR. G. WEINBLUM, *Member:* One of the very few revolutionary ideas in our old profession is the hydrofoil principle. The first part of the present paper is academic in the best sense. Especially should be mentioned the lucid exposition of the stability and seaworthiness problems and the appraisal of their importance on the development of craft. To the writer's knowledge the reasoning on the behavior of hydrofoil systems in a seaway is well supported by theory and experiments. The expository nature of the paper by no means impairs its high level and scientific value. Except for neglecting problems of steering and cavitation it is the best synopsis so far presented on the subject.

There is a minor statement with which the writer does not quite agree; that in ships and boats at higher speeds the power is proportional to about the fifth power of the speed. Probably this remark is caused by an old resistance formula proposed by Taylor, but later discarded by him. Of course, one can find limited regions where the statement is approximately correct but, since in the present case we are interested in extremely high speeds, conditions also are actually quite different.

The general shape of the wave-resistance curve of a displacement craft is similar to that shown in Fig. 11 of the paper, except that the maximum occurs earlier. Beyond a Froude number, of say 0.5, the wave-resistance increase with the speed is less than quadratic. It is agreed that the wave resistance is a stumbling block, but at extreme speeds it is rather the high frictional resistance due to the great density of water which precludes any reasonable progress in ships following orthodox lines.

D. W. Taylor has introduced the useful concept of resistance per unit displacement which is identical with the gliding member; i.e., the inverse of the lift drag ratio. In the writer's opinion naval architects should stick to the slightly modified Taylor concept.

The authors will forgive me for expressing the opinion that the second part—the evaluation of the hydrofoil concept—is not quite on the same level as the first part of the paper. This is due to an inherent difficulty of the problem as to how to appraise vessels of different classes and the lack of basic information on important elements, especially in so far as hydrofoils are concerned.

A ship has to comply with many mechanical and economical fundamental conditions of which the powering is only one though perhaps the most interesting item. Of necessity the authors have based their analysis on the latter; neglecting cavitation (a very serious omission!) it can be reduced to some extent to the simple resistance problem. A discussion of the limiting size of hydrofoils based on resistance or gliding number was performed earlier by Graff whose paper as well as those by Büller and Tietjens could be added to the list of references.

Within the limitations of the present assumptions the lowest gliding number which can be attained by a hydrofoil craft fixes immediately its maximum economical size by comparison with the performance of good orthodox ships. The concept of transport efficiency used by the authors is clearly a better figure of merit than the gliding number when sufficient data are available, but in the present state of knowledge its advantage may be treacherous. Therefore it seems to be perferable for the time being not to attach too much importance to the problem of maximum size of hydrofoil craft before some basic problems have been solved. This applies also to the maximum size of craft with surface-piercing foils estimated by the authors at about 100 tons—a value which represents fairly well present practice but which can be outdated very soon.

Mr. F. W. S. Locke, Jr.,[13] *Visitor:* The authors are to be congratulated on a thorough and useful summary and evaluation of the present state of knowledge regarding hydrofoil craft. Since the beginnings of recorded history, increased speed of transportation has been connected intimately with the rise of civilization. Man will pay almost any price to produce faster interchange of commerce and ideas with his neighbors. In slightly over a century the average speed of ocean transportation has increased from something like 2 knots to about 20 knots. Further increases in speed can come about slowly through refinement of design details or be brought about rapidly through a fresh approach.

In the aeronautical field, the maximum speed in level flight has been increased about 12 knots a year since 1903. This has been achieved by a willingness to try the fresh approach and not to be hampered by what has been done in the past. The authors are holding out a firm foundation for a fresh approach in ocean transportation. The only barrier to be seen to acceptance of the broad ideas expressed in this paper lies in the minds of men. With a bold and unfettered imagination, these ideas can be applied to produce remarkable increases in performance. The resulting craft will not look like present-day ships, or will they be operated in the same manner.

Now it is quite true in the case of hydrofoil craft that inventors have put forward what seemed to be preposterous claims in order to have their case examined by the more conservative authorities. Moreover, this situation has been equally true with a number of other notable inventions such as the airplane, the automobile, and perhaps even steam-propelled ships.

