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WASHINGTON, D.C.

A SUMMARY OF INFORMATION ON THE APPLICATION OF HYDROFOILS TO HIGH-SPEED SURFACE CRAFT

by

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J.H. Curry

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87

September 1948

Report R-335

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by

J.H. Curry

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September 1948

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A SUMMARY OF INFORMATION ON THE APPLICATION OF HYDROFOILS TO HIGH-SPEED SURFACE CRAFT

by

J.H. Curry

ABSTRACT

This report, which is the result of a survey of published articles dealing with experiments made with hydrofoils, summarizes the more important characteristics of hydrofoils as auxiliary lifting devices for high-speed surface craft. Different hydrofoil systems are compared; the effect of dihedral angle, aspect ratio, depth of submersion, angle of attack, and cavitation are discussed. Charts showing the characteristics of various profile sections are presented. Plan-form arrangements for minimizing interaction between hydrofoils are proposed. The advantages and disadvantages of hydrofoils, and their limitations as a means for power reduction, are discussed. The following conclusions are presented:

1. The multiplane system of hydrofoils is more stable than the monoplane system, but it is less efficient in operation and is more difficult and more costly to manufacture.

2. A hydrofoil must have dihedral in order to operate stably. For general performance, an angle of 26 to 30 degrees is considered best.

3. High aspect ratios are desirable for best efficiency, but practical considerations limit the ratio to about 4.2.

4. When possible, hydrofoils should be proportioned to operate at depths of not less than one half chord.

5. Low angles of attack are necessary at high speeds to minimize suction-surface cavitation and loss of lift.

6. Thin profile sections with straight pressure surfaces and sharp leading edges are best for operating close to the surface of the water; profiles which have curved pressure surfaces are unsatisfactory.

7. Hydrofoils should be as widely spaced longitudinally as feasible - for two hydrofoils in tandem the center of gravity should be about 35 per cent of the hydrofoil spacing abaft the leading edge of the forward hydrofoil.

8. Tests are required to determine the best plan-form arrangement of hydrofoils - one which will result in a minimum of interaction between the forward and after hydrofoils and also contribute a maximum toward stability.

9. Because underwater propulsion is inefficient at high speeds, owing to cavitation and appendage resistance, other means of propulsion should be investigated.

10. Any research program on hydrofoils should include full-scale tests. Such full-scale investigations, under conditions in which cavitation and rough water are encountered, are required before a practical application of hydrofoils may be devised for surface craft operating at high speed, with assurance that adequate stability and efficient operation will be realized. This conclusion is supported by the opinion recorded in Reference (10).

11. If model test results are to be correlated with full-scale results, the full-scale method of propulsion, i.e., underwater or air-screw, should be simulated in the model tests.

12. The advances made in the development of controlled missiles and methods of high-speed propulsion increase the possibilities of hydrofoils for use on military craft; for commercial applications the cost and the difficulties encountered in the manufacture, installation, and operation of hydrofoils would seem to make their use unprofitable.

INTRODUCTION

A hydrofoil is defined as a plane surface, flat or curved, designed to obtain reaction upon its surface from the water through which it moves.

The use of hydrofoils as auxiliary lifting devices on seaplanes and surface craft has long been an interesting possibility. It has been claimed that structural weight and air drag may be reduced by the use of hydrofoils in conjunction with smaller and more streamlined hulls than would normally be employed; that the power required at high speeds may be reduced; and that the impact of waves on the boat when it is operating in choppy water may be lessened.

H.C. Richardson, as early as 1909, installed hydrofoils on a canoe, and in 1911 he and Nat White fitted controllable hydrovanes to the dinghy shown in Figure 1. Again in 1912 Richardson designed hydrofoils for use on Curtiss and Wright airplanes at San Diego, California.

Guidoni (1)* used hydrofoils with more or less success on seaplanes whose stalling speeds were relatively low. Bell (2), Figures 2 and 3, employed a rather complicated ladder system on his HD-4, in combination with air-screw propulsion. Coombes and Davies (3) made extensive experiments with models of flying-boat hulls fitted with hydrofoils, investigating in

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* Numbers in parentheses indicate References on page 37.

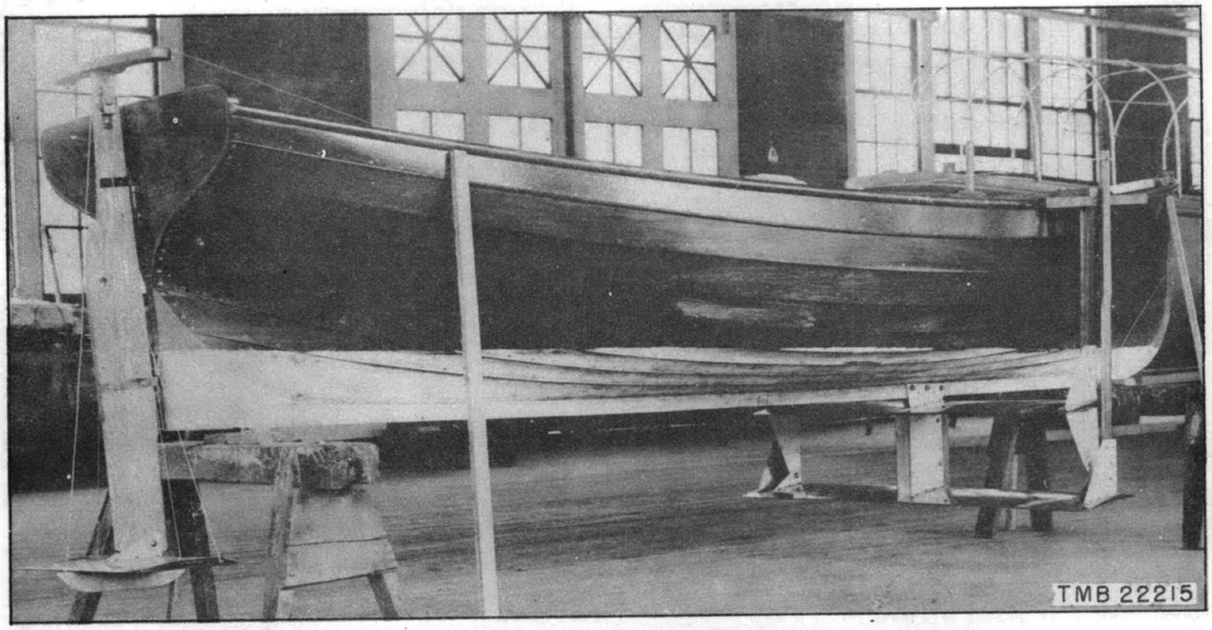


Figure 1 - Dinghy Equipped with Controllable Hydrovanes by Richardson and White, Philadelphia Naval Ship Yard, 1911

The forward hydrovanes had a span of 5 ft and a chord of 5 in. The outboard ends of the lower vane could be warped by means of the vertical levers shown.

The stern vane was attached to the lower end of the rudder and was rotated with the rudder. In addition, the vane was pivoted in the horizontal plane so it could act as an elevator.

When towed by a motor-boat at about 6 knots, the dinghy rose clear of the surface.

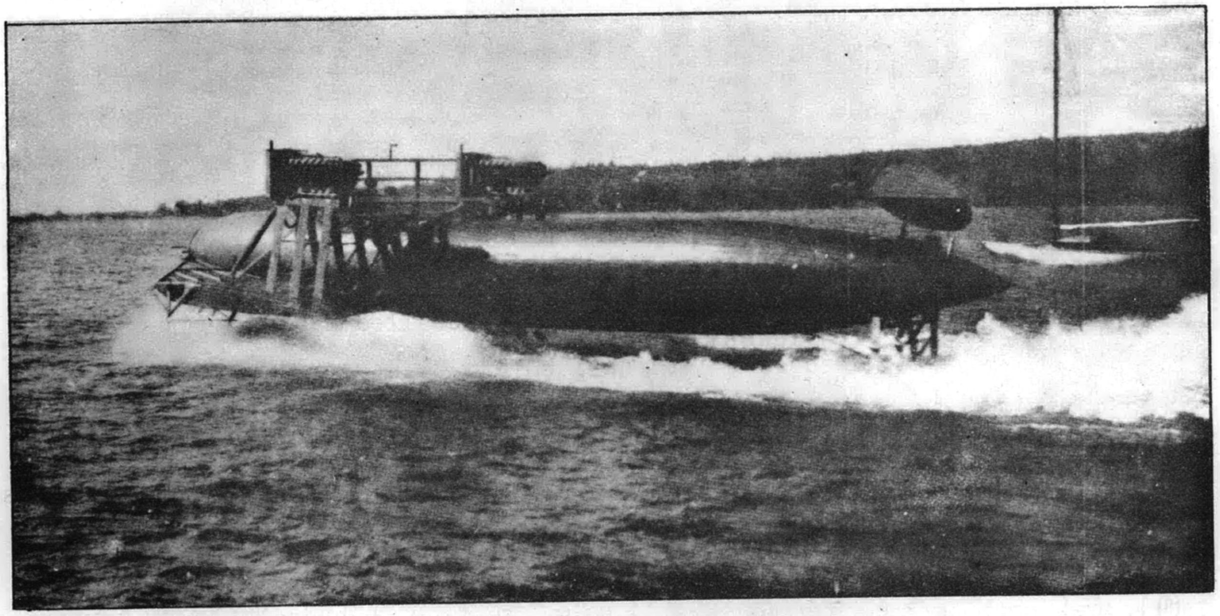


Figure 2 - Alexander Graham Bell's HD-4 Running at Full Speed on Baddeck Bay

This hydrofoil boat, developed at Dr. Bell's Laboratories on the Bras d'Or Lakes, was driven by twin airplane engines and is reported to have developed a speed of 52 knots.

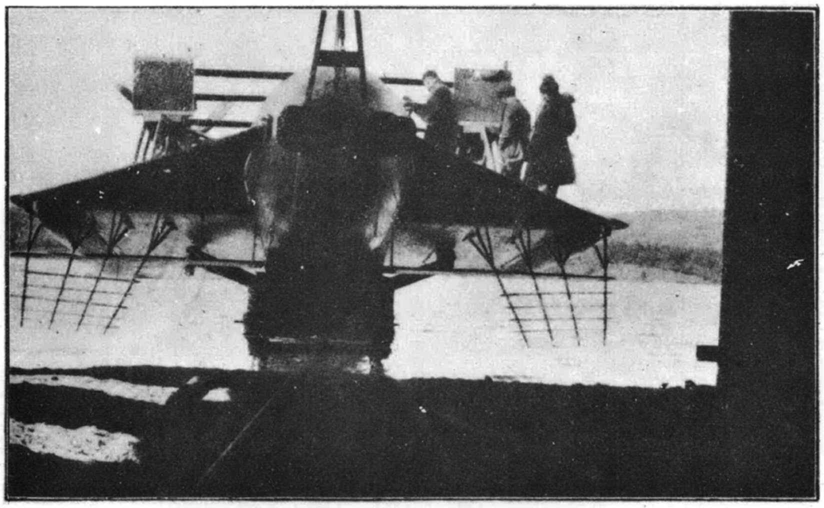


Figure 3a - Bow View of the HD-4 on Her Cradle, Showing Starboard and Port Hydrofoils

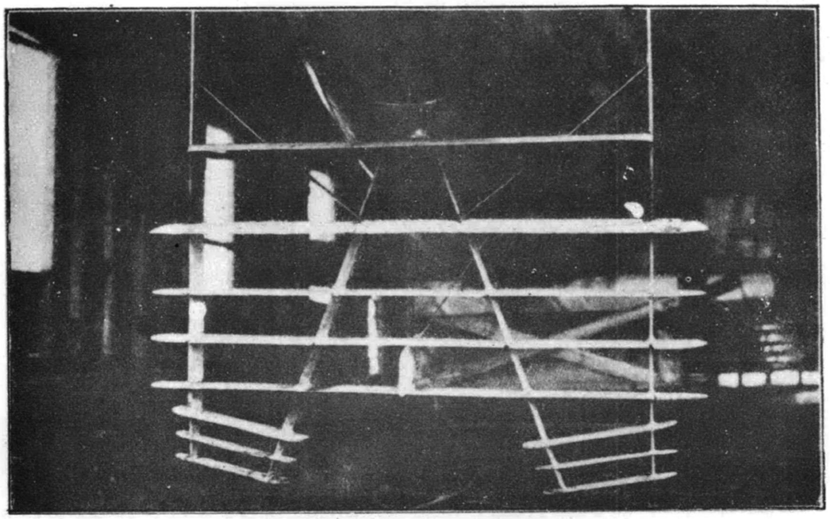


Figure 3b - Rear View of the HD-4 in Her Shed, Showing Stern Hydrofoils

Figure 3 - Views Showing the Ladder-Type Hydrofoil used by Dr. Bell on his HD-4

In addition to the hydrofoils shown, a smaller retractable hydrofoil, which was mounted at the extreme bow, prevented nosing down.

particular the effects that the depth of submergence and the angle of attack had on lift and stability. The National Advisory Committee for Aeronautics (4), (5), (6), (7) conducted several model tests with hydrofoils to investigate the characteristics of hydrofoils and hydrofoil systems.

