DESIGN AND OPERATING PROBLEMS OF COMMERCIAL HYDROFOILS

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Development of modern means of transportation undoubtedly trends towards a progressive increase of speed in combination with an improved riding comfort. Speed on the water is still far behind the speeds already achieved with road or rail vehicles and aircraft.
Conventional types of watercraft cannot attain the speed of land vehicles under economically acceptable conditions. The solution of the problem by means of the hydrofoil boat is examined and the specific qualities are discussed by which the requirements are fulfilled.
The paper then deals with the fundamental physical aspects of the foil system as the most important design problem, and comparison is made between the surface-piercing foil and the fully submerged foil in relation to drag-lift ratio and behavior in a seaway. The section ends with a review of the practical adaptability of these two basic foil systems.
In the second part of the paper the commercial application of hydrofoil boats is discussed. Technical data are given about the types which are already being operated in regular passenger service. After a short review about the introduction of the hydrofoil boat in public transportation, follows an enumeration of the various existing hydrofoil passenger lines.
Finally the economic transportation problems are dealt with and data are given about the profitableness of hydrofoil passenger services. The field of application of commercially operated hydrofoil craft within the framework of modern communications and their limitations as regards speed is investigated.

INTRODUCTION

Development of modern means of transportation undoubtedly trends toward a progressive increase of speed in combination with improved riding comfort. Considering the progress achieved in passenger vehicles on road, on rail, and in the air from their first use in public service until the present, one finds that their speeds have increased about tenfold. The first railroad between Stockton and Darlington inaugurated in 1825 attained a speed of 10 miles per hour, while European express trains nowadays run at top speeds of 100 mph. The first serviceable automobiles reached about 12 mph, which in the course of time was stepped up in normal passenger cars to 120 mph. The passengers of the first commercial aircraft were carried at speeds between 60 to 75 mph. Today we cross the Atlantic at nearly 600 mph.

Conditions in waterborne transportation are very different. Already in 1860 the "Great Eastern," the largest vessel of its time, attained a speed of 14.5 knots whereas the cruising speed of the fastest passenger ship of today, the "United States," surpasses this hardly 2-1/2 times. On inland waters the increase of speed has been by no means greater. The most modern and fastest ships on European lakes surpass their 100 years older predecessors only by twice their speed. The reason for this lagging behind of waterborne craft compared with other means of transportation lies in the well-known large increase of drag with augmented speed.

It is, therefore, not surprising that inventors, engineers, and scientists of several nations have been endeavoring for many decades to find solutions which will result in comparable speeds on the water. Conviction that the shape of modern displacement bodies can hardly be further improved, and that the solution can only be found in a reduction of the immersed volume and of the wetted surface, led to the development of gliding or planing vessels (V-bottom boats), in which dynamic lifting forces take the place of the static displacement lift, and later on to the construction of hydrofoil boats in which the hull is finally lifted completely out of the water.

The planing boats did not solve the problem of attaining the travelling times of land vehicles under economically acceptable conditions and with good behavior in a seaway. The reason for this must be attributed to the relatively high drag/weight ratio at the required speed and to the extremely hard buffeting to which planing boats are exposed and which the passengers cannot be expected to endure.

SPECIFIC CHARACTERISTICS OF HYDROFOIL BOATS IN COMPARISON WITH OTHER FAST WATER CRAFT

Drag, Speed, and Economy

In Fig. 1 in which the specific power requirements of various water- and aircraft are plotted against speed, displacement boats, planing vessels, and hydrofoil boats are compared

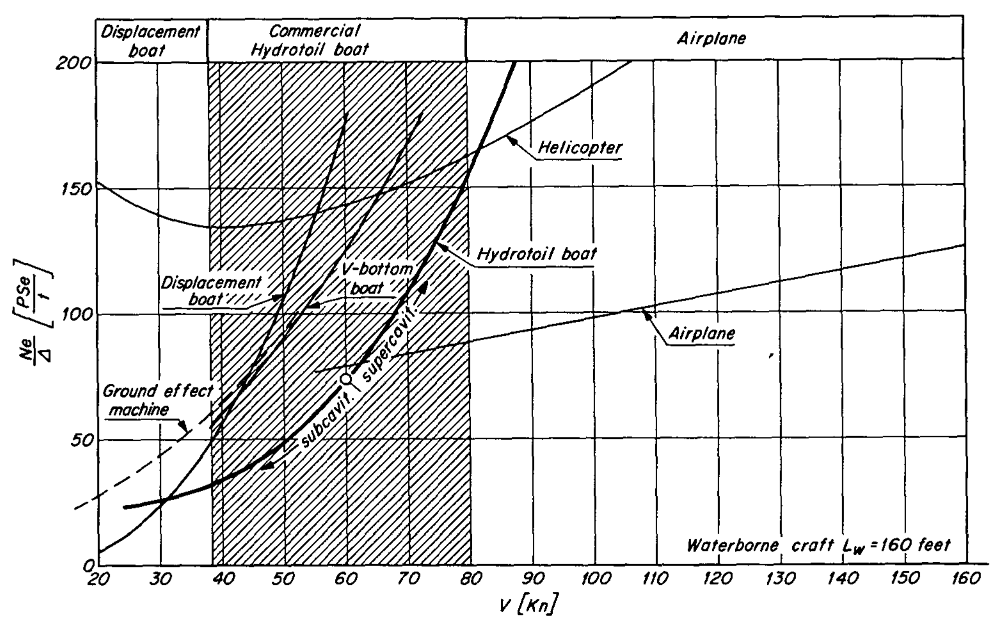

Fig. 1. Power coefficient of various craft

with each other, all of them having—with regard to the Froude number—the same length of 160 feet, representing vessels of about 300-ton displacement.* It can be seen that hydrofoil boats in the interesting speed range between 40 and 60 knots require only about 55 percent of the propelling power of planing vessels, which shows that foil-supported craft can be designed for comparatively high speeds and that they can operate at such speeds with reasonable efficiency. This is to say that at high Froude numbers, hydrofoil systems are known to function at drag/weight ratios below these of conventional motorboats. In conclusion, hydrofoil boats must be expected to be comparatively economical within certain size and speed ranges where other types of waterborne craft cannot operate effectively.