It has been the writer's pleasure and privilege to work with the authors on this project in a very minor capacity. The authors have tackled the sweeping problems brought about by the fresh approach by the basically sound method of building a number of prototype craft, so that the advantages and deficiencies can be seen clearly. It is believed, therefore, that we are on the threshold of notable improvements in performance in ocean transportation with the aid of hydrofoils.

Mr. John Bader, *Member:* The authors of this highly interesting discussion of hydrofoil craft are to be congratulated for bringing together information on this subject. The authors state as their third purpose, "to outline the problems inherent in the development of these vessels." Parts of this phase are somewhat obscure and could be elaborated.

The engineers who design ships instead of airplanes would be assisted by definitions of terms such as "circulation" and "vortex." The question of drag is outlined, and unknown factors such as surface roughness are mentioned. However, the seriousness of air drag on the hull should receive further discussion. As the speeds involved are high and with the relatively low power, head winds could become an important factor on whether the craft will fly. It is not clear what the equation $D = C_D \rho/2 S V^2$ represents as the total drag of the hydrofoil craft includes different densities for air drag on the hull and water drag on the foils. Perhaps a summation symbol in front of C is desirable.

In the discussion of miscellaneous design considerations, the statement is made: "Foil area contributes greatly to parasite drag and should be kept to reasonable proportions." Parasitic drag such as surface interference is given as a function of thickness, not area, in another section of the paper.

For speeds between maximum and takeoff, the increased area improves the foil efficiency. Induced drag is a function of the lift coefficient squared so that the decrease of this coefficient by increased area improves the performance of the foil. Increasing area through increased span will increase the aspect ratio and tend to cancel the drag for area increase as induced drag is

$$D_i = \frac{C_l^2 \text{ area}}{\text{aspect ratio}}$$

The limitation would be the strength of the material used for the foils.

While the hull design is a straightforward naval architectural problem as stated, it is also a difficult problem. The hull has to be of unusual shape to avoid bad trim for water-borne operation for some configurations. As the flying stability is dependent on the location of the fore-and-aft center of gravity its location cannot be shifted for various cargo loads. This restriction can become a serious arrangement problem. As also stated, longitudinal strength for small boats is not a problem; however as size increases, the two-point support while flying coupled with dynamic factors will magnify the structural problems.

A logical sequel to this fine paper would be one in which the engineer's viewpoint is presented. The structural problems of foils, methods of calculating turning and stability, and design charts for drag could be presented for design use.

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[13] Hydrodynamics Consultant, Research Division, Bureau of Aeronautics, United States Navy, Washington, D. C.

Mr. John G. Baker,[14] *Visitor:* The authors were careful to give the basis for their statements about scale effects in most cases, but in two instances they did not. The following statement is quoted from the paper:

"For large hydrofoil craft—where foil retraction becomes clearly impractical—. . ."

The authors' basis for this statement would be interesting. Offhand it appears that there is no scale effect detrimental to large retraction gears more severe than structural scale effects in general. The retraction problem in hydrofoil boats seems to be comparable to the retraction problem in aircraft landing gear, and the design of the latter is practiced throughout a large range in size without notable difficulty.

After outlining various propulsion schemes the following statement occurs:

"The maximum torque that can be transmitted through any of these schemes is, to date, lower than that which can be carried on conventional shafting thus establishing the number of shafts required in larger hydrofoil plants greater than in a conventional plant."

It would be interesting to know why this is so. The writer understands that there would be a limitation on size if bevel gears are used, but since bevel gears are not necessary why should there be a limitation in general?

Mr. R. H. Miller, *Associate Member:* The authors are to be congratulated on an excellent presentation.

In the Summer of 1952, the writer built and tested a model hydrofoil boat 4 ft long and about 3 ft wide. It consisted of three surface-piercing hydrofoils mounted on a catamaran type of hull. The model had a lift over drag ratio of approximately 5½, which was fairly good considering that there were seven supporting struts adding to the drag of the hydrofoils.

This model is mentioned because the catamaran or twin-hull type of boat or a modification thereof would seem to be particularly well suited for hydrofoil craft. It provides a wide platform which eliminates foils projecting beyond the hull and protects the foils when docking or maneuvering in close quarters, and at the same time presents a small, narrow surface should the hull strike a wave crest while under way.