In more recent years Sottorf (8) and Tietjens (9) experimented with various profile sections in an effort to find a form suitable for use with

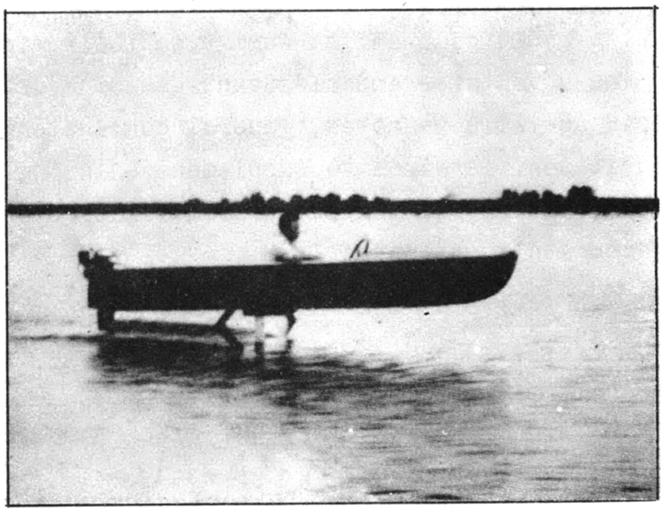


Figure 4a - Hydrofoil Boat on the Delaware River near Philadelphia, Pa. (1932); speed 22 knots.

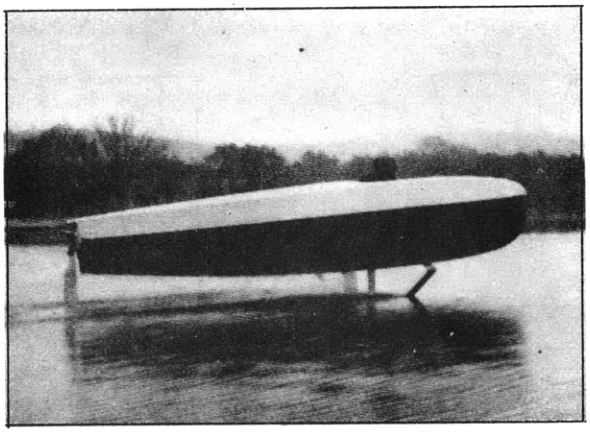


Figure 4b - Second modification of the Tietjens Hydrofoil Boat on the Langen See near Berlin, (1936); speed 24 knots.

Figure 4 - Model and Small Sporting Boat Illustrating the Tietjens System of Hydrofoil Design

high-speed planing-type boats. Tietjens applied hydrofoils to sport boats of about 20 feet in length, which, with moderate power, attained speeds of 22 knots in restricted waters; see Figure 4.

The German firm Sachsenberg is reported to have built full-scale hydrofoil boats (10) which were based on the Hamburg Model Basin model tests. However, according to the report, neither the model tests nor the full-scale trials yielded the anticipated results.

Since World War II, research on hydrofoil boats has been renewed, but little has been published about their performance.

This report purports to survey published articles dealing with experiments made with hydrofoils and to summarize their more important characteristics. The advantages and disadvantages of hydrofoils, and the limitations to their use will be noted; general conclusions and suggestions on the need for additional research to supplement existing information on the subject will be made, to the end that the potentialities of the hydrofoil boat may be more accurately evaluated.

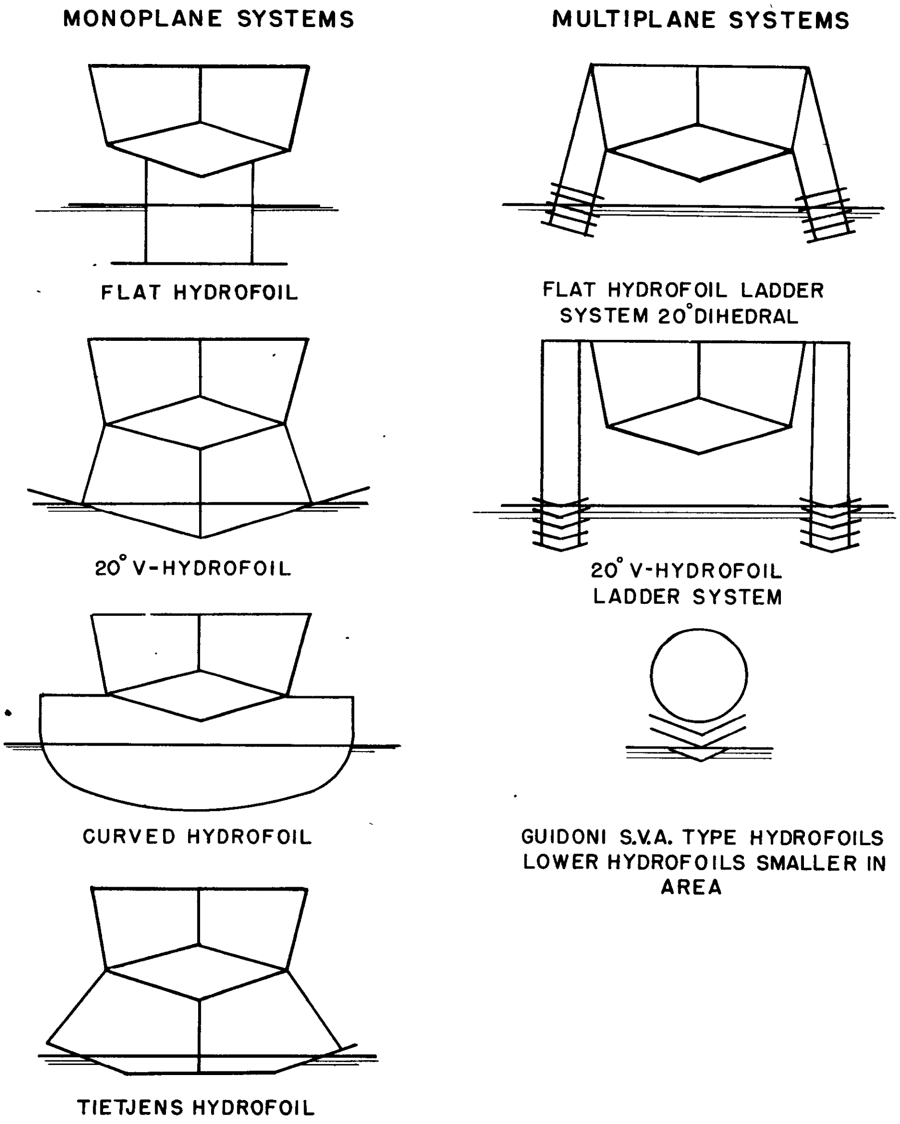


Figure 5 - Systems of Hydrofoils

HYDROFOIL SYSTEMS

There are fundamentally two systems of hydrofoils - monoplane and multiplane; these are illustrated in Figure 5. Different arrangements of the hydrofoils may be used with each system; for example, the hydrofoils may be mounted as single units, as triple units, or in tandem. The tandem arrangement has been more generally used in experiments with hydrofoils on boats.

The monoplane system, as the name implies, obtains lift from the reaction of the water on a single hydrofoil; the multiplane system employs a number of similar hydrofoils arranged one above another, ladderlike, and interconnected by struts. Figures 5 and 6 show schematically some of the combinations that have been tried.

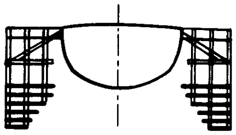
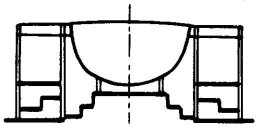
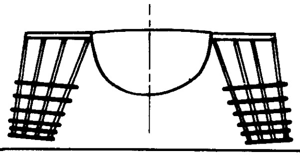
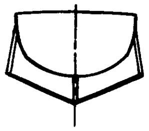
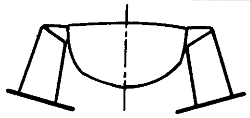
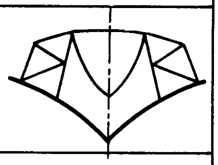
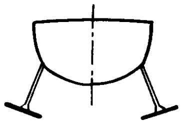
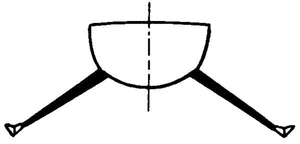
Designer	
E. Forlanini	
P. C. Hewitt	
A. G. Bell and F. W. Baldwin	
W. P. Thompson	
G. A. Crocco	 
R. D. Parker	
G. Pegna	

Figure 6 - Arrangements of Hydrofoils used in Early Experiments

FACTORS AFFECTING CHOICE OF SYSTEM

Stability in operation, initial cost and upkeep, and efficiency in operation are the principal factors to consider in the choice of a system of hydrofoils for any particular installation. The kind of service for which the boat is designed - whether for operation in protected waters or in the open sea - is another factor, perhaps of equal importance.

STABILITY

The successful application of hydrofoils to a high-speed boat demands that the hydrofoil system operate stably.

Benson and King (4) made tests with dynamically similar models to survey the stability characteristics of hydrofoils in several arrangements. Figure 5 contains diagrams of some of the arrangements tested. The results of these tests, although obtained under conditions in which cavitation did not occur, indicate an erratic change in lift and drag as a hydrofoil approaches the free surface of the water. The effect is more severe for a hydrofoil that is flat horizontally than for one inclined to the surface of the water. The effect is also more severe for a monoplane system than for a multiplane system.

For an installation that requires the hydrofoil to pass through the surface of the water as the boat rises, a ladder arrangement would seem to offer greater stability than a monoplane system, because the area of that part of the hydrofoil emerging through the surface would be a smaller part of the total area of the system. An arrangement of two ladderlike systems in tandem, similar to an arrangement used by Guidoni (1) on a streamlined spindle which represented the hull of a flying boat, was found to be stable over a wide range of speeds. No instability was observed when the model was lifted out of the water to simulate a takeoff.

The most violent type of instability observed in any of the NACA tests was one that involved yaw, roll, trim, and rise simultaneously. This type appeared to result from an instability in rise, which occurred whenever a hydrofoil approached so close to the surface of the water that the flow separated abruptly from the upper surface of the hydrofoil. The breakdown in flow was generally unsymmetrical and resulted in rolling and yawing.

Benson and Land (5) obtained similar results in their experiments to determine the effect of dihedral and depth of immersion of the hydrofoil. They found that in the region of very shallow immersions, less than half the hydrofoil chord, sudden changes in lift and drag are likely to occur, and the exact conditions under which such changes occur cannot be reliably predicted.

More recent experiments have centered around monoplane systems similar to those shown in Figures 5b, 5c, and 5d, in which the upper part of the hydrofoil is designed for breaking through the surface of the water, and the lower part for best efficiency when operating submerged. The design is based on the theory that the lower part of the hydrofoil will not be worked closer to the surface than one half the hydrofoil chord.

COST

The cost of commercial installations must be kept a minimum if the craft is to compete successfully with boats of other types. The necessity for maintaining uniformity and symmetry in construction naturally makes the multiplane hydrofoil system more difficult and more costly to manufacture. For military craft, cost may be of secondary importance.

EFFICIENCY

Arguments for keeping installation costs down apply equally to operating costs. The multiplane system of hydrofoils, with its multiplicity of struts, and of intersections of struts with hydrofoils, has higher resistance than the monoplane system; it is also more subject to early cavitation, because air is sucked down around the supporting struts. According to Sottorf (8) the efficiency of a hydrofoil is greatly impaired by the slightest damage to, or fouling of, the leading edge. Therefore it seems logical to assume that the monoplane system would be the better choice in this respect.

SPRAY CHARACTERISTICS

Because monoplane systems have fewer strut intersections, their spray characteristics are superior to those of the multiplane system. Most of the spray emanates from the points where struts or hydrofoils intersect the surface of the water (2). Spray is especially heavy when a juncture of hydrofoil and strut emerges from the water.

DIHEDRAL ANGLE

The dihedral angle of the hydrofoil is the angle of inclination of the arms to the horizontal. This angle plays a very important part in the performance of the individual hydrofoil and, therefore, of the hydrofoil system, whether it is of the monoplane or multiplane type. Dihedral is essential for installations in which the hydrofoil must cut the surface of the water, if the boat is to operate stably. The dihedral angle also affects the lift and drag of the hydrofoil, as well as the spray and cavitation characteristics.

