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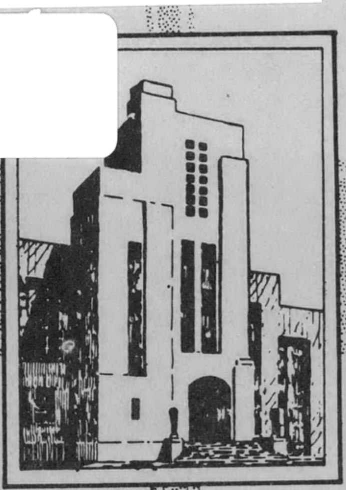

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THE PRELIMINARY DESIGN OF HYDROFOIL BOATS

(Der Vorentwurf von Tragflügelbooten)

by

Dipl.-Ing. K. Büller, Lucerne

[redacted]

Translated by E.N. Labouvie, Ph.D.

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THE PRELIMINARY DESIGN OF HYDROFOIL BOATS

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Schiffstechnik, Vol. 4 (1956/57)

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ABSTRACT

This paper presents an analysis of hydrofoil boats which the author regards as a suitable basis for preliminary designing.

It is assumed that the reader is familiar with the general theory and the principles of naval architecture and of the aerodynamics of aircraft. The theory of the hydrofoil boat resulting from these two fields is primarily based on aerodynamics although it involves a number of special difficulties and problems which result from the movement of the body at the boundary of two media.

Although the author is mainly concerned with the design studies to be undertaken for hydrofoil boats with two foils which pierce the water surface with their tips and which correspond to the System A of a previous article,* for the most part, the analysis may be logically applied to other hydrofoil systems as well.

I. STATEMENT OF THE PROBLEM

Primary considerations in the design of a hydrofoil boat must include the useful load or "payload" to be carried, the radius of action, and the maximum wave heights and draft limitations of the area in which the boat will be operating. In most cases, these data enable the designer to draw conclusions regarding the appropriate size of the boat. Thus, according to the present state of engine development and assuming the use of light metal for the hull, we are able to estimate, for instance, on a payload of 25 to 35 percent of the total displacement and from this relation, we are able to estimate the required boat size.

Figure 1 shows the relation between boat size and expected wave heights for hydrofoil boats of System A. It is generally assumed that the wave heights at which a hydrofoil boat can still travel at approximately full speed are equal to two or three times the clearance height of the hull above the water (Figure 2). Inasmuch as an excessive clearance height generally requires the installation of disproportionately long supporting struts, whereby the starting resistance is increased, the indicated relation between clearance of the water and permissible wave height may be regarded as largely applicable to other systems as well.

When determining the dimensions of hydrofoil boats, it should also be kept in mind that they must satisfy the nautical requirements of normal displacement craft under unfavorable weather conditions and in the event of damage at sea. Therefore their dimensions must not be substantially smaller than those of normal displacement craft. Draft limitations may call for the use of small hydrofoil boats or for the arrangement of retractable foils.

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*Buller, K., "Uber die Beurteilung und Verwendung von Tragflugelbooten" (The Classification and Application of Hydrofoil Boats), Schiffstechnik, No. 16, p. 218 (1956).

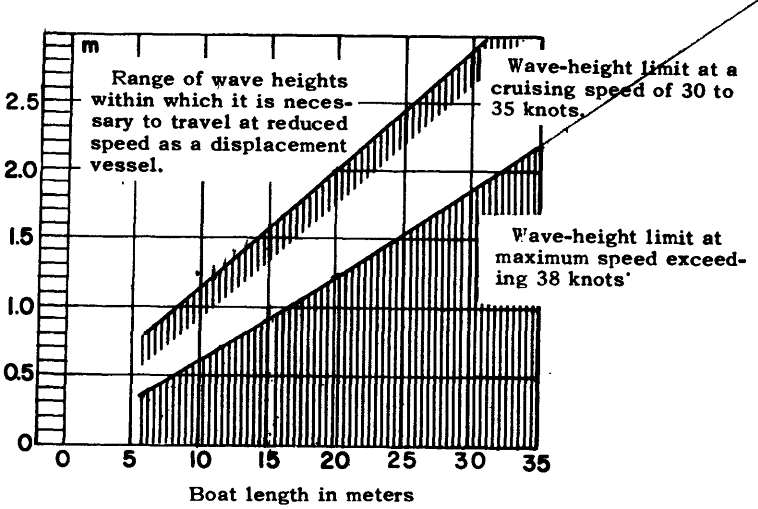

Figure 1 - Approximate Wave Heights for Hydrofoil Boat of System A to Permit the Latter to Travel at Maximum Speed and at Cruising Speed