To illustrate this last statement we show in Fig. 2 the earning power of the hydrofoil boat Type PT 20 in relation to speed. PT 20 represents a type of boat which today is operating in regular passenger service in many parts of the world. This particular diagram will be referred to in detail later on. It is shown that under the given service conditions an interest of more than 50 percent on the invested capital can be achieved. The diagram, which is based on actual experiences, reveals that the hydrofoil boat has succeeded in

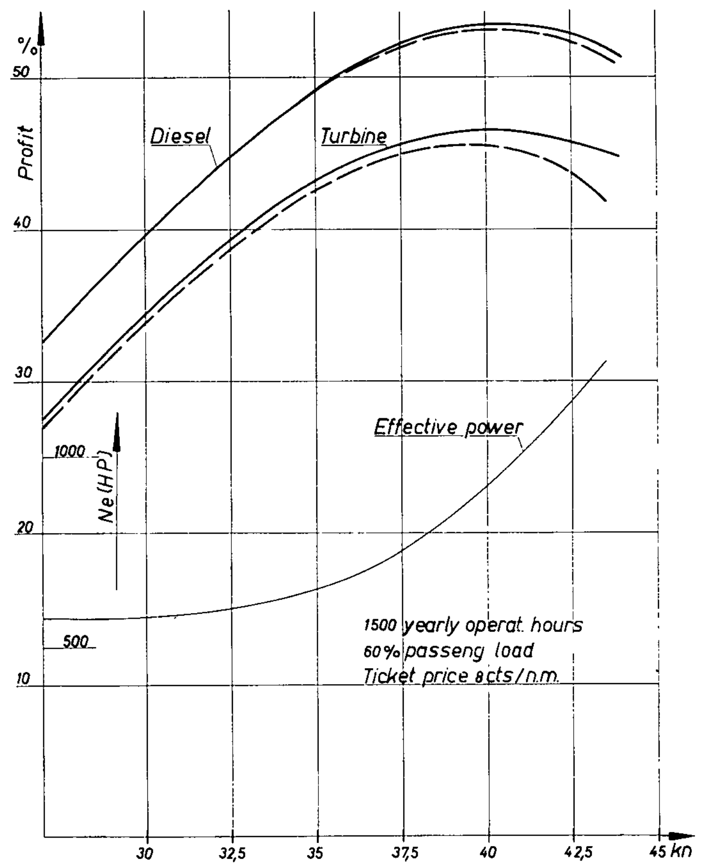

Fig. 2. Earning power of the PT 20 type hydrofoil boat in relation to speed

*Some of the notations used in the text and figures are listed at the end of the paper.

attaining economically the present-day speeds of land vehicles, since the average speed of fast trains in highly developed countries lies at 43 knots and at 32 for the whole world. But in favor of the hydrofoil boat it should be mentioned that regular passenger services and experimental trips along coastlines have demonstrated a further advantage, inasmuch as it can reach certain destinations in an appreciably shorter time than land vehicles, which—travelling with equal speed—must of necessity follow the more or less irregular coastline. Such conditions for example prevail in Scandinavia.

Even better results can be obtained with a projected 300-ton Supramar hydrofoil boat. In Fig. 3 is shown the obtainable profit for this type versus speed. Best results are achieved at a speed of 50 knots yielding an interest on the invested capital of 57 percent. When this project is realized, hydrofoil boats will show a clear superiority over land vehicles with respect to travelling time whenever they operate between the same points on the coast. This diagram also will be discussed in detail later on.

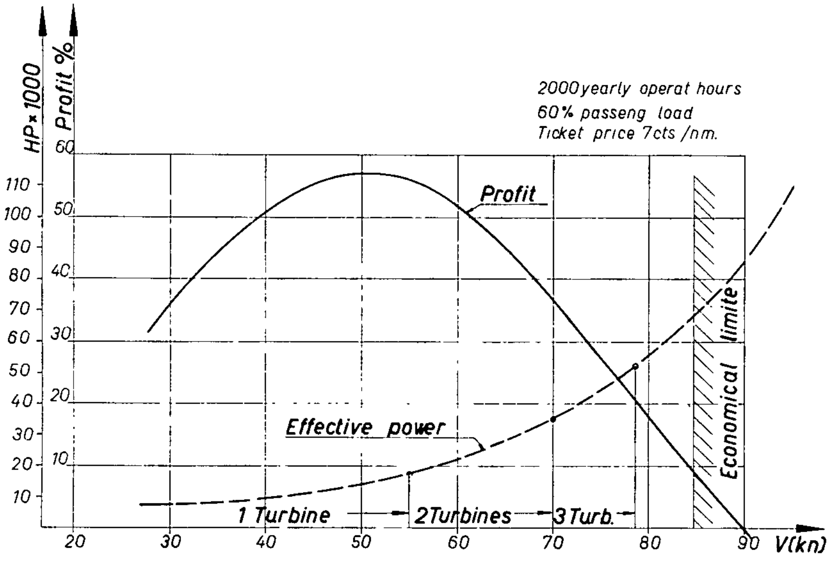

Fig. 3. Earning power of the PT 300 type hydrofoil boat (length = 160 feet)

Another quality distinguishes the hydrofoil boat from conventional craft. At higher speeds, displacement and V-bottom boats cause the formation of a wave system of considerable amplitude in their wake which can interfere with the safe operation of other craft and damage river banks. For this reason the speed of such boats is generally restricted in narrow waterways. Since hydrofoil boats develop only comparatively small wave-resistance the disturbance of the water surface is so slight that the boats can maintain high speeds on smaller lakes, rivers, and canals and in congested waters without endangering any other craft or shore installations.

Considering now the airplane as the most serious competitor, we can derive from Fig. 1 that the airplane can attain much higher speeds with lower specific propulsion power than the hydrofoil boat. Therefore aircraft represents a very economical means of transportation. However its commercial use requires an extensive and very expensive ground organization, and it is well-known that aircraft operation over short distances does not pay very well. Consequently hydrofoil craft may successfully compete with airplanes over short distances because of their lower costs of operation and maintenance and of their point-to-point rather than of airport-to-airport performance. Conditions may be such that a passenger choosing the hydrofoil boat will arrive in less time at his destination than he would when choosing the airplane. Although the airplane develops many times the speed of the hydrofoil boat the journey by air involves the trip to and from the air terminals, which are often far away from the original point of departure and destination. Over fairly short distances the helicopter might be expected to be a serious competitor of hydrofoil craft. However, as shown in Fig. 1, it requires rather high powered engines and its operation and maintenance costs are several times those of the hydrofoil boat. Thus in many cases the prevailing conditions will favor the use of hydrofoil craft instead of airborne means of transportation.

Sea-Riding Qualities and Passenger Comfort

Rapid connection between two points becomes meaningless unless the passenger can rely on the timetable: in other words transportation must be regular and not be subject to frequent interruptions on account of bad weather. Also the movements and accelerations of a vessel caused by adverse weather conditions must be considered. If they assume proportions which affect the passenger's comfort, speed must be reduced.