EFFECT ON STABILITY

Dihedral contributes to the stability of a hydrofoil, principally because the change in lift from complete immersion to zero immersion is gradual (1), (3), (4), (5), (8), (9). As a flat hydrofoil approaches close to the surface, its whole lifting area is affected by the change of flow above its upper surface; but as an inclined hydrofoil approaches close to the surface only a part of its lifting area is affected.

EFFECT ON LIFT AND DRAG

For a given span on the water, the lift increases with increase in dihedral, up to about 45 degrees, for the reason that the hydrofoil with large dihedral operates at a greater depth below the surface than a hydrofoil whose dihedral is less, and as a consequence is more efficient (8).

Dihedral generally increases the drag of a hydrofoil because, for a given span, the underwater length of the hydrofoil increases with increasing dihedral and, therefore, the profile drag and vortex resistance are relatively higher.

Figure 7 is a comparison of the lift coefficient, drag coefficient, and drag/lift ratio obtained by Sottorf from model tests of two hydrofoils that have identical profile sections and spans but different dihedral angles.

EFFECT ON SPRAY AND CAVITATION

The tests (8) reveal that a hydrofoil with a 45-degree dihedral has better spray characteristics and less cavitation over the suction surface than a hydrofoil with less dihedral.

The results of Sottorf's tests, as well as the opinions expressed in Reference (10), indicate that for general performance a dihedral angle of 26 to 30 degrees is best.

ASPECT RATIO

The maximum lift and the efficiency of a hydrofoil increase with increase in aspect ratio. It might be thought beneficial, therefore, to use high aspect ratios in hydrofoil design. In practice, however, the aspect ratio must be kept within certain limits, because of structural problems and of the desirability of incorporating dihedral in the design, with the result that the efficiency obtainable with hydrofoil structures is less than that obtainable with comparable aerofoil structures.

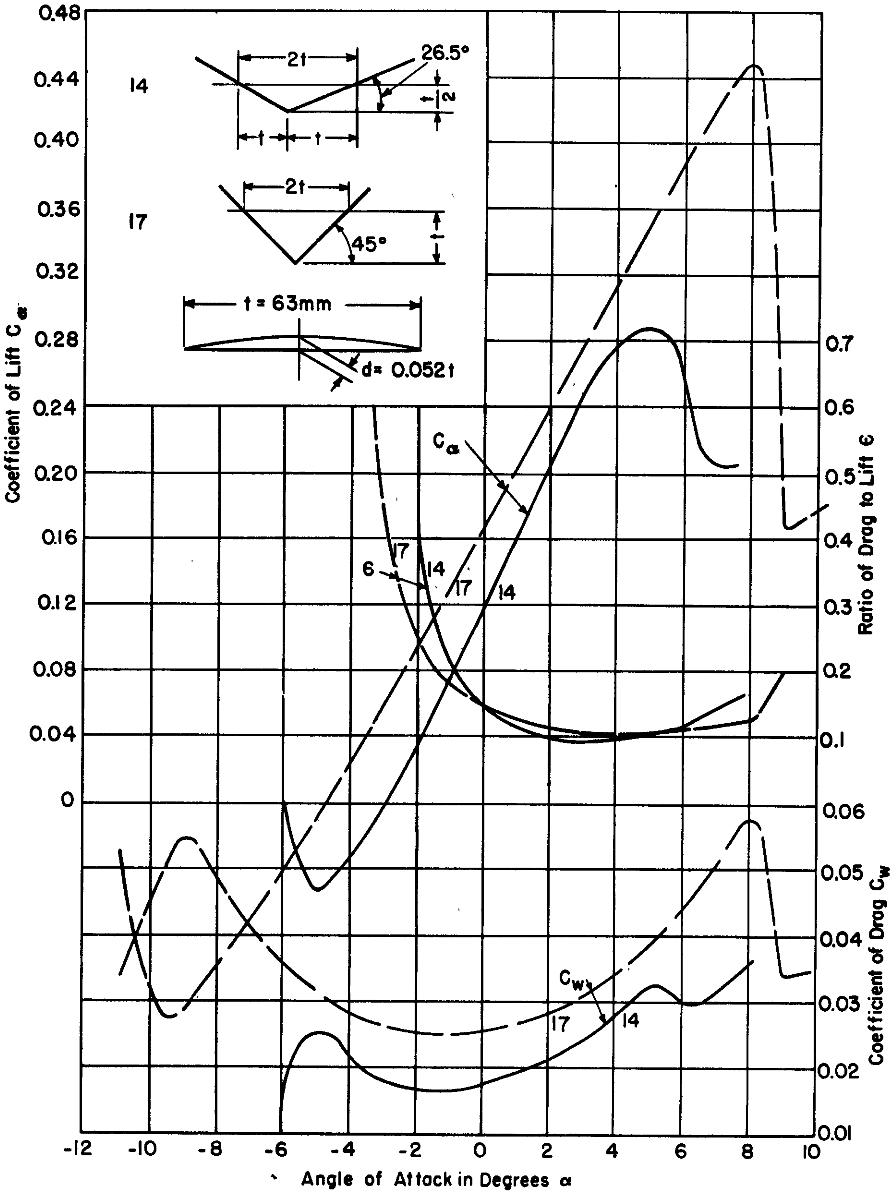


Figure 7 - Influence of Dihedral Angle on Lift and Drag Coefficients and Planing Numbers of Two Hydrofoils Whose Aspect Ratios and Profile Sections Are Identical

RELATION TO STRUCTURAL PROBLEMS

In any hydrofoil installation the span must be kept within safe and reasonable limits. A hydrofoil that projects beyond the outlines of the hull is subject to damage from collision with other boats, or from operation in close quarters. Furthermore, the greater number of supporting struts required to distribute the load on, and maintain the symmetry of, a hydrofoil of great span, multiplies the problems of hydrofoil construction.

RELATION TO EFFICIENCY

Model experiments by Sottorf (8), Figure 8, indicate that, for a given dihedral angle and for depths of immersion equal to or greater than half the hydrofoil chord, the maximum lift coefficient increases with increase in span, and the minimum drag/lift ratio decreases under similar conditions, which means that, within the limits covered by the model tests, the maximum efficiency increases with increase in aspect ratio.

Sottorf also reports increased efficiency and less interference between the sloping sides of a hydrofoil when a horizontal section connects the two sides. This construction is generally not practicable, however, because the accompanying large aspect ratio, together with the very thin profile sections necessary for best efficiency, results in structural problems similar to those mentioned earlier.

The best information indicates that, under the requirements for minimum draft and most favorable dihedral angle, an aspect ratio of about 4.15 gives best all around performance.

DEPTH OF SUBMERSION

The flow of water over a hydrofoil submerged to depths greater than 4 or 5 chord lengths is apparently not influenced by the surface of the water, and conditions similar to those of an airfoil prevail (3). But as the hydrofoil rises close to the surface of the water the flow changes, and the lift and drag characteristics of the hydrofoil change rapidly.

The flow of water over the upper surface of the hydrofoil at depths of half a chord length or less may break down rather suddenly and result in loss of lift and stability.

The breakdown may be incomplete or unsymmetrical spanwise, depending on the angle of dihedral and on the roughness of the surface of the water. The exact conditions under which the loss of lift may occur cannot be accurately predicted.

Once the flow has definitely separated from the upper surface of the hydrofoil, the rate of change in lift and drag with change in angle of attack decreases.

Figure 9, taken from Reference (8), illustrates the rate of change in lift and drag of a hydrofoil when it approaches close to the surface of the water. The breakdown of the flow over Hydrofoils 16g, $16g_1$, and $16g_2$ was delayed by the use of shields to prevent entry of air; see Figures 18 and 19. On Figure 9, the curve for Hydrofoil 16_s shows the characteristic breakdown in lift which occurs when air is permitted to enter the boundary layer of the hydrofoil. The curves for Hydrofoil 16 also illustrate the

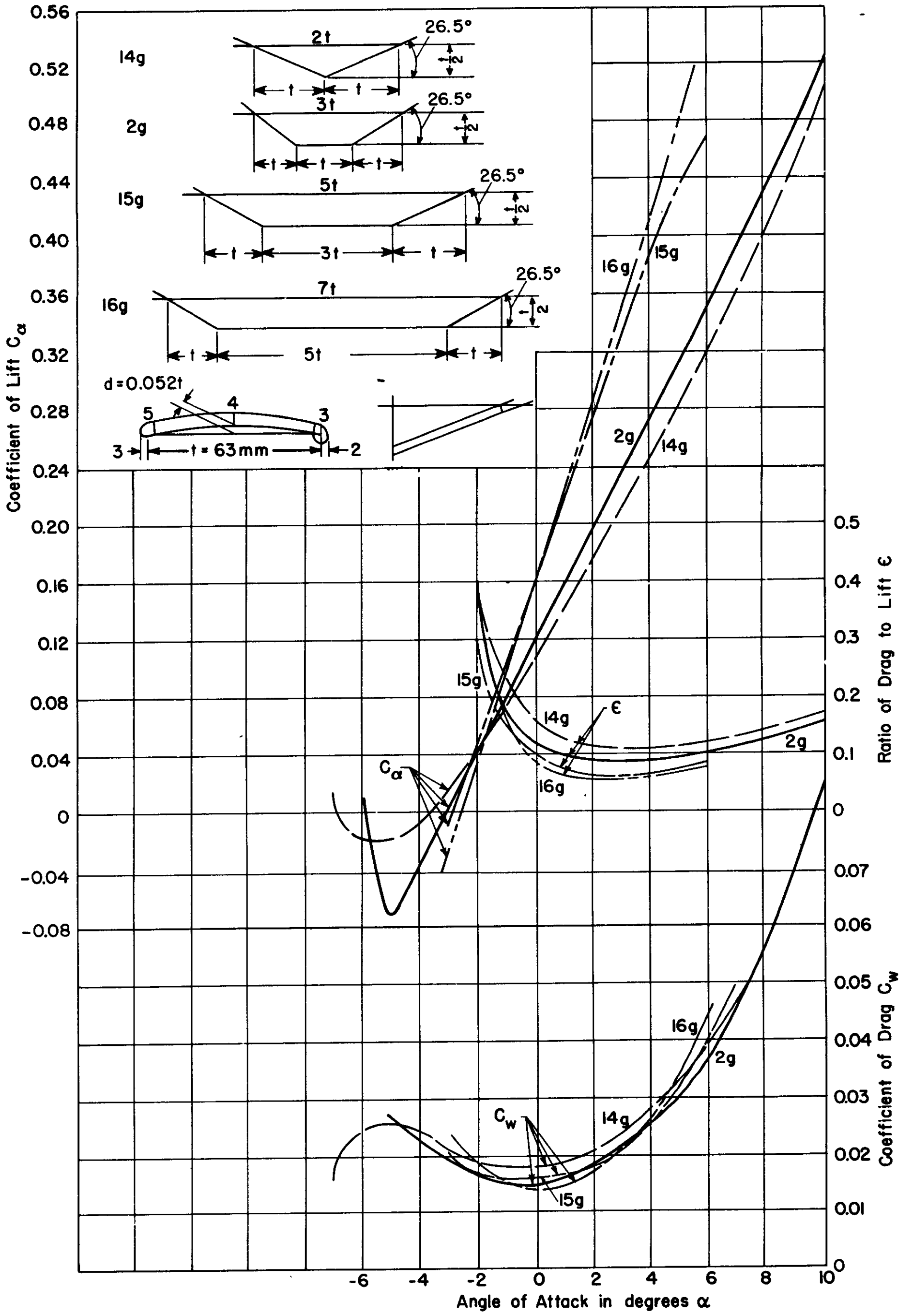


Figure 8 - Influence of Aspect Ratio on Lift and Drag Coefficients and Planing Number of Hydrofoils Whose Profile Sections, Dihedral Angles, and Depths of Submersion are Identical

The symbol g denotes that shields were used to prevent early penetration of air to the suction surface.