W. P. Carl, Jr.,[15] *Visitor:* Given the proper distribution, this paper will do more for the advancement of hydrofoils than any treatise published to date.

While dealing with a highly technical subject, the authors have presented the subject in a manner that any one interested in ships can understand.

One of the most interesting problems in connection with hydrofoil craft is the selection of the means of powering them. We have had some experience with air propellers and believe that the speed of 50 knots mentioned in the paper, as being the speed at which one should consider the use of air propulsion, is perhaps 10 knots too fast and the air propeller at least should be considered in most cases. The advantages and disadvantages of air propulsion versus water propulsion are too involved to discuss at length. However, it might be of interest to mention that one of the most serious problems of air propulsion is the erosion of the leading edges of the propellers by the spray hitting them during the take-off period. In test our propellers, which are made of aluminum, lost about ⅛ in. per 20 take-offs. This has long been a problem with seaplanes and is being worked on by propeller manufacturers constantly. The ability to solve this problem may well decide the question as to the practicability of air propulsion.

We should like to compliment the authors of this paper in demonstrating for the first time the possibilities of hydrofoil-supported craft on a sound basis.

Mr. E. P. Clement, *Associate Member:* The authors have capably discharged the responsibilities which they assumed when they undertook the preparation of the first paper on hydrofoil boats to be presented to the Society. A good case has been made in this paper for the hydrofoil boat. This has been accomplished, however, largely at the expense of the planing-type boat, and therefore it seems proper to make a few remarks in defense of the planing boat.

Several comparisons of performance between planing and hydrofoil boats are made in the paper, all indicating a considerable superiority for the hydrofoil boat. For example, a planing boat and a hydrofoil boat are compared on the basis of equal displacement and speed, and the shaft horsepower indicated for the planing boat is three times that for the hydrofoil boat. An important point here is that whereas the figures for the planing boat are representative of data for practical, operational planing craft of the conventional type, the context seems to indicate that the corresponding data for the hydrofoil boat represent predicted performance for a hypothetical boat, based on tank tests of individual hydrofoil

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[14] President, Baker Manufacturing Company, Evansville, Wis.

[15] Engineer in Charge, John H. Carl & Sons, Inc., Rockville Centre, N. Y.

components. Therefore it seems only fair to interject, that if the planing boat is examined on the same basis, i.e., if hypothetical optimum performance is calculated from towing-tank data, then the performance figures for the planing boat will be much better than indicated by the comparison data in the paper.

A specific way of attaining such improved planing-boat performance would be by means of a design utilizing two planing surfaces in tandem. Tank tests of simple planing surfaces show that a large improvement in performance over the conventional planing boat can be achieved in this way. Problems of stability and control would have to be solved in order to realize a practical boat of this type, which seems to the writer to make the situation very closely analogous to that of the hypothetical 50-knot hydrofoil boat of the present paper. A tandem-surface planing boat would probably not have as high a lift/drag ratio as a corresponding hydrofoil boat. However, the hydrofoil boat, because of its foils, would have the disadvantages of increased weight, greater complexity, greater vulnerability and higher cost.

MR. L. E. SUTTON,[16] *Visitor:* The juxtaposition of the papers entitled, "An Appraisal of Hydrofoil Supported Craft," and "On the Motions of Ships in Confused Seas," is indeed fortuitous, for, in fact, there are ties between them. It happens that the design of autopilots for certain types of hydrofoils now requires data of the form and mathematical discipline included in the latter paper. Also, there is a possibility that a hydrofoil could be used to obtain information concerning the energy spectrum of confused seas. In support of such a hypothesis, attention is invited to an analogous situation in aircraft work.

The aircraft people, as the art of automatic control of high-speed aircraft became more and more important in the latter years of World War II and increasingly so to the present day, determined that considerably more knowledge was needed concerning atmospheric turbulence encountered in flight, in order that automatic controls might be designed properly to minimize the effects of "gusts."