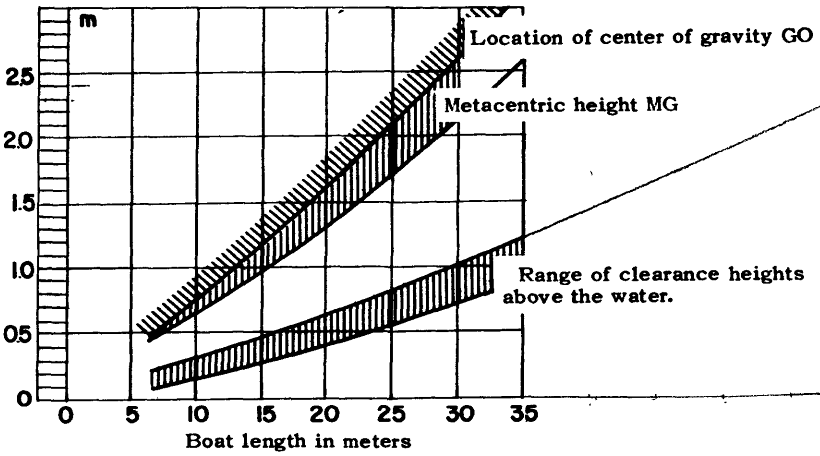

Figure 2 - Metacenters, Locations of Center of Gravity, and Heights of Clearance above the Water of Existing Hydrofoil Boats of System A (See also Figure 6)

Further considerations involved in the design of hydrofoil boats relate to the speed, the power requirements, and the engines which are to be installed.

If a certain amount of experience is available, the power necessary to satisfy the requirements of a preliminary design may be calculated according to the formula cited in the previous article (see footnote, page 1), without the benefit of a more accurate resistance calculation.

$$\text{Engine output } N_w = \frac{D \cdot v \cdot \epsilon}{75 \cdot \eta}$$

In this equation v = speed in m/sec,
D = displacement in m^3,
η = propulsive efficiency, and
$\epsilon = \text{drag-lift ratio} = \frac{\text{resistance}}{\text{lift}} = \frac{C_w}{C_a}$.

The hydrodynamic efficiency factor ϵ/η may likewise be obtained from the article previously cited. In general, we cannot proceed cautiously enough in estimating these values. If a great deal of experience with hydrofoil boats or fairly accurate data are not yet available, it is advisable to assume, for the time being, a drag-lift ratio of not less than 0.12. Only in the case of very favorable hydrofoil arrangements and in the cavitation-free speed range, which may be assumed to fall below 45 knots, may the preliminary design be based on smaller drag-lift ratios.

The propulsive efficiency may generally be assumed to be 0.6, and the losses in the transmission gear and in the shaftline may be estimated to amount to 8 to 10 percent.

After arriving at a rough determination of power, the weight and center-of-gravity calculations as well as the graphical designs for the overall plan and the lines plan will be carried out in the usual manner. In doing so, it must be kept in mind that not only the center of buoyancy and the center of mass must coincide lengthwise, but that the resultant of the lift of the hydrofoils must do likewise. The weight of the hydrofoils is hard to estimate and can be accurately determined only when the dimensions of the foils have been established. In general, this weight amounts to approximately 12 to 18 percent of the displacement. In the case of larger vessels of more than 20 tons displacement, the hydrofoils may generally be built hollow and lie then at the lower of the above-mentioned weight limits. In the case of larger vessels, high-grade steel and, wherever possible, stainless steel, is used as material for the hydrofoils. Some technical data of hydrofoil boats of Type A are indicated in Table 1.

TABLE 1
Technical Data for Several Hydrofoil Boats of the Schertel-Sachsenberg System
(Supramar Company, Inc.)