It has already been stated that the problem of rapid transportation on the water cannot be solved by planing boats on account of their buffeting in a seaway. At the cruising speeds which are here under consideration accelerations of 6 g and more have been measured in such vessels, accelerations which may be endured for a short time by the crew of a naval craft but which exclude the use of such boats in commercial operation.

Principally it can be stated that hydrofoil boats are able to maintain a higher speed level in a seaway than any other waterborne craft of similar size. Based on practical experiences, Fig. 4 shows the approximate size of waves in which hydrofoil boats of the Schertel-Sachsenberg system can still remain foilborne. The lower curve represents wave amplitudes at which the boats can operate at full power; the upper curve shows wave sizes at which a somewhat reduced cruising speed can be maintained while still keeping the vessel in foilborne condition. The diagram permits the estimation of the size of hull required for operation in waves of known sizes. With a new type of foil system presently being developed the limits indicated in the diagram will be considerably widened.

Riding comfort in any watercraft is of course affected by the extent of its movements in a seaway. Pitching, heaving, and rolling motions of hydrofoil boats are generally much smaller than those of similar-sized conventional boats. It can also be stated that the amplitude of these motions as well as the degree of submergence in the waves decrease with the increase of speed and of the frequency with which waves are encountered. This phenomenon in the performance of hydrofoil boats is due to a reduction of the influence of the waves on the vessel's inertia and of the orbital wave velocity on the foil's angle of incidence with the frequency of wave encounter. On the other hand, however, vertical accelerations increase with speed. In accordance with the linear theory they increase also in proportion to the slope of the waves.

Some indication of the extent of motion in a seaway may be gained from Fig. 5, which is based on the latest tests undertaken with a 90-foot boat in waves estimated to have reached a height of 5 to 6.5 feet and a length of 100 to 150 feet. The diagram depicts the average

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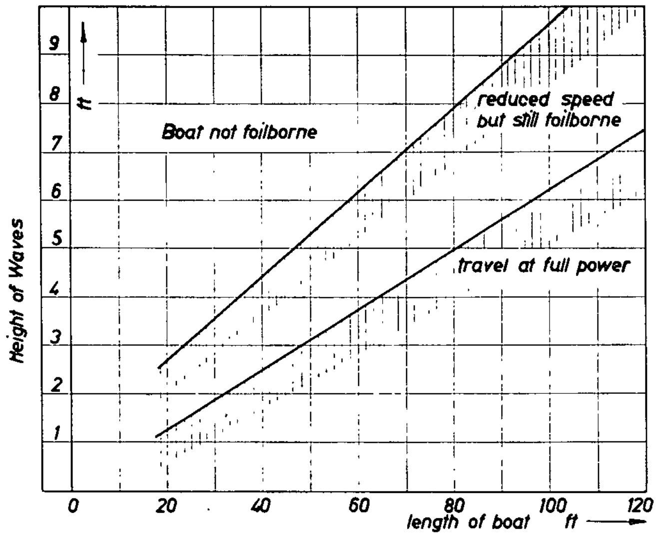

Fig. 4. Limits of seaworthiness of Supramar boats

readings of the maxima taken during a period of 4 minutes. The roll angle is, of course, at its maximum in a beam sea. Compared with displacement boats of similar size, however, that angle is still small and the angle of pitch is very small indeed.

Figures 6 and 7 show the influence of speed or Froude number respectively and of wavelength on the vertical accelerations of a surface-piercing front foil. These diagrams are taken from a hitherto unpublished theory developed by Mr. de Witt of the scientific staff of Supramar. For the accelerations shown in the figures the most unfavorable course of the boat in relation to the direction of the waves was assumed in each case. The thick curve

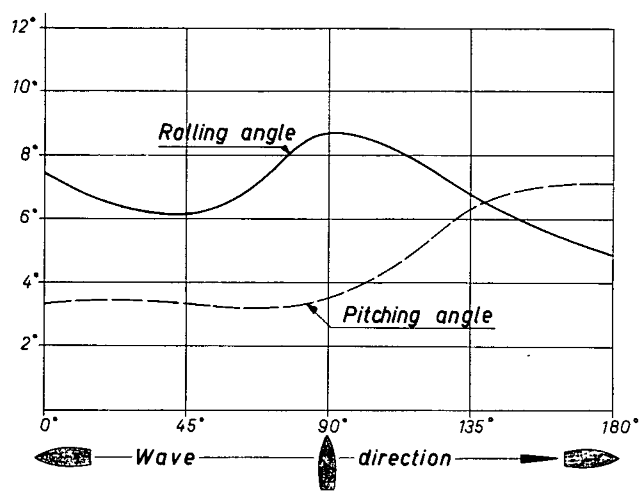

Fig. 5. Mean values of pitching and rolling in rough water for the PT 50 (wave height, 5 to 6-1/2 feet; wavelength, 100 to 150 feet)