Since it was not possible to use "magic carpets" for data gathering and since data other than those at ground level were desired, the next best thing was undertaken; i.e., to use the aeroplane as the test probe. This was done by locking the airplane control surfaces, measuring pitch rates in flight in "gusty" weather, autocorrelating the indicated rate of pitch, taking Fourier transforms, and so on. The work utilized the principles set forth in "Extrapolation, Interpolation and Smoothing of Stationary Time Series" by Norbert Weiner. It was thus possible to determine, within engineering tolerances, expressions for power spectral density of atmospheric turbulence. Further information on this work will be found in a thesis by Clementson for the Sc.D. degree at the Massachusetts Institute of Technology.

It is noted that a somewhat similar effort is now underway by the Woods Hole Oceanographic Institution, using a relatively small boat as one sensing means. It is surmised that it is possible to predict with reasonable accuracy the response of such a craft to a train of uniform waves approaching from the bow. On the other hand, it is considered that it is difficult reliably to predict the effect of such wave train coming from any point other than the bow, or in confused seas since in a displacement craft the coupling between roll, pitch, and heave is difficult to consider in view of the highly nonlinear dynamic effects of the bilge keels, flare, and the like, and last but not least, the dynamical effects of the displacement of the water itself. All these limitations in the consideration of the motion of a ship in a confused sea are noted in the St. Denis-Pierson paper, and these limitations in the opinion of the writer are of considerable moment.

Consider now a submerged foil hydrofoil, whose dynamics have been demonstrated to be calculable in very much the same way as those of an aeroplane (which are now determined with considerable accuracy), but with the simplification that the nonlinear body effects of the aeroplane are now absent. The thought is therefore proffered that such a hydrofoil could be used to obtain reliable data more readily, leading to more intensive determination of the energy spectrum of confused seas.

COMMODORE HENRY A. SCHADE, USN (Ret.), *Member:* I want only to call attention to the effects of some research work recently completed at the University of California, which Paul Scherer also has mentioned, upon some of the implications in statements in the paper. This work is reported in the Ph.D. dissertation of John Stanley Ausman, entitled, "Pressure Limitation on the Upper Surface of a Hydrofoil," dated August, 1953.

The important result really is the analytical and experimental determination that there exists an upper limit of the pressure coefficient, on the upper surface of a hydrofoil, which is directly proportional to the submergence, and inversely pro-

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[16] Gibbs and Cox. Inc., New York, N. Y.

portional to the square of the velocity. In effect, this places a very definite limitation on the lift-drag ratio that can be obtained by a hydrofoil when the submergence is low, which is not taken in account in the two-dimensional theory of Keldysch and Lavrentiev referred to in the paper. Consequently, the statement in the paper that the effect of submergence upon lift may be neglected if the value of the submergence ratio is in the neighborhood of unity, seems to me not quite defensible. The two-dimensional theory which involves neglecting the surface effect upon lift which is used by the authors, will give an erroneous result, I believe, if this effect which I mentioned is not taken into account.

This really means that the flow of surface of water of the hydrofoil not very deeply submerged is in effect weir flow, and the upper limit of lift can be determined in exactly the same way. Physically this means in the extreme limit that the pressure upon the upper surface cannot be less than that which results from atmospheric pressure.

MR. BUERMANN, Lieut. COMDR. LEEHEY, AND COMDR STILWELL: The authors feel a warm and humble glow at the number and high caliber of the commen s on this paper. The paper is general in nature and attempts to cover the whole field of hydrofoils. The comments cover a field as broad as the paper. The authors, therefore, decided to answer the more general comments, particularly those not well covered in the paper. There is no attempt to ignore certain specific comments, but some of these are primarily in the category where opinion is predominant and actual test data are still lacking.

As mentioned in the comments of Dr. Bush the paper does not make mention, specifically, of the principle of constant lift. It also was stated very fairly that at the time the paper was written, this particular item was denied because of security classification, which has since been lifted. The constant-lift system described in the comment represents a novel method of minimizing the effects of orbital motion. It does not, however, simplify the hydrofoil-control problem, as stated, since balancing the forces on the foil has a destabilizing effect, and constant lift in itself does not control foil submergence. This principle, therefore, does not obviate the need in a submerged-foil craft for a reliable, well-developed control system which maintains the foil depth. Furthermore, the introduction of a constant-lift system between the servo and foil must increase the friction and inertia effects in any practical application, making it more difficult for a control system to provide the necessary response.