No.	Type Designation	Displacement t	Length Overall m	Speed kn	Payload t	Power EHP	Hydrodynamic Efficiency Factor ϵ/η	Froude Number F^x	Number of Propellers	Material of the Hull
1	K.B.	2.8	9.9	38	0.7	150	0.22	5.4	1	Wood
2	TS.1-5	6.4	11.96	39	1.67	380	0.24	4.8	1	Steel
4	VS.6	17.0	16.0	47	3.5	1400	0.27	4.9	2	Steel
6	VS.8	80.0	31.9	40	11.0	4000	0.18	3.2	2	Light metal
12	TK	57	25.4	47	17.0	5000	0.28	4.0	2	Light metal
18	Po.T. 3/53	4.1	10.6	31	1.1	150	0.17	4.1	1	Light metal
21	PT. 10/52	9.5	14.2	46	2.6	540	0.18	5.3	1	Wood
25	PT. 20/52	24.5	20.1	43	4.8	1300	0.18	4.3	2	Light metal
26	PT. 20/54	28	20	43	6.8	1350	0.17	4.2	1	Light metal
27	PT. 50/56	50	20.7	43	13.0	2700	0.19	3.8	2	Light metal

II. THE HULL

The hull of a hydrofoil boat in a floating condition must satisfy the usual requirements of naval architecture regarding strength and seaworthiness. In addition, it must also withstand the loads resulting from the fact that it runs on foils. In the case of vessels with tandem foil arrangement, the hull may be regarded as a beam which rests on two supports and which is loaded by the weight of the vessel and by the accelerations which occur. When the boat is running on foils in a seaway, heavy impact loads must be expected just as in the case of seaplanes or planing boats. Moreover, the hull is subjected to torsional moments when waves strike the boat obliquely, and also when the boat goes into a turn. In the static calculation it must be assumed that the maximum stresses occur when the boat rides on the foils.

As far as hydrofoil boats of the tandem system are concerned, the deck portion lying between the foils is subjected to compression while the bottom is in tension. The local stresses resulting from the impacts in a seaway are of primary importance in determining bottom dimensions. The dimensions of the deck plating must allow for buckling resulting from compression while that of the sides and of the other frames, which are subjected to shear stresses, must allow for buckling due to compression and shear. When calculating the impacts which occur in a seaway, it is desirable to refer to the corresponding literature on seaplanes (Wagner, "Ueber den Landestoss von Seeflugzeugen" (On the Landing Impact of Seaplanes), ZFM, No. 1, for instance).

In addition to satisfying the above requirements, the hull must exhibit resistance qualities which are as favorable as possible at all speeds and moreover it must assist in the take-off process too. On the basis of our experience, a form has been adopted which is similar to the normal stepped and seagoing V-section boats, but with a modified step location and keel dihedral angle. For small boats designed for inland waterways, the dihedral angle may be very small whereas for larger seagoing vessels it amounts to 20 to 30 degrees in the region of the midship section or at the step, respectively.

A step may be provided for the purpose of assisting the take-off process and is also useful in a seaway. The location and the angle of attack of the step are chosen in such a manner that a restoring moment is produced when the boat emerges from the water or drives into the waves, respectively. Moreover, as in the case of planing boats, the step also prevents extreme frictional resistance of the body in the water by producing separation of the flow and thereby reducing the frictional area. In view of the small starting speeds, the step loading shall be assumed to be small.

$$\text{Step loading } C_a = \frac{D}{\gamma \cdot b_{st}^3} \approx 0.5$$

In this equation D = displacement in kilograms and b_s = width of the step in meters.

Attempts at choosing hull dimensions and shapes similar to those of airplane floats or seaplanes have produced no satisfactory results. This is due to the fact that the take-off of airplanes occurs at considerably higher speeds than the take-off of a hydrofoil boat. Nevertheless, it is desirable to study the pertinent literature since it contains basic information regarding the interaction between hull and lifting surface (see Sottorf, "Gestaltung von Schwimmwerken" (The Design of Float Gear), Luftforschung, 1937, No. 4/5).

As in the construction of high-speed boats in general, it has also been found in the case of hydrofoil boats that maintaining certain coefficients of the immersed portion of the hull is important for obtaining low resistances when the boat is emerging from the water or is immersed in a seaway. Accordingly, the coefficient of the midship section should not exceed 0.55 - 0.65 while the block coefficient should not exceed 0.25 - 0.38. The ratio of length to beam may be chosen to be 4.5 - 5.5.