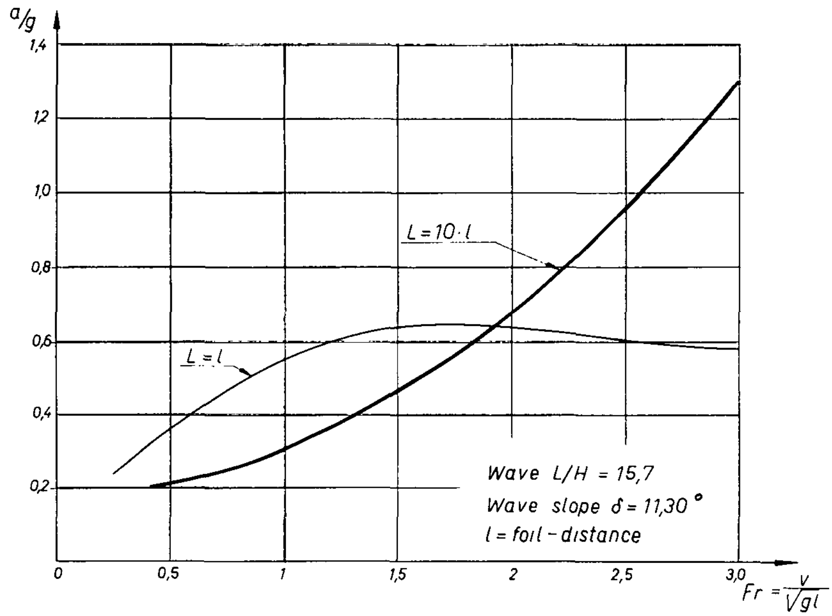

Fig. 6. Influence of the Froude number on vertical accelerations

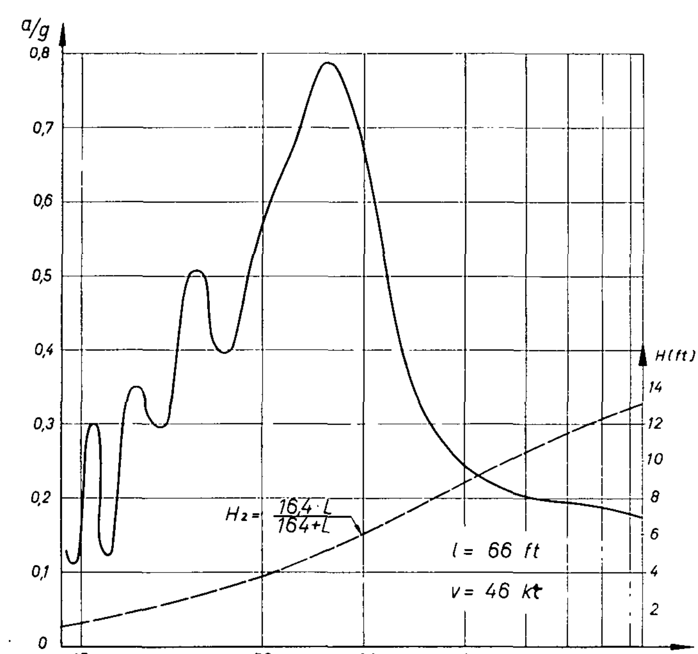

Fig. 7. Influence of the wavelength on vertical accelerations

in Fig. 6 corresponding to an extremely long wave of ten times the foil distance shows the typical increase of acceleration with increasing Froude number. Accelerations in medium waves, however, equaling the foil distance, are less dependent on the Froude number as may be seen from the thin curve. The calculations represented in Fig. 7 are based on a foil distance of 66 feet and a speed of 46 knots. The wave height for each respective wavelength is shown by the dashed curve. Figure 7 shows that under the assumed conditions the vertical accelerations increase only up to wavelengths approximately equal to the foil distance and decrease beyond that size, which is due to the decrease of the slope of the wave with its increasing length.

Figure 8 shows the influence on vertical accelerations of the direction of travel with regard to the wave direction for two different relations of wavelength to foil distance. Under

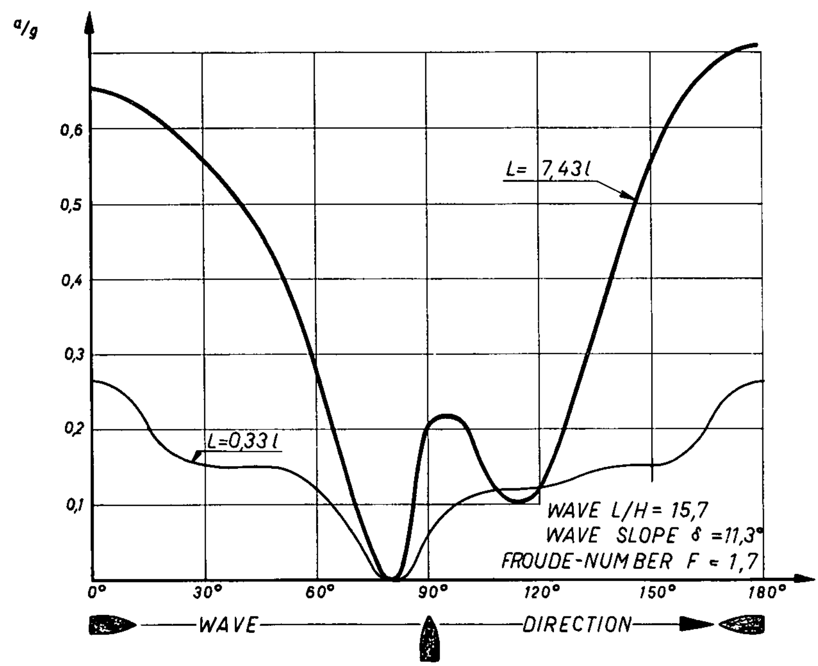

Fig. 8. Influence of the wave direction on vertical accelerations

the given conditions (L/H = 15.7, F = 1.7) the maximum values are attained against the sea and with a following sea, while at a course of about 80 degrees the boat remains at the same place in the wave, which results in the disappearance of accelerations.

TECHNICAL CHARACTERISTICS OF THE TWO BASIC FOIL SYSTEMS

Having examined the suitability of hydrofoil craft for commercial transportation in general, we shall now consider the main design problem in hydrofoil engineering, i.e., the foil system itself, as it naturally has a decisive influence on the all-round performance of the craft. Since it is not the purpose of this paper to present a survey of all the various designs already in existence we shall limit the discussion to the two basic foil systems which during recent years frequently formed the subject of discussions and led to differences of opinions between the experts:

1. Surface-piercing hydrofoil systems—The surface-piercing systems consist either of single V-shaped foils or of a combination of smaller foils arranged one on top of the other like rungs of a ladder. A deviation from the equilibrium of the craft causes a change of the wetted lift-producing area of the foil and automatically creates restoring forces. The system therefore is automatically stable.

2. Fully-submerged hydrofoil systems—Fully-submerged foils have no inherent self-stability. Depth of immergence must be maintained by means of mechanical, electrical, or other controlling devices which—measuring either the distance between the hull and the water surface or the foil submergence—give signals to contrivances which in turn affect the lift by changing the angle of incidence of the foil or of flaps at its trailing edge.

We shall now compare drag and compare behavior of the two basic foil systems, and shall consider their possible future application.

Drag/Lift Ratio

We shall assume equal speed (45 knots), equal aspect ratio of $A = b/c = 8.3$, and a suitable foil section for either type. An average submergence ratio of $h = 1.2c$ is provided for the dihedral surface-piercing foil (lowest point $h = 2c$) in accordance with the boats which are at present in operation, and a lift coefficient of only $C_L = 0.22$ with respect to aeration.

The fully-submerged foil, however, requires a submergence ratio of not less than $h = 2c$ in order to avoid an excessive approach to wave-troughs but it is permissible to apply a lift coefficient of 0.26, since this foil is not exposed to air-entrainment, and only cavitation by influence of orbital motion has to be considered.