In extending this thought to the subject of control in general, we have among the discussers a wide band of ideas as to where the foil should operate with respect to the surface of the water, particularly considering operation in rough water. At one end of the scale, it is claimed in the discussions that the foil should follow a level path and that the struts should be made so long that the entire wave will pass between the foil and the hull. At the other extreme, we are asked to consider following the surface contours, and accepting the surface effects on lift and drag of the foils.

The authors take a middle course in this controversy. From purely practical considerations it is felt that a foil craft cannot afford the weight, added strut drag, and general complexity of support required to carry long tenuous struts necessary to permit level flight through any sea. On the other hand, it is not intended in the paper to convey the idea, from surface sensing, that the craft must follow the contour of the wave exactly. Rather, a middle course should be achieved in which the craft tends to average the two extremes and come out with reasonable accelerations without unreasonably long struts.

In concluding the discussion on this point it should be emphasized that the subject of flight path and control systems is as important as it is controversial. It is hoped that investigations presently being conducted will provide the necessary answers.

It is natural to proceed from control to a discussion of theories that indicate a condition which gives the foil a downward tendency when it nears the surface. This is in effect an aid to hydrofoil control.

With regard to the comments of Commodore Schade and the recent unpublished work of J. S. Ausman (also referred to by Dr. Bush) there is no doubt as to the existence of effects which tend to reduce the lift produced by a foil as it approaches the surface. With only the degree in question, NACA data [11] on hydrofoils of finite aspect ratio, as well as Ausman's own work for two-dimensional flow, show that the lift coefficient does not vary greatly for submergence of one chord or greater. From a practical design point of view, as noted in the paper, lift coefficients are restricted to relatively low values for other reasons, and submergences of one chord or greater are recommended.

As to foil submergence for maximum lift-drag ratio, data taken from a hydrofoil craft with submerged foils showed highest lift-drag ratios at about one-half chord submergence. This is because reducing the submergence (where possible) produces a beneficial reduction in parasite strut drag which outweighs the adverse surface effects on the foil.

Considerable discussion has arisen concerning the question of hydrofoils and their comparison with planing boats. The authors have apparently been reasonably fair in this regard, since one discusser says we are unfair to hydrofoils, while another discusser says we are unfair to planing boats.

It is necessary to discuss this subject further, since one of the comments indicates that the comparison made was based on a calculated hypothetical hydrofoil. We wish to correct any such impression at this time. In the paper, it was the earnest endeavor of the authors to use proved data, or where proved data were not available, to make reasonable design estimates based on actual operation of test craft. There was no attempt to assemble theoretical tank test data and present them as a design. The only place that this is approached is in the analysis of large-sized hydrofoils where data are not available, and one must go into the blue a certain amount.

The question of the limitation on size is one which can merit considerable discussion. Suffice to say, as in the opening comment by Dr. Davidson, the foil boat, to be in its natural environment, must proceed on Froude scaling to higher speeds with larger sizes. The main factor which sets the limit of total size which can be achieved, is the ability to pack enough power in the craft to reach the corresponding Froude speed and still have enough weight and space left for crew, pay load and fuel.

To conclude this closure, the authors would like to restate their position that they are neither hydrofoil enthusiasts nor hydrofoil critics. The paper attempts to set forth the problem as it exists. We do not advocate rushing haphazardly into a large-sized ocean-going craft capable of unlimited all-weather transoceanic service at this time. In the small-boat sizes, as qualified by some of the comments, the hydrofoil concept is considerably beyond the infant stages accepted popularly. Further, by a painstaking development through a progression of sizes (in which the practical aspects of the development of such things as power plants, propulsion, control, and specialized structures are achieved) eventually large craft may be developed.

PRESIDENT BLEWETT: On behalf of the Society I wish to thank the authors of this paper and you gentlemen who have discussed the paper. It has been exceedingly enlightening, and perhaps to many of us in the Society it has taken out some of the speculation that we have had with respect to these hydrofoil crafts.