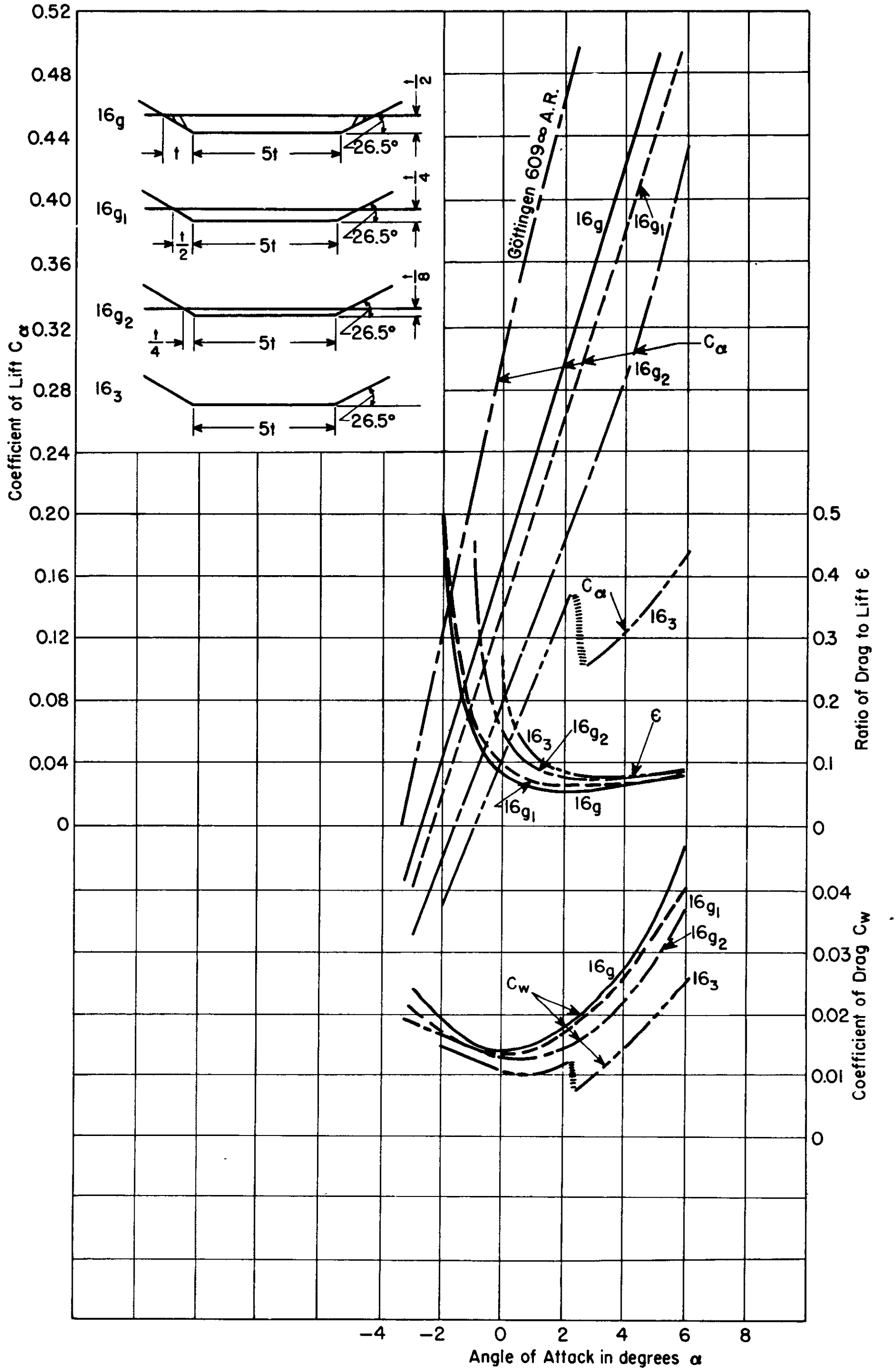


Figure 9 - Influence of Depth of Submersion on Lift and Drag Coefficients and Planing Number of a Hydrofoil Whose Aspect Ratio, Dihedral Angle, and Profile Section Are Constant

The symbol g denotes that shields were used to prevent early penetration of air to the suction surface.

decrease in the rate of change of the lift and drag with change in angle of attack after breakdown occurs.

ANGLE OF ATTACK

The stability of a hydrofoil boat depends largely on the angle of attack of the hydrofoil system. Small angles of attack are necessary in order to lessen the severity of the transition as the hull is lifted out of the water and the hydrofoil approaches the surface (1), (3), (4), (9), (10). Large angles of attack are incompatible with stable operation at high speeds. Figure 10, taken from Reference (8), shows that at high speeds suction-surface cavitation increases rapidly with increase in angle of attack.

Sottorf's experiments (8) show that the range of angles of attack at which a hydrofoil can operate free from disturbances due to cavitation is small; even at relatively low speeds it is only from about minus 4 to plus 5 degrees. The useful total range decreases rapidly, with increase in speed, to about 2 degrees at speeds over 50 knots.

CAVITATION

When a hydrofoil, operating at constant forward velocity, approaches the surface of the water, the mass of water flowing above the hydrofoil is reduced. This reduction lowers the absolute value of the negative pressure on the upper surface of the hydrofoil and decreases the lift. According to References (5), (6), (9), the principal effect of velocity on the characteristics of the hydrofoil is to limit the maximum lift. Flow around the hydrofoil is considered to be undisturbed so long as the absolute value of the negative pressure resulting from the flow is equal to or less than the supporting pressure. When the negative pressure exceeds the supporting pressure, any further increase in velocity results in the formation of a vacuum at the point of maximum negative pressure, which is followed by complete upper-surface cavitation.

The supporting pressure is defined as the atmospheric pressure plus the static water pressure minus the vapor pressure of the water.

Reference (8) mentions three types of cavitation:

1. Suction-surface cavitation starting from the leading edge of the hydrofoil.

2. Suction-surface cavitation starting about one half chord back from the leading edge of the hydrofoil.

3. Pressure-surface cavitation starting at the leading edge of the hydrofoil.

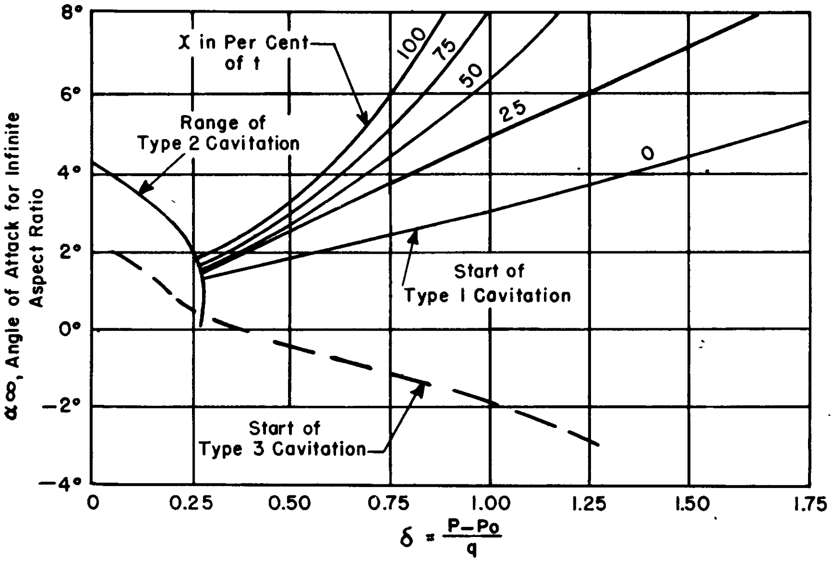


Figure 10a - Cavitation chart based on measurements by Walchner for d/t = 0.0385 and 0.0785, h = ∞; interpolated for d/t = 0.052 (DVL Profile 2g).

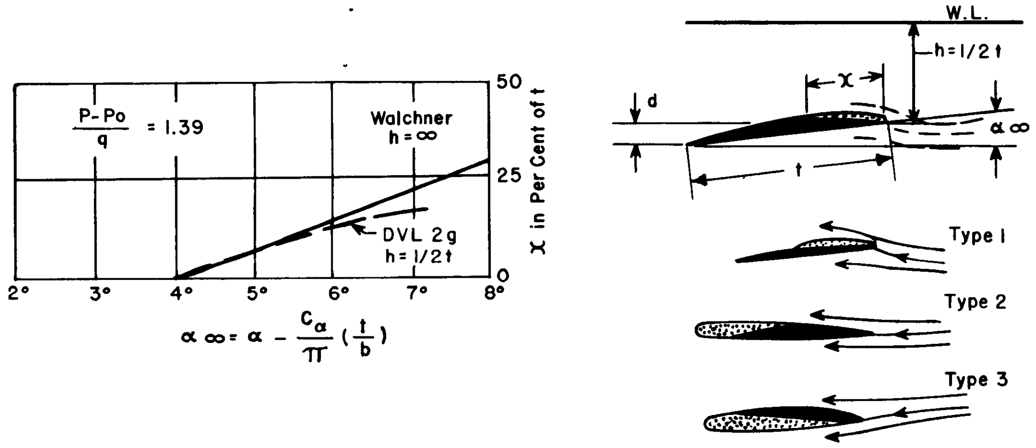


Figure 10b - Comparison of type 1 cavitation at $\frac{P - P_0}{q}$ = 1.39 for DVL profile 2g tests at h = 1/2t corrected to $\alpha = \infty$, with interpolated Walchner measurements for an identical profile.

Figure 10 - Comparison of Cavitation Measurements on DVL Profile 2g at Depth of 1/2t with Measurements by Walchner for Depth = ∞

These are illustrated in Figure 10.

The results of the experiments covered in Reference (8) indicate that type-1 cavitation may have a favorable effect so long as it does not extend more than half the chord length back of the leading edge of the profile. The thin cavitation bubble in effect increases the curvature of the streamlines over the forward half of the profile, which results in increased lift. Also the frictional resistance is reduced by the decrease in the wetted area. However, the attendant erosive action at the end of the cavitation zone precludes operation under these conditions. This type of cavitation was not observed on very thick profile sections, i.e., sections whose thickness was of the order of 14 per cent of the chord.

Figure 10 also illustrates the manner in which type-1 cavitation spreads over the suction surface of a hydrofoil as the angle of attack and the cavitation number vary.

Cavitation number δ is defined as the ratio of the supporting pressure to the dynamic pressure:

$$\delta = \frac{P - P_0}{\frac{\rho}{2} V^2} = \frac{P - P_0}{q}$$

where P is the static water pressure plus the atmospheric pressure,

P_0 is the vapor pressure of the water,

ρ is the mass density of the water, and

V is the velocity of flow.

Type-2 cavitation occurs at high speeds and is associated with comparatively thick profiles and low angles of attack.

Type-3 cavitation is associated with negative angles of attack.

Figure 10 makes clear that the range of angles of attack free from cavitation decreases more and more with increase in speed. The results of Sottorf's experiments indicate that the maximum speed attainable without serious cavitation is approximately 100 kilometers per hour (54 knots), and then only by the use of very thin profile sections and small angles of attack.

PROFILE SECTIONS SUITABLE FOR HYDROFOILS

The overall performance of a hydrofoil system depends upon the performance of the individual hydrofoils that make up the system. No single profile section has been found that gives maximum performance under all circumstances. A section most suitable for operating at deep submergence is not the best section for use at shallow submergence. Likewise a section designed for best efficiency at low speeds would not be the best at high speeds.

A useable hydrofoil must have the following characteristics:

1. Freedom from cavitation up to high speeds and, for roughwater performance, the largest possible range of angles of attack.

2. Unbroken suction-surface flow near the surface of the water for the largest possible range of angles of attack.

3. A minimum of spray.

4. Favorable drag/lift ratios, which approach aerodynamic ratios at small angles of attack.

Sottorf (8) made an extensive investigation on model hydrofoils in an effort to find a profile section that would meet the requirements listed above. He started with a basic section which had a straight pressure surface, a circular-arc suction surface, and a ratio of maximum thickness to chord length of 0.052. He varied the shape, the thickness, and the position of the maximum thickness; he tested all of the models with the leading edge of the profile at a constant depth below the surface of the water, i.e., a depth equal to one half the hydrofoil chord.

The characteristic curves obtained from these tests have been reproduced in Figures 11 through 19. They show:

1. The influence of thickness, Figure 11.

2. The influence of position of maximum thickness, Figure 12.

3. The influence of concave pressure surface, Figure 13.

4. The influence of convex pressure surface, Figure 14.

5. The influence of S-shaped sections in which the forward half of the pressure surface was straight, Figure 15.

6. The influence of S-shaped sections in which the forward half of the pressure surface was concave, Figure 16.

7. The influence of increasing curvature near the leading edge, Figure 17.

8. The influence of shields to prevent early air penetration to the suction surface, Figures 18 and 19.

These figures show the limited useful range of angles of attack that a hydrofoil has when it runs close to the surface of the water. For thick sections the range of positive angles is very small. S-shaped sections and sections with convex or concave pressure surfaces were generally unsatisfactory. They were more or less erratic in performance, and had a very limited range of positive angles of attack before breakdown.

Profile 2h, a modification of Profile 2, gave the best results. This profile, illustrated in Figure 17, had a straight pressure surface, with maximum thickness $0.45\,t$ abaft the leading edge, where t is the chord. The after part of the suction surface was circular; the forward part was elliptic and terminated in a leading edge whose included angle was about 25 degrees.

(Text continued on page 28.)