The total drag of a hydrofoil system may be expressed as

$$D = C_D S q$$

where S is the projected foil area and q is the dynamic pressure. The drag coefficient is composed of four main components:

$$C_D = C_{D_i} + C_{D_o} + C_{D_w} + C_{D_{pa}}.$$

The first component is $C_{D_i} = C_L{}^2/\pi A$ = minimum induced drag for infinite submergence. When approaching the water surface the second component has to be considered:

$$C_{D_o} = C_{D_f} + C_{D_{pr}} = \text{section drag.}$$

The frictional component C_{D_f} is strongly dependent on roughness of foil surface. For smooth conditions and the applicable section thickness ratios of 0.05 to 0.10 skin friction drag amounts to over 90 percent of section drag, so that the pressure drag $C_{D_{pr}}$ is very small. For the determination of section drag mostly results of experiments are used.

C_{D_o} of a V-shaped foil with an dihedral angle ϑ is increased to

$$C_{D_o} = C_{D_o} / \cos \vartheta$$

due to the increased length of wetted surface. The third component

$$C_{D_w} = \text{wave drag}$$

is negligibly small for high Froude number hydrofoil boats. The fourth component

$$C_{D_{pa}} = \text{parasitic drag}$$

refers in this case to the foil struts, piercing the water surface. V-shaped foils with their tips above the water surface during travel permit the use of relatively narrow struts since the produced transverse forces can be taken up by structural elements which remain above the water surface when the boat is travelling in foilborne condition. Because the struts are only little immersed at cruising speed the parasitic drag of the foil is small. The fully-submerged foil however requires very long struts which in view of the existing bending moments must also be rather wide. Therefore a considerable parasitic drag is caused which offsets the more favorable hydrodynamic qualities of the straight fully-submerged foil.

Calculation of the four drag components for the given example and on the assumptions stated above yields a drag/lift ratio for the surface-piercing foil of 6.9 percent and for the fully-submerged foil of 6.7 percent. Towing tank results obtained from two model foils of the two systems confirm the theoretical analysis. They both produced drag/lift ratios of approximately 7 percent. In conclusion, we can thus consider the two basic foil systems as being equally favorable in regard to resistance at design cruising speed. In travelling beyond cruising speed, however, the conditions change in favor of the surface-piercing foil system. The area of the fully-submerged foil is determined by the capacity of takeoff at the attainable $C_{L\,max}$ value. The lift coefficient decreases then with the square of speed and as a rule attains an unfavorably small value at top speed. On the other hand, when speed of the surface-piercing foil exceeds cruising speed the wetted areas of the foil as well as that of the appendages (struts emerge completely) are reduced to such an extent that their frictional drag becomes less than that of the fully-submerged foil.

Experiments carried out recently with a 1-ton test boat originally fitted with surface-piercing foils which were later replaced by a new system of automatically controlled submerged foils also confirmed these inherent characteristics of the two types. Figure 9 shows that cruising speed of the boat of about 50 km/h (27 knots) is reached with any of the two foils at the same engine speed whereas the top speed attained with the surface-piercing foil is 65 km/h (35 knots) as against 59 km/h (about 32 knots) with the fully-submerged foil.

Behavior in Sea Waves

The behavior of a hydrofoil vessel in sea waves is essentially the result of two functions. The first one, called the "wing characteristic Z" indicates the stabilizing variation (dL/dh); thus

$$Z = (dL/L_o) \,/\, (dh/b_o)$$

where L_o = lift when travelling at normal waterline
b_o = normal wetted span of foil between surface-piercing points
h = depth of submergence.

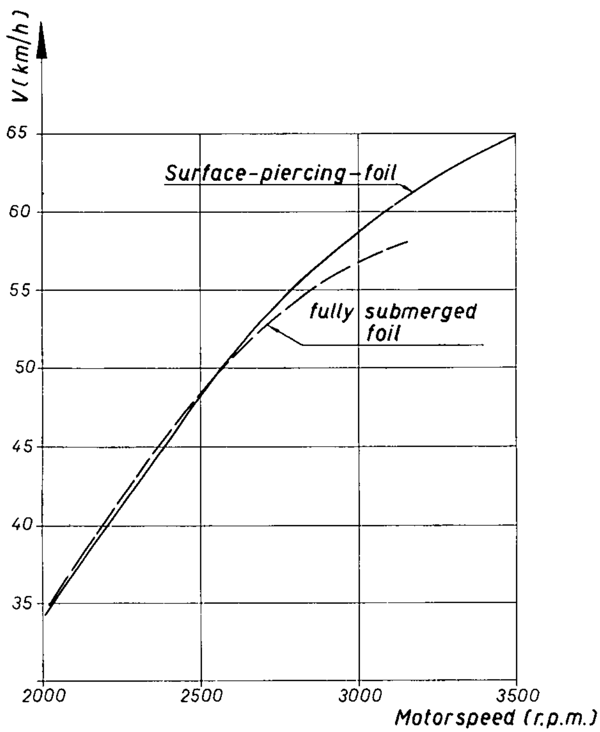

Fig. 9. Comparison of the two foil systems on a test boat

The wing characteristic obtained with a surface-piercing foil in the Saunders-Roe towing tank and measurements carried out on the 60-ton Supramar craft (dotted line) is presented in Fig. 10. The hump in the curve of the 60-ton boat is produced by the stern-heavy trim of the boat at low speed.

In designing a surface-piercing hydrofoil the value of the characteristic Z can be influenced to a certain extent by selection of the dihedral angle, by suitable variation of foil chord, foil camber, and angle of incidence in the vicinity of the piercing points. High values of Z provide for efficacious stabilization but involve hard riding in a choppy sea. Vice versa, reducing the slope of the curve shown in Fig. 10 leads to gentler behavior in a seaway but low stability. In order to achieve better riding comfort it is obvious that the wing characteristic should be adapted to wave heights and wavelengths; this, however, presents difficulties with this type of foil. Nevertheless, trials which have been recently undertaken in this respect with a smaller craft and an adjustable front foil of rather simple design gave very encouraging results.