In this connection, it should be kept in mind that we should strive for great width of the forward portion of the bottom in order to obtain higher dynamic lifting forces. A small length-beam ratio also results in smaller bending moments of the hull and therefore in lighter construction weights. Moreover, the attachment of the hydrofoils and their protection may be more easily accomplished under these conditions. On the other hand, if certain portions of the hull are wide, heavy local stresses must be anticipated in a seaway. In general, the fineness ratio $L : \sqrt[3]{D}$ lies in the neighborhood of 6 or better yet 7. In the region of the step, the chine should be set at 5 to 6 degrees with the horizontal and the keel at 2 to 4 degrees.

A comparison of the specific weights and of the strength characteristics of various materials is significant only in the case of pure tensile stresses. In the case of more complicated stresses, such as are produced around the hull of a ship, these characteristics cannot be so readily compared mathematically since the section moduli, the moments of inertia, and the moduli of elasticity play a part and since any changes in material affect the geometrical dimensions of the structure. In a structural comparison which was worked out for a 57-ton hydrofoil boat, a payload of 30 percent of the displacement was obtained when light metal was used for the hull. For a hull made of steel 42 (strength of 42 kg/mm^2), the payload would have been 2.6 percent; for a hull made of steel 52, it would have been approximately 12 percent; and for steel of a strength of 70 kg/mm^2, it would have amounted to about 18 percent.

III. THE HYDROFOILS

The design of the hydrofoils presupposes that one has arrived at a clear decision regarding the system of boat and foils as a whole, i.e., that one has decided in favor of one of the four groups of systems as described in No. 16 of this journal. However, even within these groups, it is possible to arrive at boat designs which deviate greatly from one another if the shapes of the hydrofoils and their dimensions are varied.

Of fundamental importance is the longitudinal location of the foils with respect to the hull and, most particularly, with respect to the center of gravity. This location results partially from structural factors although it is primarily determined by the load component which one desires to prescribe for the foils on the basis of stability considerations.

In the case of boats of Group A, the bow foil is assigned 50 to 75 percent of the weight of the boat. If this component is increased, we arrive at the so-called single-foil vessel in which the stern foil has to assume the functions of an elevator rather than those of a lifting surface and is of decisive importance for the longitudinal stability. We may also reverse this procedure and assign the main portion of the load to the stern foil, i.e., we arrange the latter closely behind the center of gravity. We thus obtain a boat which in an analogous arrangement in aeronautics is known as the "canard type." Theoretically speaking, such an arrangement of the foils should produce a very high longitudinal stability. Thus far, however, the construction of such boats has not been undertaken since considerations regarding seaworthiness, maneuverability, and structural design do not favor this foil arrangement.

In order to determine the size of the hydrofoil which corresponds to the load component, i.e., in order to determine its area and thus its dimensions, it is first necessary to determine the appropriate hydrofoil section and the lift coefficient of the latter.

$$\text{Area } F = \frac{A}{C_a \cdot q}$$

In this equation A = lift component of the foil,
C_a = lift coefficient of the foil, and
q = dynamic pressure.

If a certain amount of experience in designing hydrofoil boats is available, we may, in the preliminary design, operate with mean lift coefficients on the basis of the usual profiles (Karman-Trefftz profiles, for instance), i.e., ogival sections. Without this kind of experience, however, it is advisable even in the preliminary-design stage, to investigate more carefully the hydrodynamic performance associated with the required dimensions.

IIIa. HYDROFOIL PROFILES

The profiles are chosen on the basis of hydrodynamic and strength considerations which can hardly be separated from one another. We may choose from among a great variety of profiles of various model basins (Göttingen, DVL, NACA, RAF, etc.); in actual practice, however, only a few of these are useful for the purposes of hydrofoil boats. The profiles from which we may choose may be adapted to the given requirements by varying the mean camber line and the thicknesses. In reference to the structural dimensions of the hydrofoil, especially in reference to its aspect ratio (span-chord ratio), certain recomputations are necessary (see Section IIIb). Generally speaking, as long as the effects of the free water surface are not important, the hydrodynamics of the foil may be dealt with on the basis of aerodynamic principles. In both media, water and air, the configurations of flow and coefficients of resistance of geometrically similar bodies are equal if their Reynolds numbers

$$Re = \frac{t \cdot v}{\nu}$$

coincide. In this equation t = chord of the hydrofoil in meters,
v = speed in meters per second, and
ν = kinematic viscosity in meters squared per second.