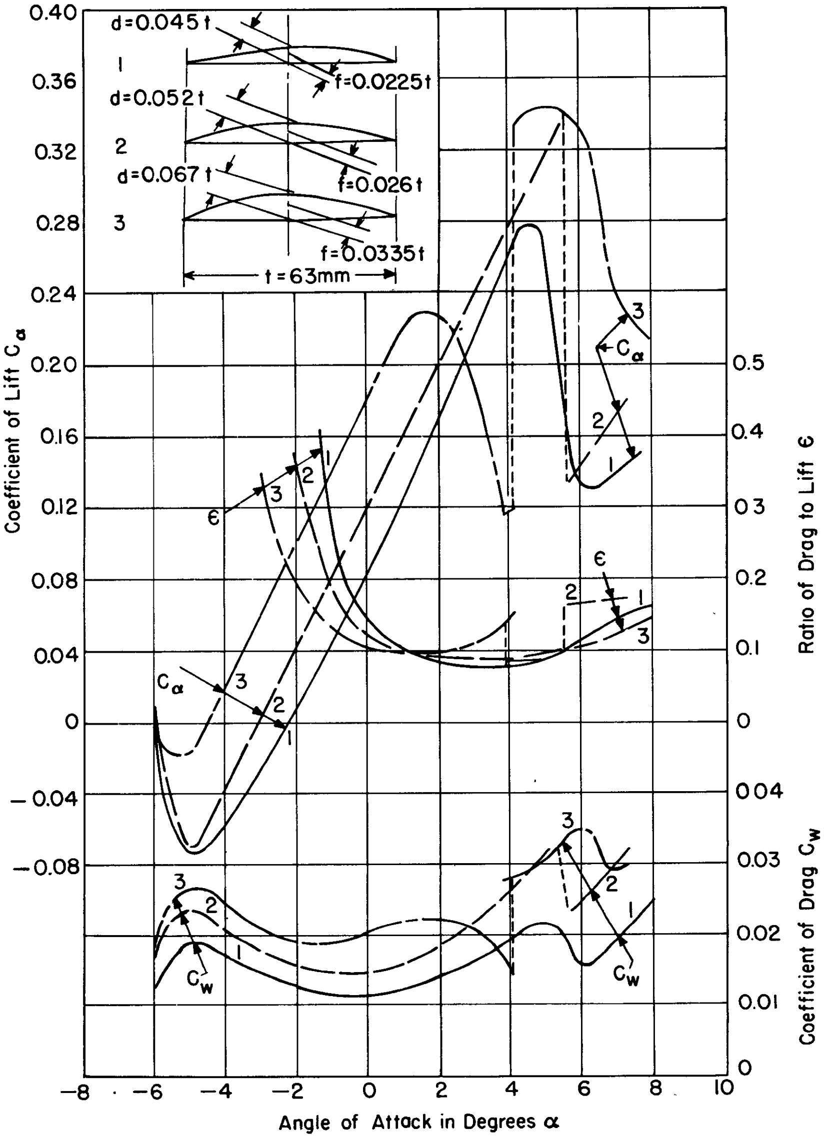


Figure 11 - Influence of Profile Thickness on Lift and Drag Coefficients and Planing Number of Hydrofoils Whose Aspect Ratios and Depths of Submersion Are Identical

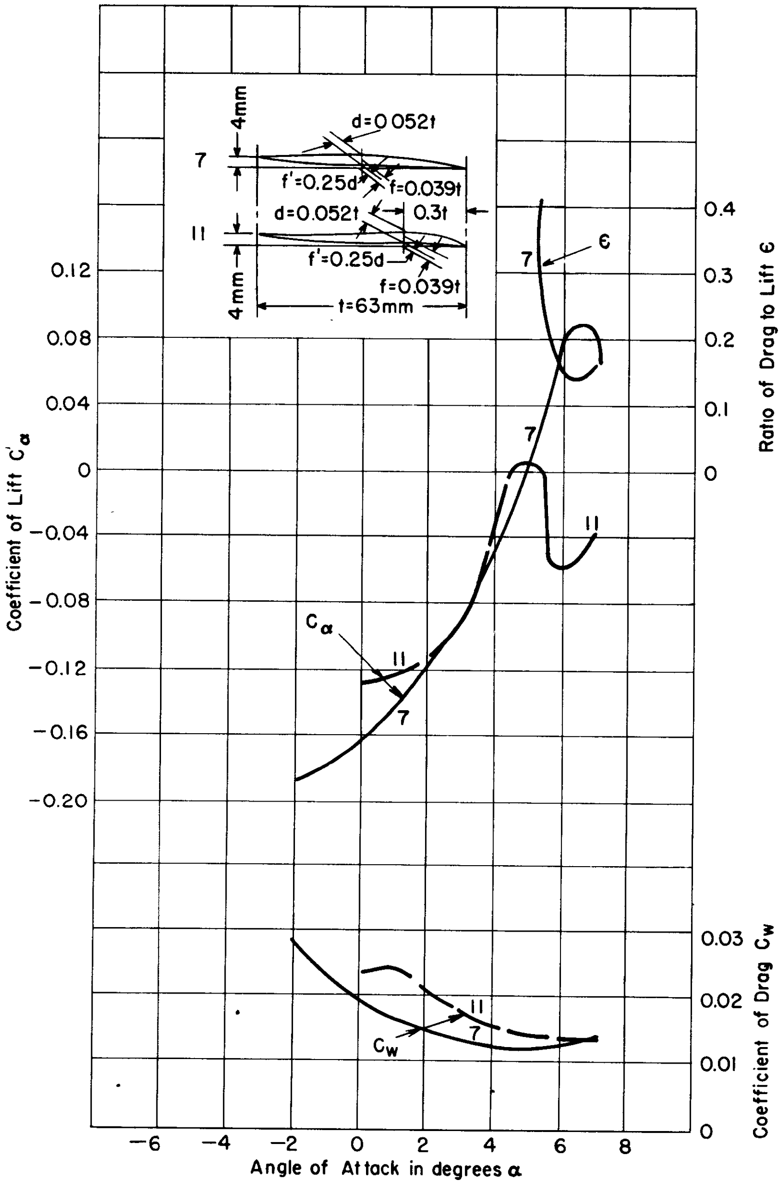


Figure 12 - Influence of Position of Maximum Thickness on Lift and Drag Coefficients and Planing Number of Hydrofoils Whose Aspect Ratios and Depths of Submersion Are Identical

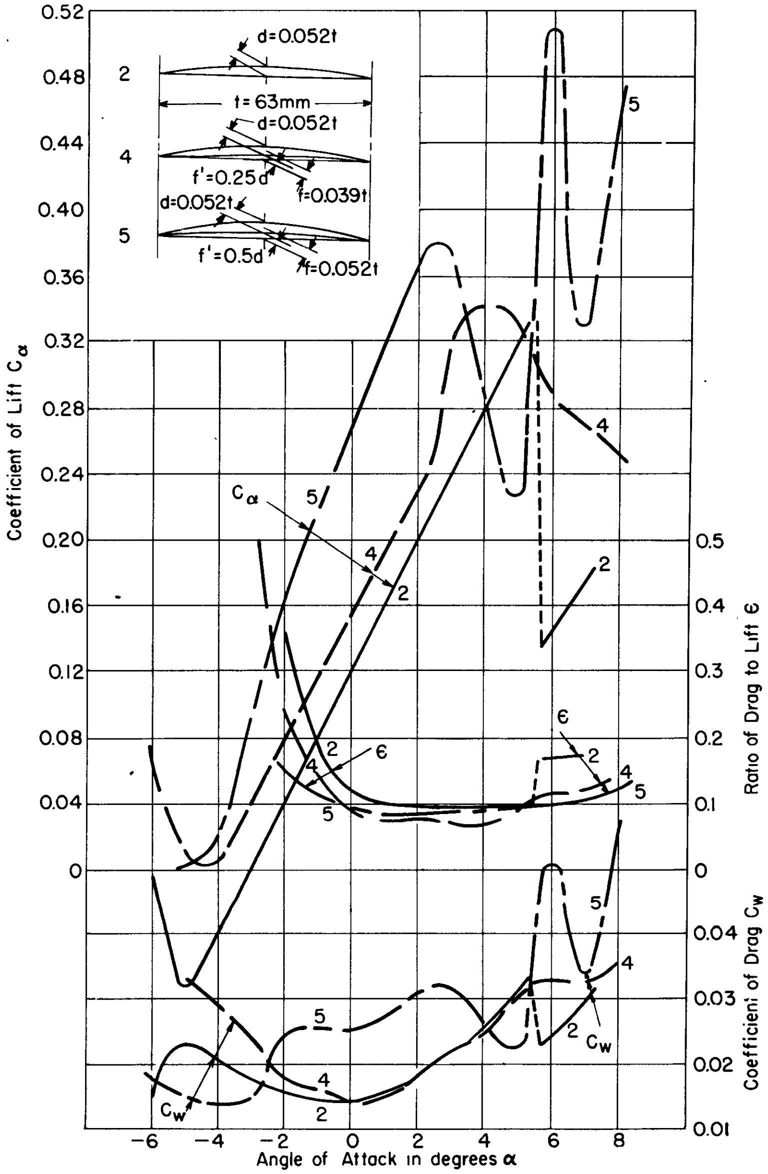


Figure 13 - Influence of Concave Pressure Surface on Lift and Drag Coefficients and Planing Number for Hydrofoils Whose Aspect Ratios and Depths of Submersion Are Identical

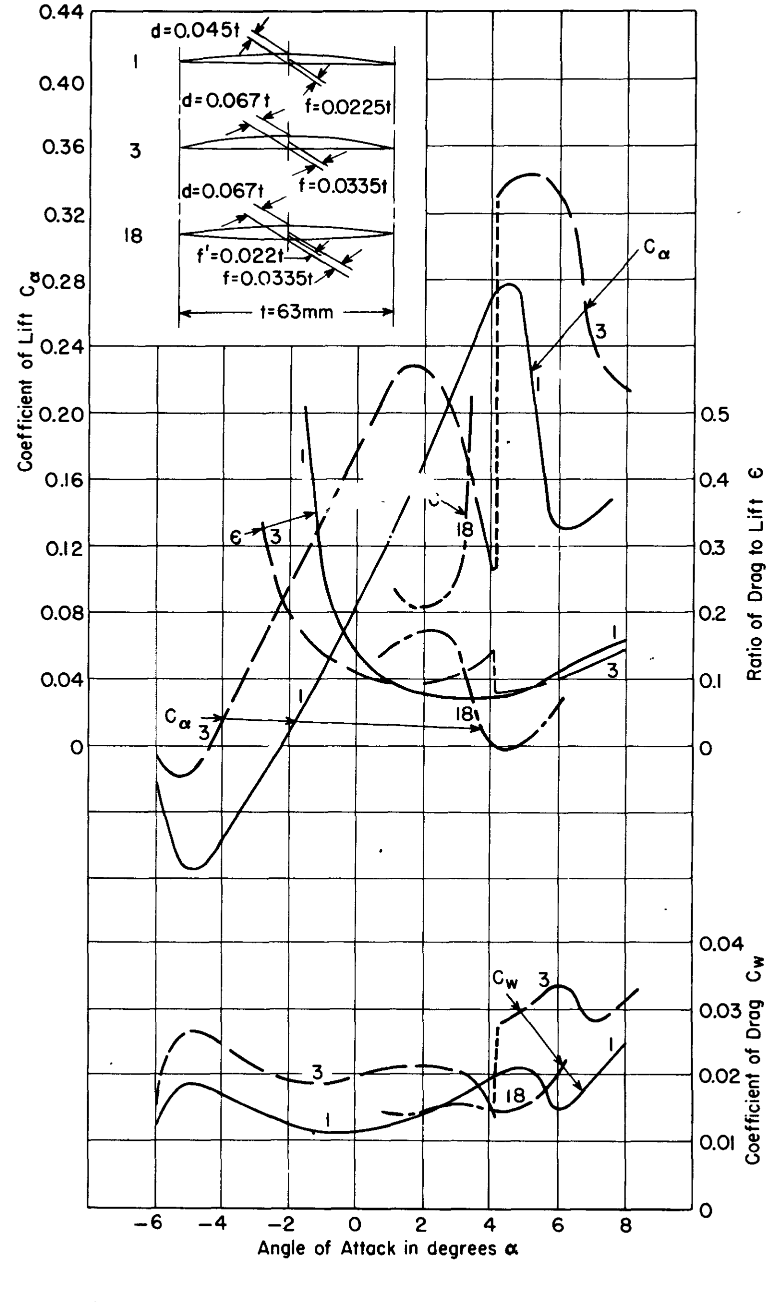


Figure 14 - Influence of Convex Pressure Surface on Lift and Drag Coefficients and Planing Number of Hydrofoils Whose Aspect Ratios and Depths of Submersion Are Identical