In order to make a vessel with fully-submerged foils stable, variations of lift as a function of h must be provided by proper variation of the angle of incidence of the foil or

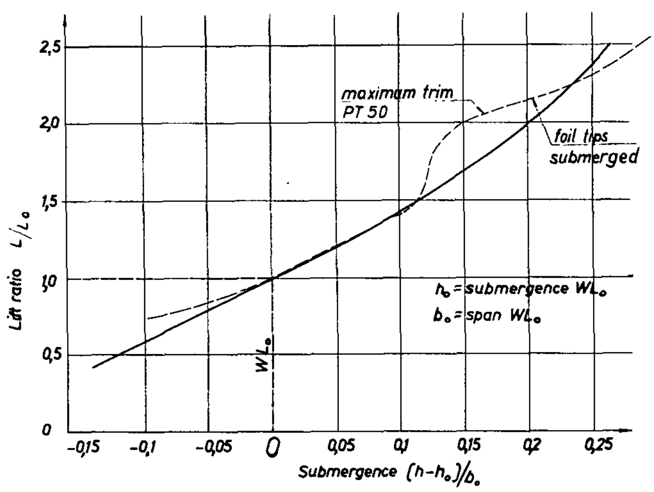

Fig. 10. Wing characteristic of a surface-piercing V-foil

its flaps. The respective control device must be designed in such a way that it reacts to a change of submergence, corresponding to the same value of Z as for surface-piercing foils. The fully-submerged hydrofoil, however, has a significant advantage over the surface-piercing type inasmuch as the value of Z can be changed at will whenever desirable and inasmuch as a damping or filtering function can be introduced in such a manner that the foil does not react to short waves and follows the contours of longer waves only insofar as to keep the hull clear from the water surface. Furthermore, lift is being gradually modified in conformity with the signal, whereas in the case of the surface-piercing foil, lift-variation occurs more or less suddenly with an impact when travelling in waves. Consequently boats with fully-submerged foils give better riding comfort. In rough sea conditions it is possible to differentiate submergence against time and to modify the foil angle reaction accordingly. The control device may also respond to accelerations; pitch and rolling angles can be reduced by means of a gyroscope stabilizer. Such control is difficult to materialize for surface-piercing foils because of their high autostability.

The second characteristic of a foil in a seaway is its reaction to orbital motion indicated by

$$W = (dC_L/d\alpha)/C_{L_o} = \frac{1}{\alpha-\alpha_0}$$

where $dC_L/d\alpha$ = lift-curve slope. A high value of W means that a foil has a tendency to react strongly to orbital velocites in waves. To make a foil less susceptible to these motions, it would be desirable to make the lift-curve slope as small as possible and the design-lift coefficient C_{L_o} as high as possible. Since the lift-curve slope is primarily a function of aspect ratio, its reduction is bound to increase the drag, and since, on the other hand, the lift coefficient C_{L_o} is limited by considerations of cavitation and ventilation, the value of this parameter W cannot be reduced effectively.

Rigid hydrofoils are, therefore, always subjected to the influence of orbital wave motions. This fact is without practical consequence when running against the sea, but the influence of orbital motion is a very undesirable reality in a following sea. In such conditions a maximum reduction of lift occurs when approaching a wave crest, and, on the other hand, when approaching a wave trough, orbital motions have the tendency to increase the foil's lift. Consequently the phase of the foil travel is shifted under the effect of inertia in relation to the wave contour (by about 120 degrees) and moves against it. Under unfavorable conditions the hull may be forced into the crest of the waves, thereby reducing the speed of the craft considerably.

The amplitude of orbital motions reduces at a progressive rate, with increasing submergence. A fully-submerged foil is therefore exposed to a smaller amplitude than the average encountered by a comparable surface-piercing foil. Since, as already explained, the maximum lift coefficient will also be usually higher, a fully-submerged foil suffers less from orbital motion. Apart from that, the control device can be adapted to compensate the orbital influence by corresponding variation of lift.

Conclusion Regarding Practical Applications

After having discussed the characteristics of the two basic hydrofoil systems we can make the following statements in conclusion of the first part of this paper:

Boats of the surface-piercing hydrofoil type have sufficiently low drag/lift ratios to justify their use for high-speed commercial passenger service. Under equal conditions and having equal cruising speed they can be expected to reach a higher top speed than vessels provided with fully-submerged foils. Natural stability, simplicity of construction, operational reliability, ease of handling and maintenance, and, last but not least, a remarkable invulnerability of the foil-system have contributed to the acceptance of hydrofoil boats as a means of commercial passenger transportation. It can be taken for granted that the described qualities will lead to a preference for this type for use on inland waters, in coastal regions, and within protected sea areas.

Fully submerged foil-systems are in the same drag/lift bracket as the surface-piercing type. They possess superior seariding qualities and offer higher riding comfort because of their smaller and smoother heave and pitch response to sea waves. However, the complexity of the height- and stability-control which is needed for this type of boat must be considered to constitute a serious drawback of this system. No doubt the electronically controlled hydrofoil boats, which have been developed in the U.S., have shown excellent riding qualities. In spite of this fact there remains for the traditional shipbuilder the unusual conception that stability, naturally inherent to any properly built ship from historical times, should now be subjected to the faultless functioning of a number of complicated gadgets. In case of a failure of such a control system, there may not remain sufficient time to cut off the automatic and to "land" the boat by hand as is possible with an airplane. Although an unexpected sudden tilting of a commercial vessel will not necessarily result in any catastrophic situation, such an incident is liable to destroy the confidence of passengers. In consequence the introduction of the fully-submerged hydrofoil system in public service still presents problems and meets opposition of orthodox shipowners.

Therefore the requirement exists to maintain the stability of the fully-submerged foil type directly by dynamic forces, similar to the surface-piercing foil, without inserting bulky and vulnerable mechanical devices or electronic appliances. Based on ideas and experiments carried out 15 years ago by the author, a new self-controlling system is in development which — not being dependent on servo power sources and amplifiers etc. — can be expected to offer sufficient reliability. In heavy seas the system can perform in the manner described in the preceding subsection and there can also be introduced an additional simplified gyroscope control. A trial boat equipped with this new system is at present undergoing tests conducted by the Supramar company, and has, so far, been successful.

Undoubtedly boats with fully-submerged foils will have a large field of application in the future in less protected sea areas and as long-distance ferry boats on open sea. But their range of operation will always be restricted by their faster competitor, the airplane, to which preference will be given in all cases where its travelling time between two points, including airport feeder service time, is considerably shorter.

PRESENT TYPES OF COMMERCIAL PASSENGER BOATS

In the second part of the paper we will deal with commercial application of hydrofoil boats. We shall first regard the type of passenger boats which are at present in operation. It is known that the first hydrofoil design which was used in scheduled commercial passenger services was the Schertel-Sachsenberg type. The reason for the advanced technical stage of this system lies in its structural simplicity and the reliability of the surface-piercing foils used in this type. Another reason for the perfection of these boats is the fact that they are the result of organized development efforts which began with the author's experiments in the thirties and which were continued through the following years without interruption. Design and construction have always been accompanied by extensive theoretical and experimental research as well as by trials with full-scaled craft. With the construction of 16 different types and a total of nearly 60 hydrofoil boats to this date, of which 26 are passenger ferries, experience has accumulated to such an extent that Supramar's engineering staff is in the position to go ahead with the design of larger and faster economical passenger craft.