As long as no critical conditions exist in applying these results to the prototype, differences in Reynolds numbers may, in most cases, be neglected for the purposes of a preliminary design. The surface conditions, however, must be taken into consideration in each case.

Basically, when choosing and recomputing the profiles, the following must be kept in mind:

1. Within the range of the required speeds and of small angles of attack, we must strive for the highest possible lift coefficients and the smallest possible coefficients of resistance in order that the drag-lift ratio of the profile be reduced to a minimum. In most cases, these requirements cannot be entirely fulfilled since they may lead to extremely thin foils which do not satisfy the strength requirements and necessitate the installation of a correspondingly larger number of supports. Because of the resistance of these additional supports, the drag-lift ratio of the entire hydrofoil system may, under certain conditions, become more unfavorable than if less slender profiles had been chosen.

2. Even if slender profiles are used, cavitation must be expected in the range of higher speeds. For the preliminary design, it suffices to calculate the maximum lift coefficient permissible without inception of cavitation according to the following formula:

$$\text{Permissible } C_a = \frac{\pi}{2} \cdot \sigma - 4 \cdot \delta$$

In this equation (see Figure 3)

σ = cavitation number $\approx p/q$,
p = static pressure,
q = dynamic pressure $= \rho/2 \cdot v^2$, and
δ = thickness ratio d/t.

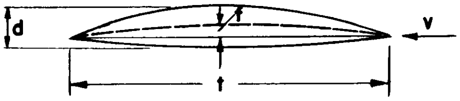

Figure 3

This relation applies when the flow strikes without impact against profiles whose mean line is an arc of a circle (i.e., $\alpha = 0$ degree) and it therefore requires a correction for $\alpha \lessgtr 0$ degree. This correction may be taken from experimental values and may be introduced in the form of a safety factor. Since any deviation from the shock-free inflow is unfavorable and above all increases the danger of cavitation, the lift must be influenced by varying the profile camber. For profiles whose mean line is an arc of a circle, the following applies for the height of the mean camber line:

$$f = \frac{C_a}{4\pi} \cdot t$$

The range of lift coefficients which insures a cavitation-free design of the hydrofoil profile lies within the narrow limits from $C_a = 0.1$ to about 0.3. In general, it will be found that cavitation-free hydrofoils with satisfactory drag-lift ratios and strength may be built up to speeds of about 60 knots.

In choosing the profile shape, we must strive for the fullest possible pressure distribution without any pronounced minimum pressure points. For a more accurate determination of the cavitation conditions, it is advisable to compare the selected profiles with similar ones as investigated by Walchner (Hydrodynamische Probleme des Schiffsantrieb, 1932).

3. The orbital motion of the water in a seaway must be taken into consideration in determining the cavitation limits and the lift coefficients to be attained as well as the corresponding angles of attack. The possible variations of the angle of attack resulting therefrom must be considered in the cavitation calculation. These are obtained from the ratio of the orbital velocity of the waves to the speed of the ship (Horn, Theorie des Schiffes, 1929).

$$\Delta \alpha^\circ = \pm 225 \cdot \frac{H}{v_s \cdot \sqrt{\lambda}}$$

In this equation v_s = ship speed in meters per second,
H = wave height in meters, and
λ = wave length in meters.

4. In the case of hydrofoils which pierce the water surface or come close to the latter, there is the danger of aeration, i.e., of ventilation. This phenomenon is created by the underpressure prevailing on the suction side of the hydrofoil and it may lead to an instability of the lift. In order to avoid this danger, the hydrofoil portions which lie close to the water surface are provided with special aeration-proof profiles (for instance, profiles with sharp leading edges and a smaller underpressure component). By installing vertical partitions, so-called air bulkheads, any possible ventilation can be limited to small areas.

From the knowledge of the profile polars and after determining the hydrofoil shapes which will be dealt with subsequently, we can go beyond the framework of the preliminary design and carry out the hydrodynamic calculation of the entire hydrofoil. The calculation will first be carried out by neglecting the variations of immersion and by assuming a constant lift and a uniform lift distribution over the width of immersion.