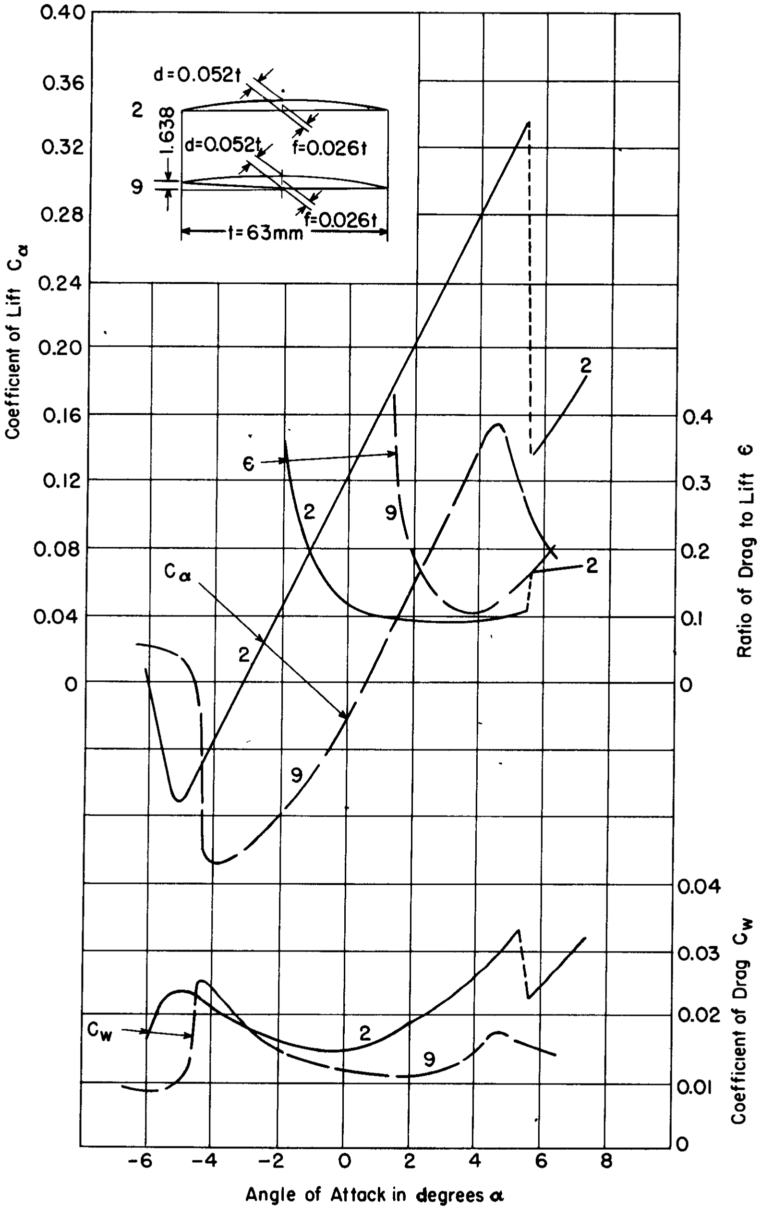


Figure 15 - Influence of S-Shaped Sections on Lift and Drag Coefficients and Planing Number of Hydrofoils Whose Aspect Ratios and Depths of Submersion Are Identical

The forward half of the pressure surface is straight.

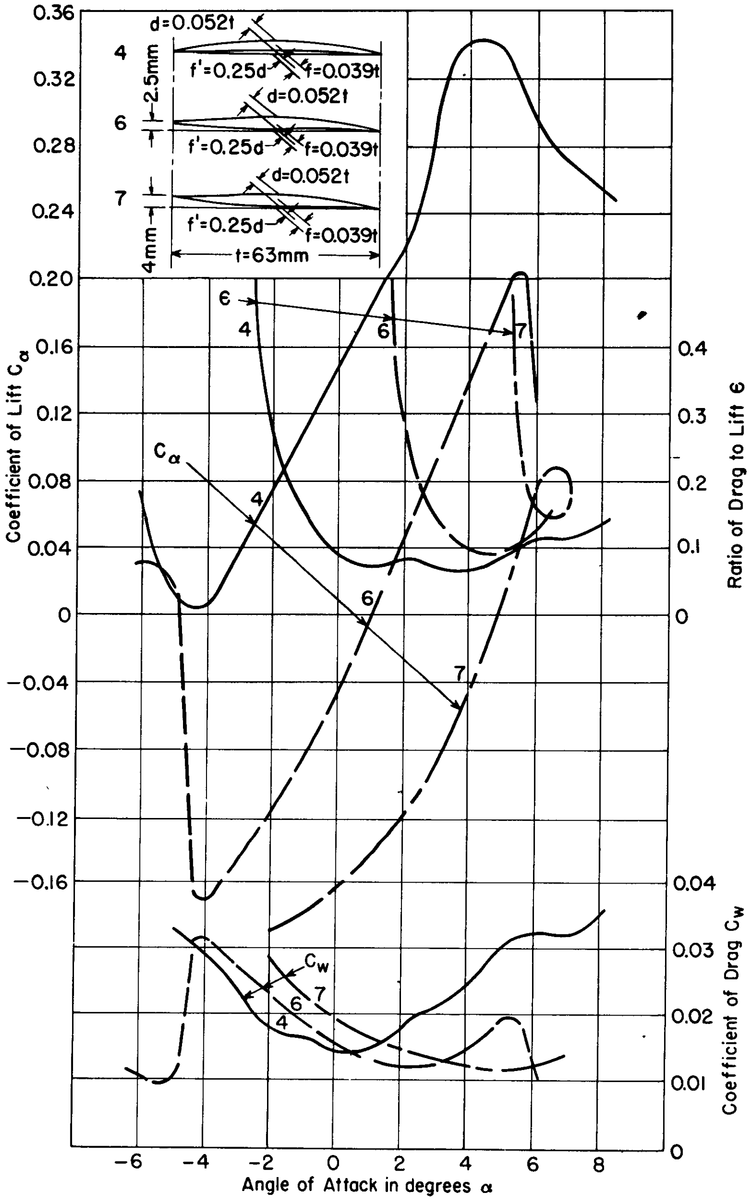


Figure 16 - Influence of S-Shaped Sections on Lift and Drag Coefficients and Planing Number of Hydrofoils Whose Aspect Ratios and Depths of Submersion Are Identical

The forward half of the pressure surface is concave.

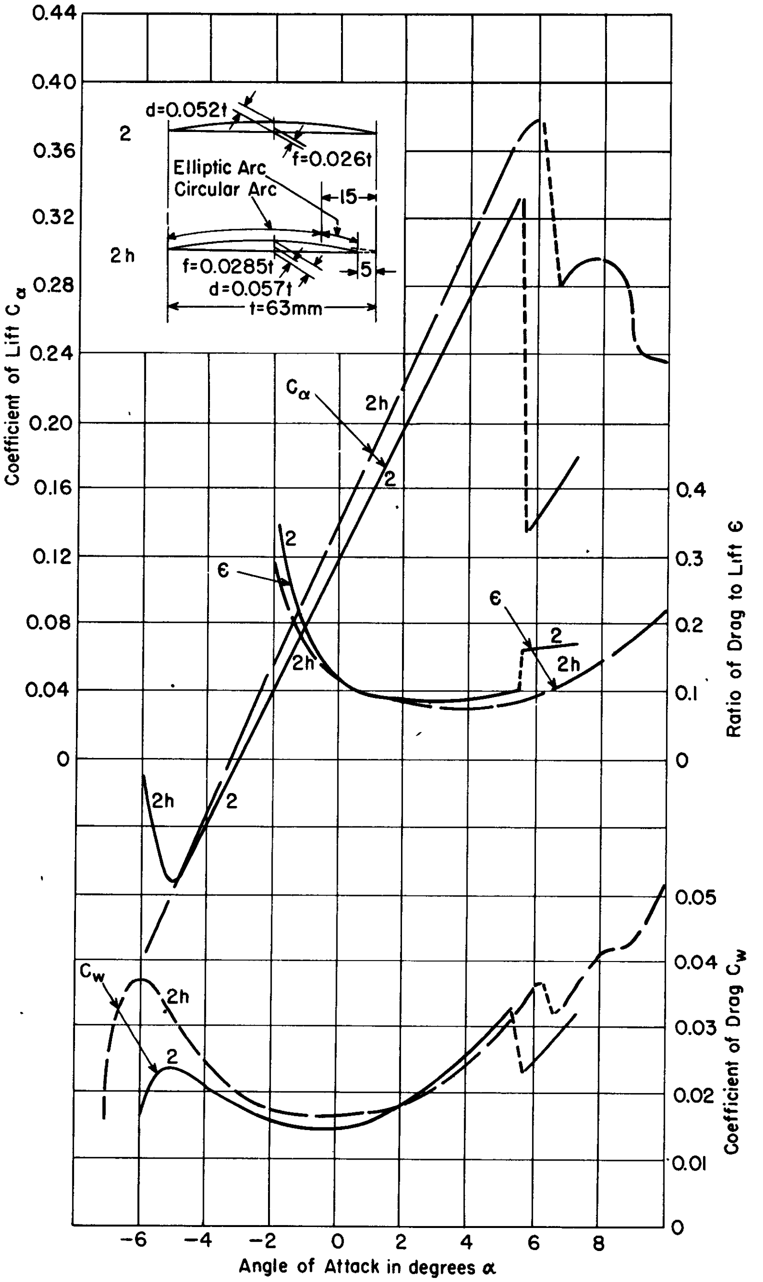


Figure 17 - Influence of Increased Curvature Near Leaving Edge on Lift and Drag Coefficients and Planing Number of Hydrofoils Whose Aspect Ratios and Depths of Submersion Are Identical

The after part of the suction surface is circular-arched; the forward part elliptic.

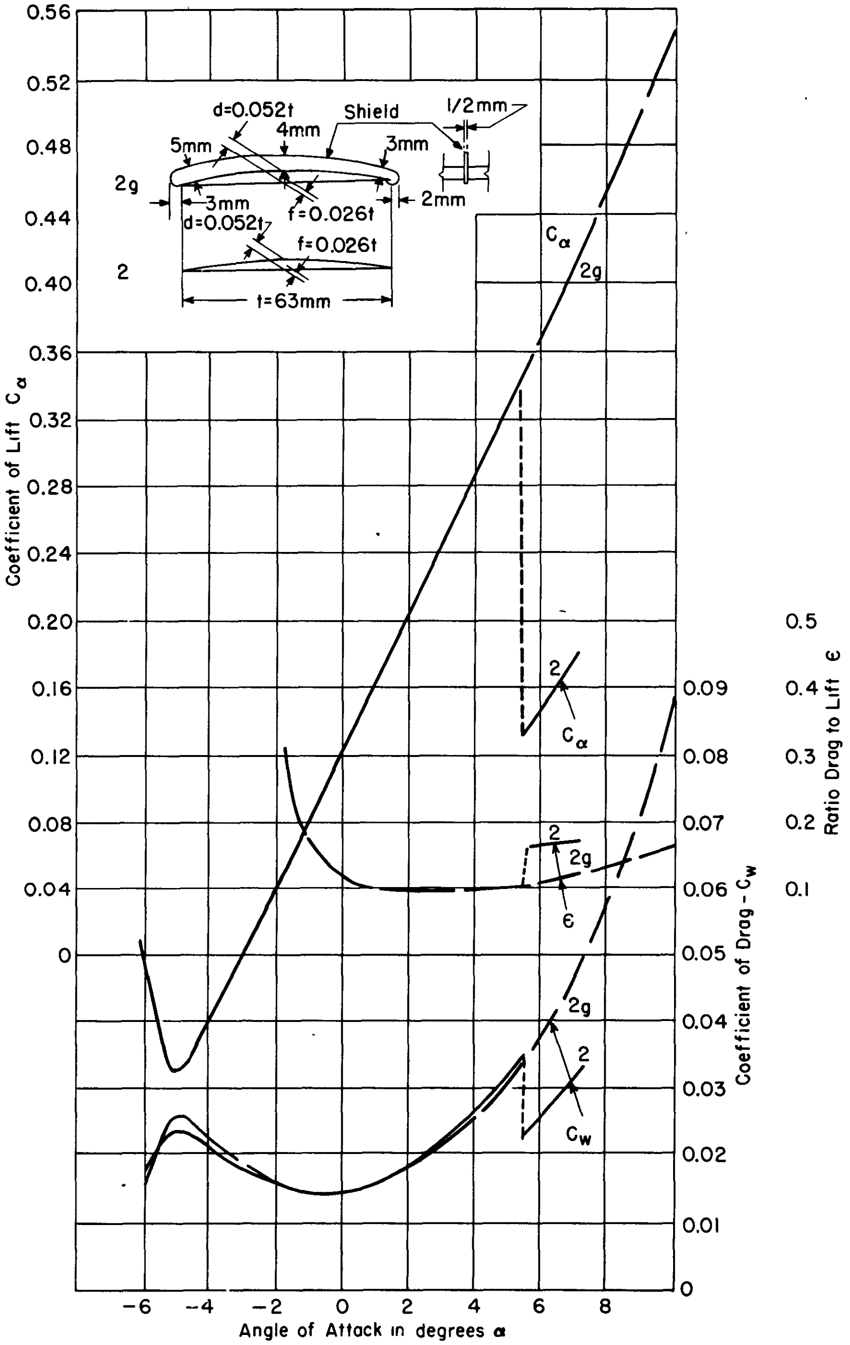


Figure 18 - Influence of Shields on Lift and Drag Coefficients and Planing Number of a Hydrofoil Whose Aspect Ratio, Profile Section, and Depth of Submersion Are Constant

Shields to prevent early penetration of air to the suction surface consist of thin plates mounted perpendicular to the suction surface near the surface of the water.