The predecessors of the present commercial boats were built during World War II. Out of the six types which were designed for speeds up to 60 knots we shall mention the 80-ton type VS 8 launched in 1943. This craft deserves attention because it was the largest hydrofoil boat ever constructed and has not been surpassed even today. It was designed as a high-speed long-range cargo carrier for operation between Sicily and Africa. The 105-foot-long hull was constructed in light metal alloy. A maximum speed of 40 knots was obtained using a twin arrangement of Mercedes-Benz Diesel engines with a combined output of 3600 hp. Although the corresponding ratio of 45 hp/ton is considered to be marginal for satisfactory operation, the boat was nevertheless able to run at 37 knots against seawaves up to 6 feet in height and 150 feet in length.

To date two prototypes find application in established passenger lines, the PT 20 (a 27-ton boat for 75 passengers) and the PT 50 (a 60-ton boat for 140 passengers). The first PT 20 was built in 1955 in the Rodriquez Shipyard at Messina. This craft (Fig. 11) turned out to be the first of a series of very successful boats, 19 of which have been built or are nearing completion.

The light-metal alloy materials used in building the PT 20 hulls are Al-Mg and Al-Mg-Si. Watertight compartments are provided below the passenger decks and in other parts of the hull. Several of these compartments are filled with foam-type plastic which makes these boats practically unsinkable.

The engines installed in the PT 20 are supercharged 1350 Daimler-Benz Diesel engines of the type MB 820 Db. The reversible gear, placed between the engine and drive shaft, represents a special type developed by Zahnradfabrik Friedrichshafen. A 110-hp auxiliary engine is located in the stern of the hull for emergency operation. Driving a small separate propeller, this engine can be used to maneuver the boat in displacement condition.

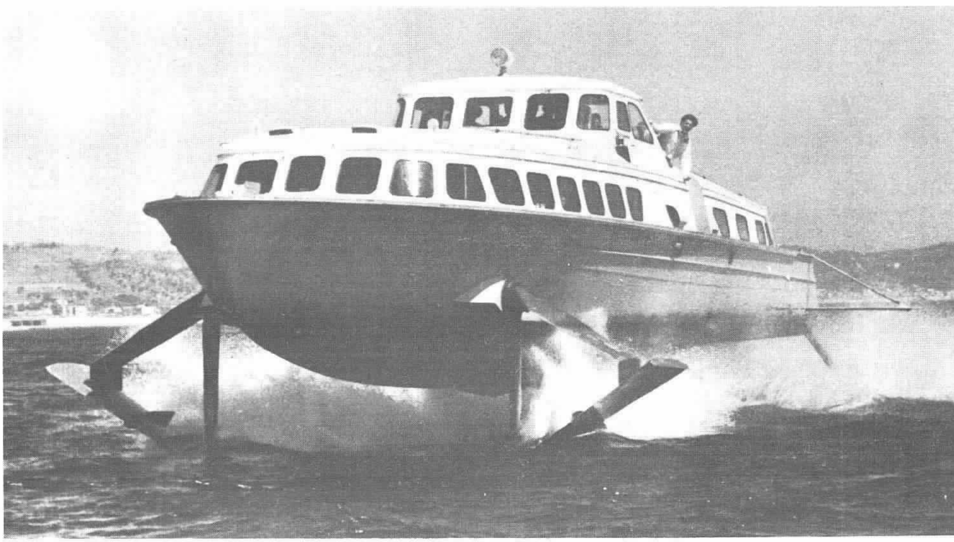

Fig. 11. The PT 20 hydrofoil boat

The general arrangement of the PT 20 type is shown in Fig. 12. The boat is operated and the machinery controlled entirely from the bridge which is located above the engine room. Forty-five passengers can be accomodated in the forward cabin, while the rear cabin is somewhat smaller and can take 30 passengers.

Together with the struts and a horizontal girder each foil forms a uniform framework which, apart from giving static advantages, facilitates the exchange of the foil structure. The foils themselves are made from medium steel as shells welded at the seams. The forward foil can be tilted with narrow limits by means of a hydraulic ram acting on the girder across the hull. It is therefore possible to adjust the angle of attack of that foil during operation, thus counteracting the effect of larger variations in passenger loads and to ensure optimum behavior in seawaves.

The PT 20 can be considered to be the smallest type of foilborne craft suitable for passenger-carrying coastal service. In view of its novel and unconventional characteristics the first boat of its class was originally licensed as "experimental" and restricted to operation in a 6-mile zone off the coast of Italy. After frequent inspections and supervision of the service, the Registro Italiano Navale extended the license in 1958 to operation within a 20-mile coastal zone and in 1960 within a 50-mile limit. Today the PT 20 as well as the PT 50 have been classed by the authorities of several countries.

Technical data which have an influence on the profitable operation of the type PT 20 are presented in Fig. 13. The shaft power of the engine was measured during operation by means of a torque meter. The propeller was model-tested, thereby taking proper account of the influence of shaft inclination. The drag/lift ratio was then derived from net power. This