IIIb. HYDROFOIL CONTOURS

The hydrodynamic aspects which are determinative in the evaluation of hydrofoil contours may be compared with those of the airplane. The elliptical contour produces the least induced resistance; however, it can be used only in the case of fully immersed foils and is hard to manufacture. Aside from this contour, hydrofoils may be designed to have rectangular, trapezoidal, or triangular shape or combinations of these; the aim is to approach the elliptical lift distribution by means of geometrical or hydrodynamic warping. Warping of the hydrofoils may also be provided in order to increase stability; it must be kept in mind, however, that in the vicinity of the water surface, the danger of ventilation and of flow separation is aggravated by any increase in the angle of attack. It must also be remembered that any warping of the hydrofoils increases the expense of manufacture. From the construction standpoint, simple rectilinear contours which are as rectangular as possible and which have the same profile extending over the entire span are cheapest, of course.

For reasons of transverse stability and for hydrodynamic reasons, the greatest possible span of the foils is to be desired. The effect of the aspect ratio may be computed from Prandtl's airfoil theory; however, it applies to V-section and surface-piercing foils in, at best, only a first approximation. A formula developed by Muttray appears to be more favorable and more general although certain reservations and assumptions are involved in this formula also. It takes into account the aspect ratio (span-chord ratio) and the dihedral angle of the foils, and from this formula the lift coefficient or its gradient, respectively, may be computed:

$$C_a' = \frac{2\pi \cdot \eta}{1 + \frac{z \cdot \eta}{\lambda}}$$

$$C_a = C_a' \cdot \alpha$$

$$z = f(\vartheta) > 2$$

The profile efficiency contained herein may be introduced in the amount of 0.9 to 1.

The effect which the aspect ratio of the foil exerts on the lift coefficients may be seen in Figure 4 in an example for ogival sections as a function of the dihedral angle of the hydrofoils.

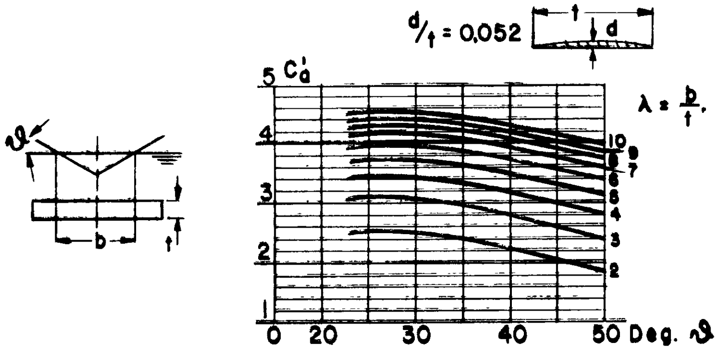

Figure 4 - Lift Gradients of Rectangular V-Shaped Hydrofoils of System A

Lift $A = C_a \cdot v^2 \cdot \frac{\rho}{2} \cdot F$ Lift Gradient $C_a' = \frac{C_a}{\alpha}$

The hydrodynamic requirement for the greatest possible aspect ratio of the foil is in conflict with the requirements for small stresses and for small structural weight. To what extent the first requirements can be reconciled with the others depends on the structural factors and the required speeds. Taking the transverse stability into account, one may, under certain circumstances, end up by using divided hydrofoils (see Figure 5, Sketch 4) with more unfavorable aspect ratios, but with fewer supports.

IIIc. HYDROFOIL ARRANGEMENTS

Figure 5 shows a few front elevations of hydrofoils, but no claim is made that this survey is in any way complete. Within the groups of systems A to D (see footnote on page 1), the views of the foils shown here may be modified still further, especially with respect to their dimensions, dihedral angle, etc. Insofar as a tandem arrangement of the foils has been chosen, it is possible to shape and combine the bow foil and stern foil in a different manner. In this connection, the transverse stability must be

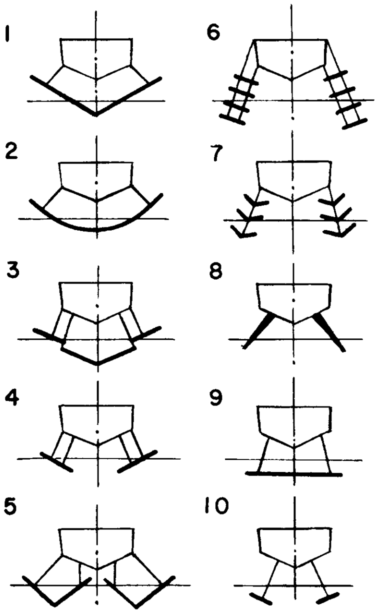

Figure 5 - Front Views of Various Hydrofoil Arrangements

taken into account if the hydrofoil system is supposed to be self-stabilizing. Moreover, it must be borne in mind that the lateral tilt or the dihedral angle of the foils, respectively, influence the seaway characteristics and the maneuverability of the vessels. Foils of a pronounced V-section result in reduced stability, smoother motions and better flow conditions at equal width of immersion than do foils having a smaller dihedral angle but they impair the maneuverability of the boat.