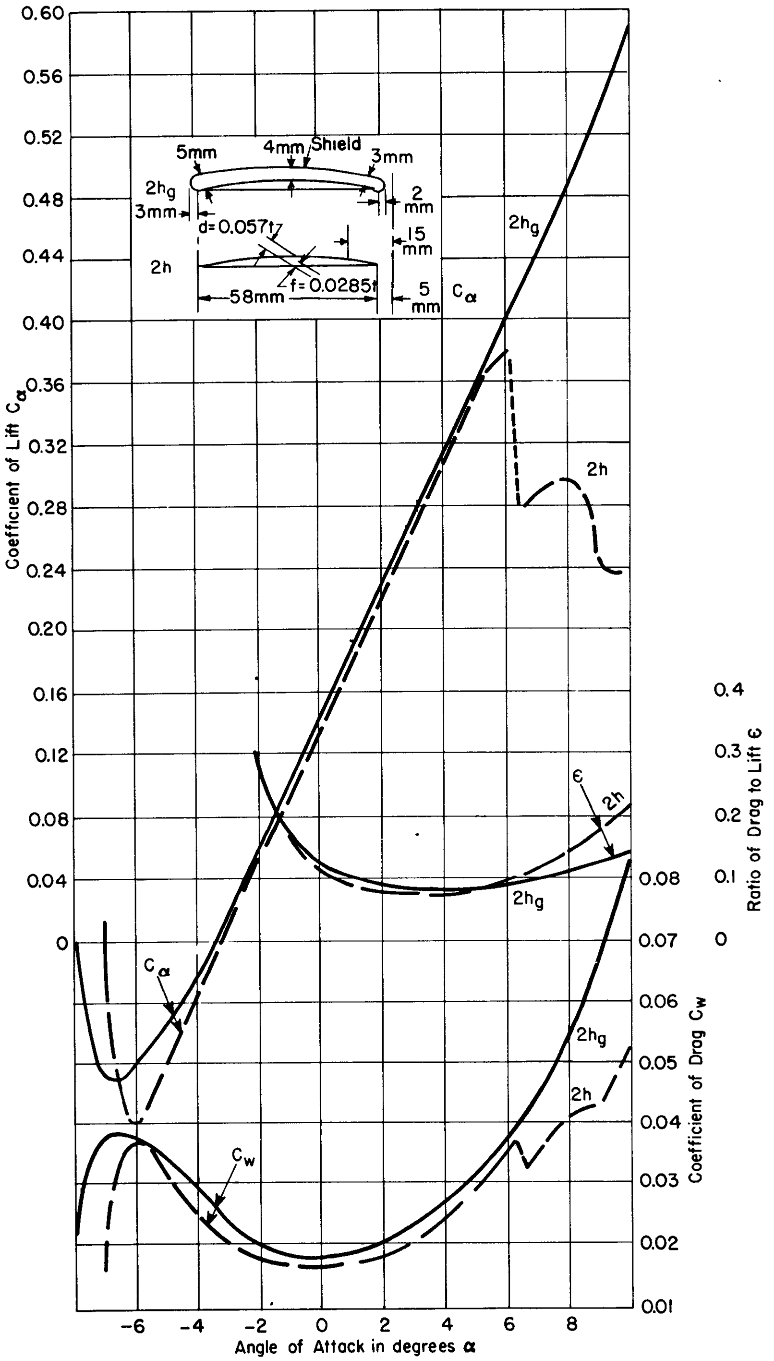


Figure 19 - Influence of Shields with Profile 2h (See Figure 17)

Penetration of air to the suction surface of a hydrofoil is the predominant factor which limits the working range of the hydrofoil. In his model experiments Sottorf succeeded in delaying air penetration by the use of shields secured perpendicular to the suction surface near the surface of the water, as indicated in Figures 18 and 19. Although this expedient made it possible to evaluate the test results more accurately, the effect of shields in actual service, where the depth of submergence is constantly changing, is unknown.

The slightest damage to, or soiling of, the leading edge of a hydrofoil causes early air penetration to the suction surface; it also causes radical changes in lift and drag as well as objectionable spray.

Slight rounding of the leading edge of the profile causes separation of the flow from the suction surface when the profile is close to the surface of the water, and produces heavy spray. High-speed airfoil sections are, therefore, not suitable for use at shallow depths.

For an installation in which the lower part of the hydrofoil can operate at depths greater than one half chord, or for large boats whose hydrofoils extend well below the surface, a combination may be desirable - one consisting of an aerodynamic section for the lower part of the hydrofoil and a sharp-edged section for the upper part of the hydrofoil. Very thin sections which have sharp leading edges, similar to the one shown in Figure 17, must be used for hydrofoils that operate close to the surface or cut through the surface of the water.

PLAN-FORM ARRANGEMENTS

A satisfactory arrangement of hydrofoils on a high-speed boat requires that the system provide adequate longitudinal and lateral stability for all conditions under which the boat is expected to operate. The arrangement should also aim toward minimum interference between the forward and after hydrofoils.

LOCATION OF HYDROFOILS IN RELATION TO CENTER OF GRAVITY

Reference (11) presents the results of a study of the theoretical motions of hydrofoil systems to determine some of the important parameters, primarily with respect to the longitudinal behavior of tandem systems; see Figure 20. The conclusions set forth in that study are as follows:

1. The hydrofoils should be as widely spaced longitudinally as feasible.

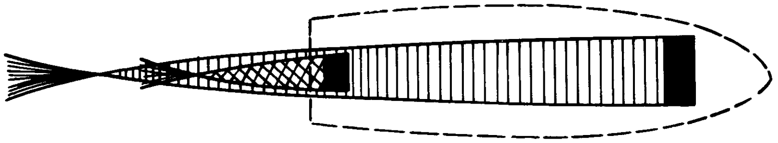


Figure 20 - Interaction between Hydrofoils in a Tandem Arrangement

2. The rate of change of lift with change in depth of immersion of the hydrofoils should be large. The rate of change of lift with immersion is insufficient for hydrofoils with no dihedral unless the area is composed of several panels in a multiple arrangement.

3. The after hydrofoil area should be as large as the forward hydrofoil area, or larger, if large variations in center of gravity are to be accommodated when longitudinal spacing of the hydrofoils is close - of the order of 10 chords. With more open spacing, an arrangement with the main surface forward appears to be sufficiently stable.

4. The choice of horizontal center-of-gravity location should be based on considerations of the resultant characteristics of the longitudinal motions and the hydrofoil loadings. The location should be abaft the hydrodynamic center of the forward hydrofoil in order to avoid undesirable loading. The location should be as far ahead of the rear boundaries of the stable region as feasible without incurring objectionable oscillations. For two equal hydrofoils in tandem the best location appears to be about 35 per cent of the hydrofoil spacing abaft the forward hydrofoil.

5. If the effects of power are neglected, the vertical center-of-gravity location appears to be of minor importance.

6. A reduction of the pitching radius of gyration causes an appreciable increase in the range over which the horizontal center-of-gravity location is stable.

INTERACTION BETWEEN HYDROFOILS

In an unpublished article Sottorf maintains that in a system of two hydrofoils operating in tandem, as in Figure 20, the wash from the forward hydrofoil may so affect the performance of the after hydrofoil as to result in an unstable system. The sides of the after hydrofoil are so near the walls of the trough created by the forward hydrofoil that they cut the water at unfavorable angles. Alternate suction on the opposite sides of the hydrofoil causes yawing. The downwash of the forward hydrofoil causes an increase in the induced resistance of the after hydrofoil.

PROPOSED ARRANGEMENTS

Sottorf offers three possibilities for avoiding the interaction between the forward and after hydrofoils:

1. Make the forward hydrofoil flat-arched and with small chord; the after hydrofoil sharply inclined, i.e., with large dihedral, and of great chord. In this arrangement, shown in Figure 21, the after hydrofoil operates within the trough created by the forward hydrofoil. The high induced resistance of the after hydrofoil still remains, however.

Figure 21a - The forward hydrofoil is flat-arched with small chord which produces a wide shallow trough.

Figure 21b - The after hydrofoil has large deadrise and small chord to permit it to run within the trough created by the forward hydrofoil.

Figure 21 - Arrangement Proposed for Minimizing Interaction between Hydrofoils in a Tandem Arrangement

2. To avoid the high induced resistance of the after hydrofoil in a tandem arrangement, a framework is proposed consisting of three hydrofoils - one forward and two abreast in the after position; see Figure 22. The after hydrofoils are spread sufficiently to avoid the spray and the trough created by the forward hydrofoil.

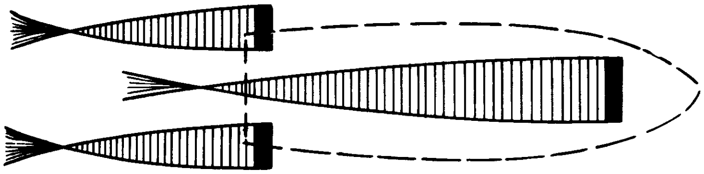


Figure 22 - Arrangement Proposed for Avoiding Interaction between Forward and After Hydrofoils

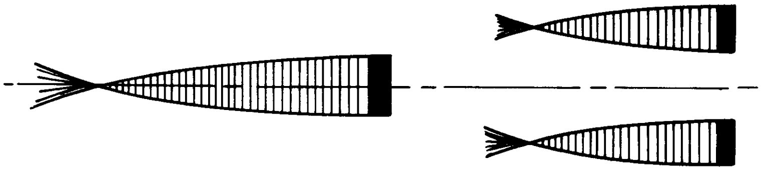


Figure 23 - Alternate Arrangement Proposed for Avoiding Interaction between Forward and After Hydrofoils

3. The third arrangement is similar to the second except that the two athwartship hydrofoils are located forward, as shown in Figure 23.

Tests are required to determine the relative merits of arrangements 2 and 3.

LIMITATIONS OF HYDROFOILS AS MEANS OF REDUCING POWER REQUIREMENTS

If it is assumed that the problems of installation and stability can be solved, the question to be decided is what, if any, saving in power can be effected by the use of hydrofoils. Generally speaking, a planing hull is no more efficient than a displacement hull, at low Froude numbers. On the basis of power requirements, the commercial application of hydrofoils to a boat is justified only when the planing number, i.e., resistance/displacement, of the hull without hydrofoils is higher than the planing number of the hydrofoil system supporting an equal weight.

COMPARISON OF PLANING NUMBERS OF DIFFERENT TYPES OF HULLS

Figure 24 shows curves of planing numbers plotted against Froude numbers, obtained from model test data for different types of hulls - including destroyers, round-bottom motorboats, V-bottom motorboats, and PT boats. It will be noted that the curve for PT boats breaks away from the curves for displacement hulls at a Froude number of about 0.8, assuming a mean of the curves for the destroyers and the round-bottom motorboats.