The arrangement of the hydrofoils in relation to the hull must be considered from the standpoint of the possible mutual interaction in the stage of emersion, i.e., at approximately 40 percent of the maximum speed, both in a seaway and in connection with the increase in resistance resulting therefrom. For this reason, the hydrofoils should not be arranged too close to the hull. Caution should also be exercised in locating the two foils behind one another since as a rule, the stern foil comes to lie in the wake of the bow foil. This wake produces a trough behind the bow foil which brings about a change of the angle of attack of the stern foil. The longitudinal shape of this trough may be determined according to an empirical formula by Sottorf (Jahrbuch der Luftfahrt 1937, Vol. 1, p. 320).

$$t + c = 1.8 \cdot F \cdot b$$

In this equation

$$F = \frac{v}{\sqrt{g\left(\frac{A}{\gamma}\right)^{1/3}}}$$

t = profile depth in meters,

C = length of the trough from the trailing edge of the profile in meters,

b = depth of immersion in meters,

A = lift of the bow foil in kilograms,

g = acceleration of gravity in meters per second squared,

γ = specific weight of the water in kilo~~meters~~grams per meters cubed, and

v = speed in meters per second.

One should attempt to arrange the two foils as far apart as possible.

Dividing the available hydrofoil area in the manner of the former biplanes or multiplanes (see Figure 5, sketches 6 and 7) brings about unfavorable resistance conditions resulting from interference phenomena. Fundamentally, it may be said that the most advantageous hydrodynamic utilization of the lifting area is obtained in the case of the "monoplane." If one should nevertheless decide in favor of a multiplane arrangement, it must be borne in mind that the distance between foils arranged one above the other should be as great as possible. In no case should it be smaller than the chord of the hydrofoil profiles.

Two hydrofoils arranged side by side (see Figure 5, sketches 4, 5, and 10) likewise result in a greater induced resistance than a corresponding continuous foil of equal size since, among other things, the aspect ratio of the latter is more favorable. For structural and static reasons, this arrangement may become necessary, and in certain cases it may even be advantageous from the standpoint of resistance if the provision of additional supports can be avoided by subdividing the foils.

In conclusion, let us point out that the free water surface has a lift-reducing effect on all hydrofoil portions which lie close to the surface or pierce it. As far as the designing of normally arranged hydrofoils is concerned, this water-surface effect (see Weinig, "Theorie der Unterwassertragflachen," DVL report and Wladimirow, "Zur Frage der Fortbewegung mit Unterwassertragflachen") may be disregarded or taken into account on the basis of a very rough calculation. It extends over a depth of immersion which approximately equals the profile chord in each case. The lift decreases and attains about half its value at the point where the foils pierce the surface. It is therefore advisable to arrange the foils in such manner that they come to lie at greater depths of immersion than one chord if possible.

IIId. LIFT-VARYING ELEMENTS

The need often arises to provide for an adjustable arrangement of the hydrofoils in order to be able to vary their angle of attack and thus the lift. This requirement may become necessary for the purpose of accelerating the process of emersion and to increase the clearance above the water surface. From the structural standpoint, it is generally difficult to solve the problem of adjusting the hydrofoils, especially for large boats, and it is for this reason that one makes use of the arrangement of flaps. Various types of flaps are known in aircraft construction which, in principle, may also be used for hydrofoil boats. Except for the so-called normal flap, they result in a small increase of resistance; however, at deflections of a few degrees, they increase the lift considerably and, moreover, they improve the maneuverability of the vessel. By means of an asymmetrical adjustment of the starboard and port flaps, the turning-circle diameters may be sharply reduced and banking during turns may be produced to the extent desired.

IV. THE TRANSVERSE AND LONGITUDINAL STABILITY

For the purpose of estimating the static transverse stability of hydrofoil boats in an emersed condition, one may make use of the definitions commonly used in ship theory, such as metacentric height, lever arm curves, etc. The static forces which come into play in the case of a ship are to be replaced by dynamic forces which one may imagine to be reduced to a static condition. If we neglect the effect of the free water surface and if we assume that the lift is distributed uniformly over the entire width of the foil, we obtain from Figure 6 the following equation:

$$\overline{MG} = \frac{1}{2}\left(\frac{m}{l} \cdot \frac{b_B}{tg\vartheta_B} + \frac{n}{l} \cdot \frac{b_H}{tg\vartheta_H}\right) - \overline{OG}$$

The location of the metacenter can be determined geometrically with sufficient accuracy by erecting a perpendicular to the hydrofoil at the point where the foil intersects the water surface. This perpendicular intersects the axis of symmetry at the metacenter.

So far we do not command a sufficient number of empirical values to be able to give a general indication of the required metacentric heights for hydrofoil boats. Just as in the case of displacement vessels, different aspects are determinative for hydrofoil boats, which lead to different requirements with respect to the required stability. The latter also depends on the size of the boats. Figure 2 shows a range within which the values of the metacentric heights of various hydrofoil boats constructed according to System A remain.

Insofar as no additional stabilizing elements in the form of floats, planing surfaces, etc., are arranged, the stability requirement for heeling which does not exceed reasonable limits, leads to hydrofoil parts of considerable size which in an emersed condition project out over the water surface. If possible, these must be arranged in such fashion that in the process of emersion when only the middlebody of the hull is still immersed, the stability is already assured by the foils.

The foil arrangement shown in Sketch 8 in Figure 5 occupies a special position. In this case also, each heel produces a righting moment which, however, is usually connected with unpleasant attendant phenomena with respect to the directional stability.

The longitudinal stability of hydrofoil boats can only be determined by means of tedious calculations and need not be carried out, in general, within the scope of a preliminary design. Each change of trim

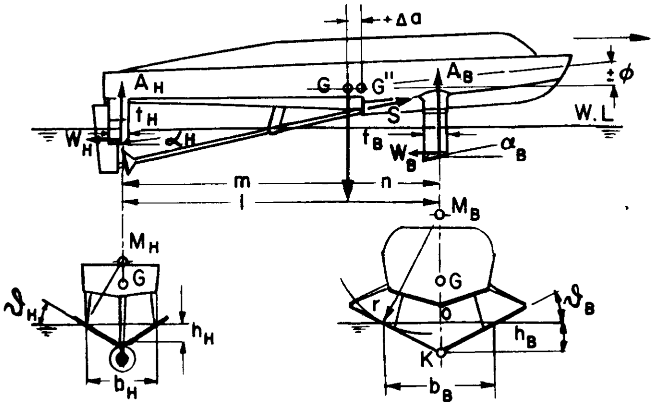

Figure 6 - Static Longitudinal and Transverse Stability without Regard for the Effect of the Water Surface and with Uniform Lift Distribution over the Width of Immersion b

results in a variation of the width of immersion, of the aspect ratio, of the foil area of the angle of attack, etc. The dynamic effects which may result from the variation of the resistance are not taken into consideration in this connection. For the purpose of providing a clear understanding, Figure 6 gives a schematic representation of the points of application of the forces which determine the vertical and longitudinal stability. In the state of equilibrium, the sum of all the forces and moments must be equal to zero. The lever arm of the static stability is $\Delta a = M/G$.

The longitudinal metacentric height is as follows:

$$\overline{M_L G} = \frac{1}{G} \cdot \frac{d\Sigma M}{d\phi}$$

On the basis of experience, this value should amount to about five or six times the foil gap. The permissible weight displacement is limited by a trim angle which still assures sufficient lift. In this connection, it should be noted that within the trim-angle variations the hull and the tips of the foils should not become immersed and that the foils on the other hand, do not emerge to a point where the transverse stability is impaired. In general, when carrying out the preliminary design it should be borne in mind that the angle of attack of the bow foil is to be as large as possible and that of the stern foil as small as possible. In this case, $\Delta C_a{}'_B$ must be smaller than $\Delta C_a{}'_H$ when changes of trim occur. This requirement produces a restoring stabilizing moment and it means that the stern foil steers the bow foil. Finally, we must also strive for a foil gap which is as large as possible.