For V-bottom motorboats in general the corresponding Froude number is nearer 1.0. If, to be on the safe side, this Froude number is assumed, the curve for F = 1.0 in Figure 25, which shows boat speed in knots as a function of boat length for Froude numbers of 0.8 and 1.0, may be used to illustrate under what conditions the application of hydrofoils to boats is advantageous. From Figure 24 the planing number for a V-bottom boat at

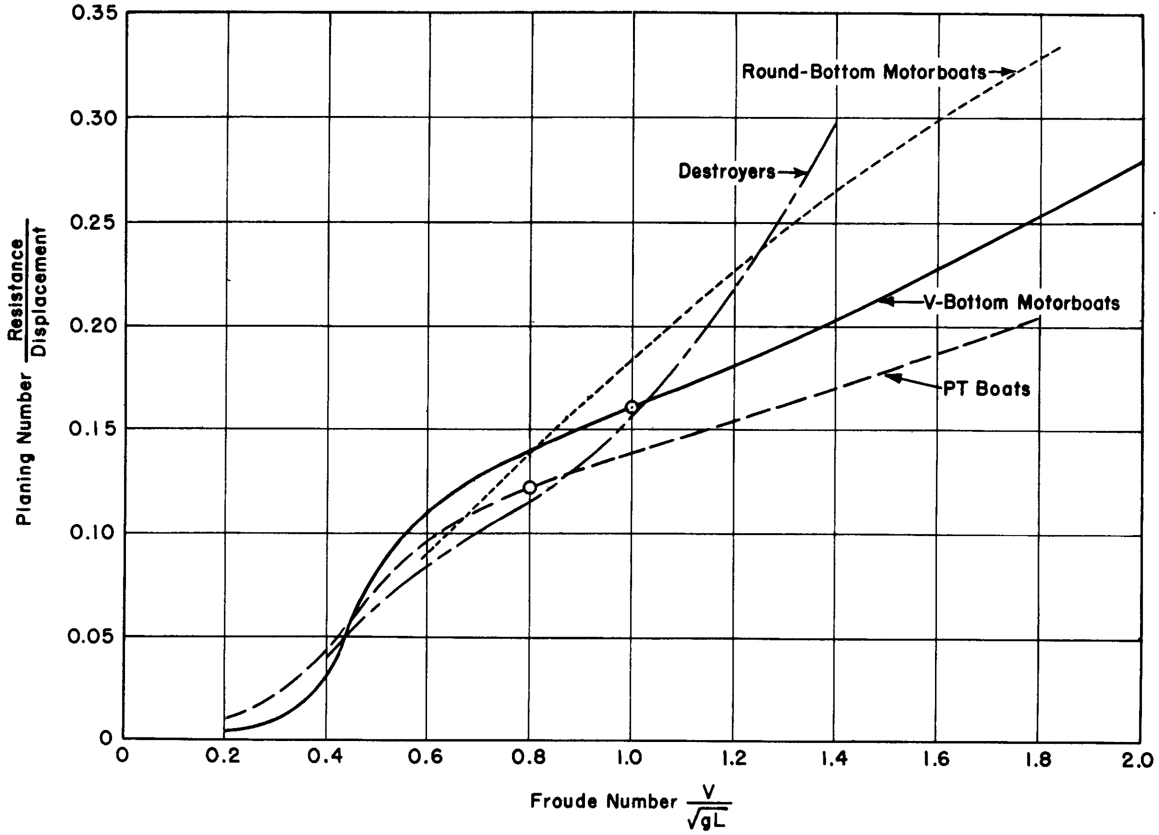


Figure 24 - Curves of Planing Numbers for Different Types of Boats Plotted against Froude Number

Froude number 1.0 is 0.16. If it is assumed that a hydrofoil system can be designed to give a lower planing number than this, then, referring to Figure 25, for a 30-foot boat, hydrofoils should effect a saving in power at speeds above 18 knots. Similarly, for a 60-foot boat the limiting speed would be 26 knots. Conversely, for a boat having a speed of 26 knots, hydrofoils would be of no benefit unless the length of the boat was less than 60 feet.

Very little information has been published concerning the relative efficiency of hydrofoil boats. In some recent tests at the Stevens Experimental Towing Tank (12) with models equipped with hydrofoils, a planing number of 0.13 was obtained in smooth water at a model speed of about 20 feet per second.

DECLINE OF PLANING NUMBER IN ROUGH WATER

The trim of a small boat which operates in rough water varies considerably. The trim of a hydrofoil boat in similar circumstances would also vary, but perhaps not as much.

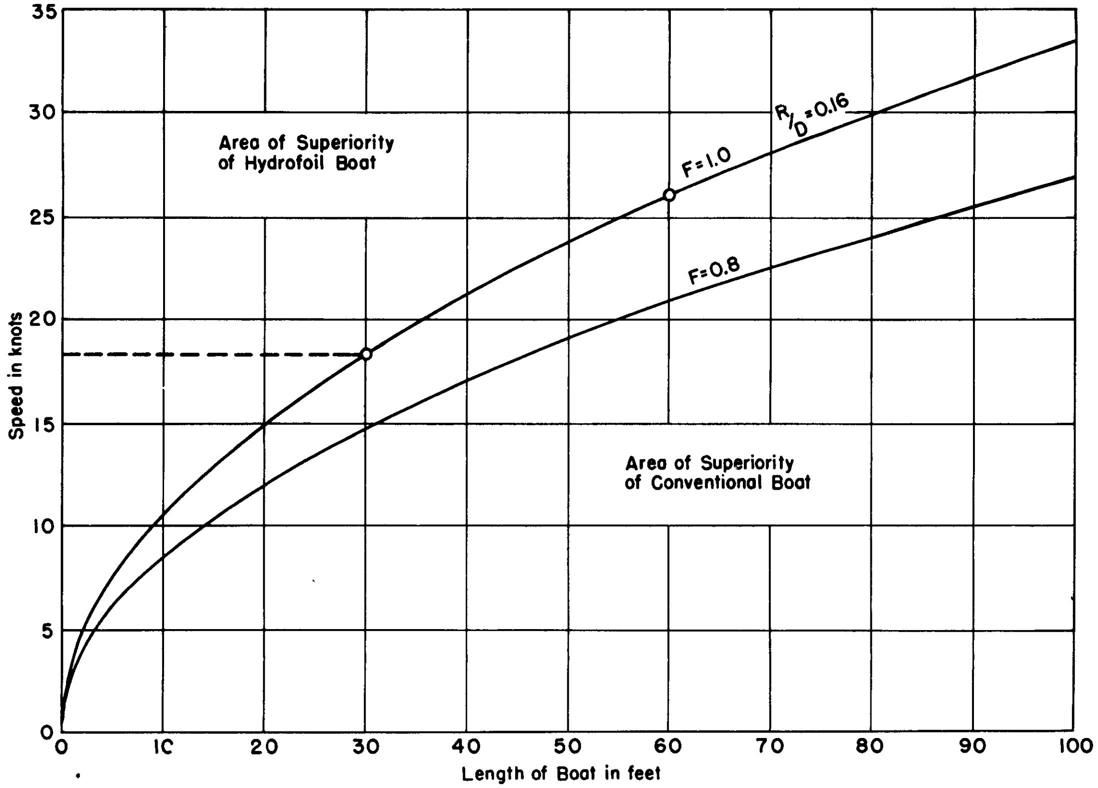


Figure 25 - Curves of Speed as a Function of Boat Length for Froude Numbers of 0.8 and 1.0

Figure 10a indicates that at high speeds a variation of 4 or 5 degrees in angle of attack may result in complete suction-surface cavitation. It seems logical, therefore, that a hydrofoil operating in rough water and cutting through one wave into another will have wide variations in resistance. According to Reference (8), resistances of hydrofoils in waves are several times those of hydrofoils in smooth water.

ADVANTAGES OF HYDROFOILS

The principal arguments advanced by those advocating the use of hydrofoils on high-speed surface craft are:

1. Their use makes possible the adoption of simplified hull forms, with a saving in fixed hull weight.

2. For the same power, higher speed may be attained than is possible with conventional hulls, or for the same speed, less power and fuel will be required, and consequently a further saving in weight may be effected.

3. The objectionable shocks felt by personnel on speed boats on conventional design as they operate in waves are not felt on boats that are equipped with hydrofoils (2) (9).

The fact remains, however, that at low speeds hydrofoil boats operate as displacement craft and must therefore be soundly constructed and seaworthy.

The great advances which have been made in the development of controlled missiles and methods of high-speed propulsion open new possibilities for the use of hydrofoils on military devices, e.g., surface torpedoes, gunnery targets, and demolition craft.

DISADVANTAGES OF HYDROFOILS

Many arguments can be advanced against the use of hydrofoils. A few will be discussed here under the headings: "Difficulties of Manufacture and Installation," and "Difficulties of Operation."

DIFFICULTIES OF MANUFACTURE AND INSTALLATION

One of the greatest problems encountered in the development of the hydrofoil boat has been that of design - to secure sufficient hydrofoil strength with the thin sections necessary for efficient operation and to maintain proper symmetry with a minimum number of supporting struts.

A difficulty encountered in the manufacture of hydrofoils stems from the fact that the efficiency of a hydrofoil is very sensitive to variations in the shape of the leading edge. Consequently the hydrofoil must be very accurately made. The surfaces must be free from irregularities and must be supported in such manner that premature cavitation is avoided.

DIFFICULTIES OF OPERATION

The major problem in operation is one of adequate stability at high speeds and in rough water.

In References (4) and (5) the most severe instability mentioned was one involving yaw, roll, trim, and rise simultaneously; a condition which stems largely from instability in rise, or lift, as the hydrofoil approaches the surface. This instability is most likely to occur in rough water where the hydrofoil is subject to varying immersion and to varying angle of the onflowing water. The loss of lift, together with the small angle of attack necessary at high speeds to ease the shock of transition, introduces the hazard of a possible total loss of lift if the craft should nose down in a seaway.

For PT-type boats equipped with hydrofoils, instability at high speeds might well result from an unbalanced loading on the hydrofoils caused by the change in the center of gravity when a torpedo is released.

The inefficiency of underwater propulsion at high speeds and the cumulative effects of cavitation on the operation of hydrofoils, struts, and propellers contribute to the problems of the hydrofoil boat. Sottorf found that, in model hydrofoil boats, the increase in resistance at high speeds due to shafts, struts, and other appendages was of the order of 100 per cent. To overcome such a handicap, profile sections must be used which for small angles of attack have drag-lift ratios that approach the drag/lift ratios of aerodynamic profiles.

The sharp leading edge of hydrofoils, which was found necessary for efficient operation, is subject to damage in handling and from floating debris; such damage results in increase in cavitation and loss of lift.

The effectiveness of PT boats results largely from their ability to strike at short range from protected harbors, many of which are in shallow water. The usefulness of hydrofoil boats in shallow water is restricted by the overall depth of the hydrofoil system below the hull. That depth is determined in part by the angle of dihedral incorporated in the system and in part by the clearance under the hull required to avoid contact with waves in rough water.

A hydrofoil boat operating in a sea, where the hydrofoils emerge periodically as they cut through the waves, may not have good maneuvering qualities. References (2) and (9) report that the boats used in the experiments there reported handled well. However, the sea conditions during those experiments were not as severe as those which military craft are required to endure. Additional information from full-scale operation, or from self-propulsion tests of large models, is needed before the seagoing qualities of the hydrofoil boat can be definitely established.

CONCLUSIONS

The results of this survey lead to the following conclusions:

1. Successful application of hydrofoils to speedboats has been limited to small boats of comparatively low speed, which operate under favorable conditions. Despite the successes reported in References (2) and (9), much additional research, in model and full-scale testing, is needed for evaluating the potentialities of hydrofoils for high-speed planing craft.

2. The multiplane system of hydrofoils appears to be more stable than the monoplane system, but it is less efficient in operation and is more difficult and more costly to manufacture.

3. Dihedral is essential for stable operation of hydrofoils. For general performance an angle of 26 to 30 degrees is considered best.

4. High aspect ratios are desirable for best efficiency, but practical considerations limit the ratio to about 4.2.

5. Hydrofoils should be proportioned to operate at a depth of not less than one half chord, and they should have a favorable dihedral angle and a minimum overall draft.

6. Low angles of attack are necessary to minimize suction-surface cavitation and loss of lift at high speeds.

7. Very thin profile sections with straight pressure surfaces and sharp leading edges are best for operating close to the surface of the water; profiles which have curved pressure surfaces are unsatisfactory. Where it is possible to operate at depths greater than one half chord, aerodynamic sections may be found desirable. Additional research is needed to develop hydrofoil sections which are suitable for use at cavitation speeds.

8. Hydrofoils should be as widely spaced longitudinally as feasible - for two equal hydrofoils in tandem, the center of gravity should be about 35 per cent of the hydrofoil spacing abaft the leading edge of the forward hydrofoil.

9. Tests are required to determine the best plan-form arrangement of hydrofoils - one which will result in a minimum of interaction between the forward and after hydrofoils and also contribute a maximum toward the longitudinal and lateral stability of the hydrofoil system.

10. Where the power required to propel a boat is of primary importance, hydrofoils are justified only when they effect a reduction in the power required.

11. Information from full-scale tests, or from self-propulsion tests of large models, is needed to determine the maneuverability of hydrofoil craft in rough water.

12. Because underwater propulsion at high speeds is inefficient, owing to cavitation and appendage resistance, other means of propulsion should be investigated.

13. Past experimental work on hydrofoils indicates that any research program must include full-scale tests. The Taylor Model Basin has no published data on systematic full-scale tests with hydrofoil boats. Such full-scale investigations under conditions in which cavitation and rough water are encountered are required before a practical application of hydrofoils may be devised for surface craft operating at high speed, with assurance that

adequate stability and efficient operation will be realized. This conclusion is supported by the opinion recorded in Reference (10).

14. If model test results are to be correlated with full-scale results, the full-scale method of propulsion, i.e., underwater or air-screw, should be simulated in the model tests.

15. Any research on models and full-scale boats equipped with hydrofoils must be thorough and systematically planned and conducted. Sottorf in an unpublished article attributes many of the setbacks of the Germans in hydrofoil-boat development to their failure to concentrate on any one type of boat and develope it systematically.

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