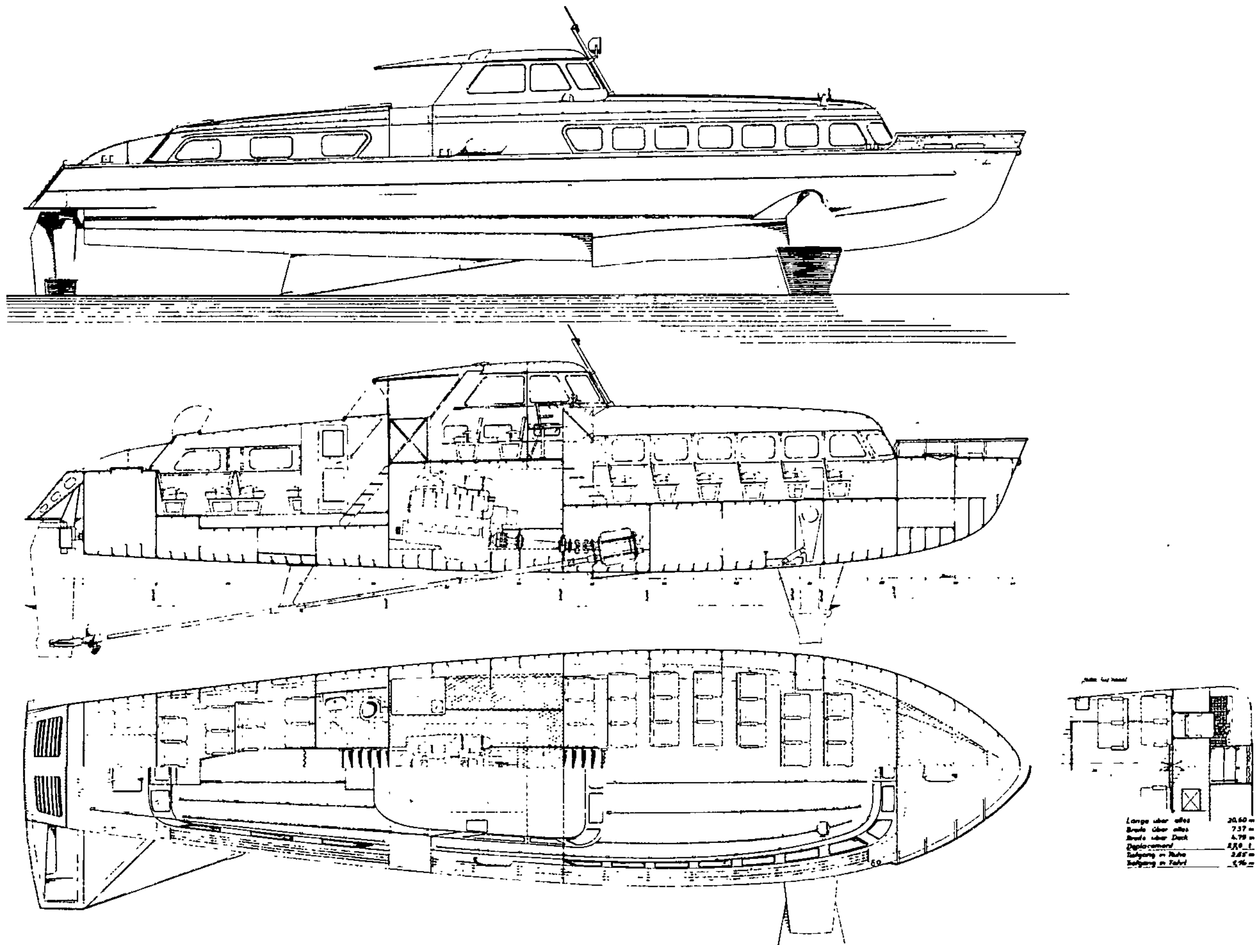

Fig. 12. The PT 20 hydrofoil boat

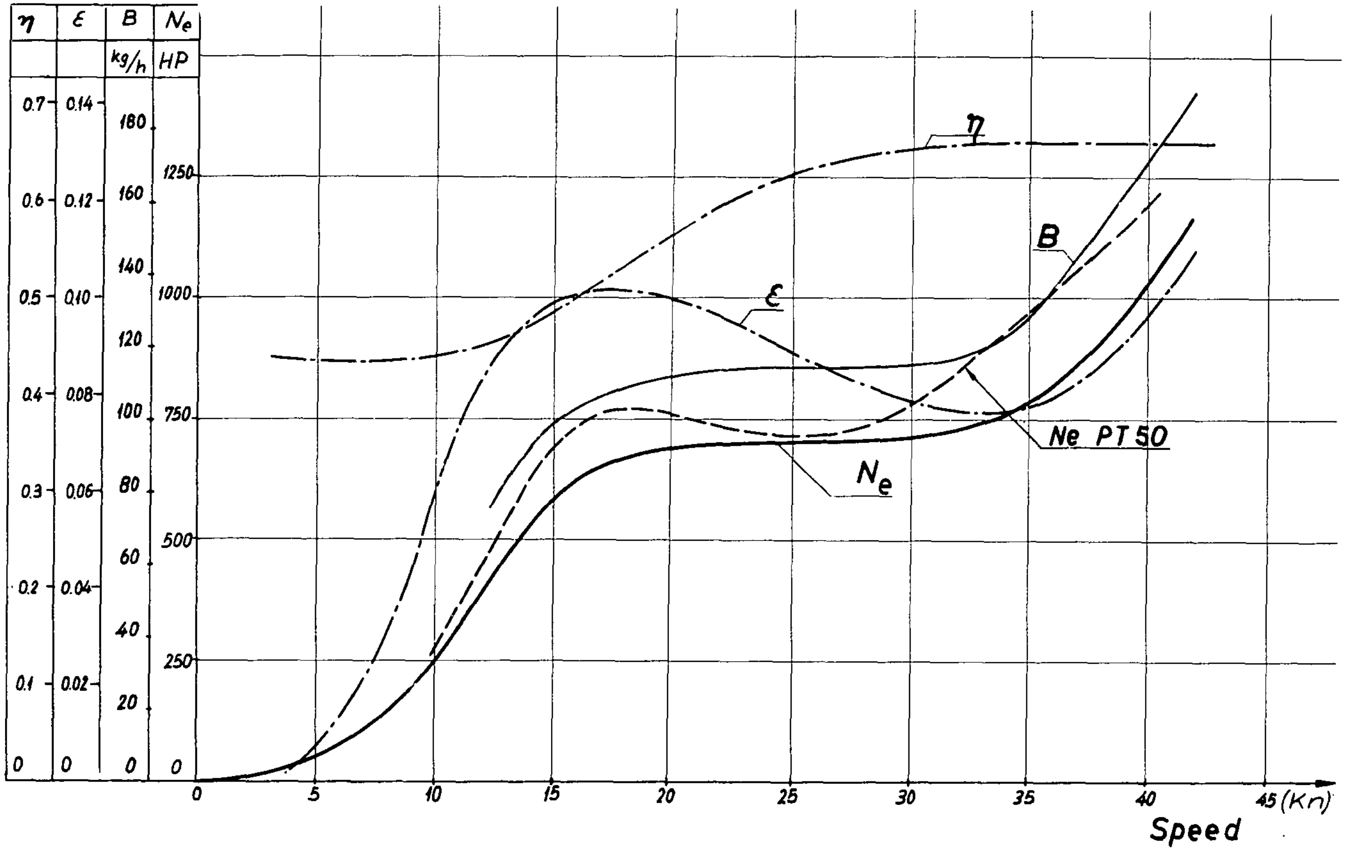

Fig. 13. Performance of the PT 20

ratio is D/W = 8.6 percent at cruising speed (38 knots) and its minimum is 7.7 percent at a speed of 34 knots. The corresponding maximum lift/drag is W/D = 14.3.

A special type of PT 20 was designed for the transportation of engineers and workers to offshore oil-drilling and pumping stations for oil-producing organizations in tropical waters (Fig. 14). In this type, bridge and engine room have been arranged in the foreship in order to obtain better vision since tropical waters have an occasional influx of driftwood.

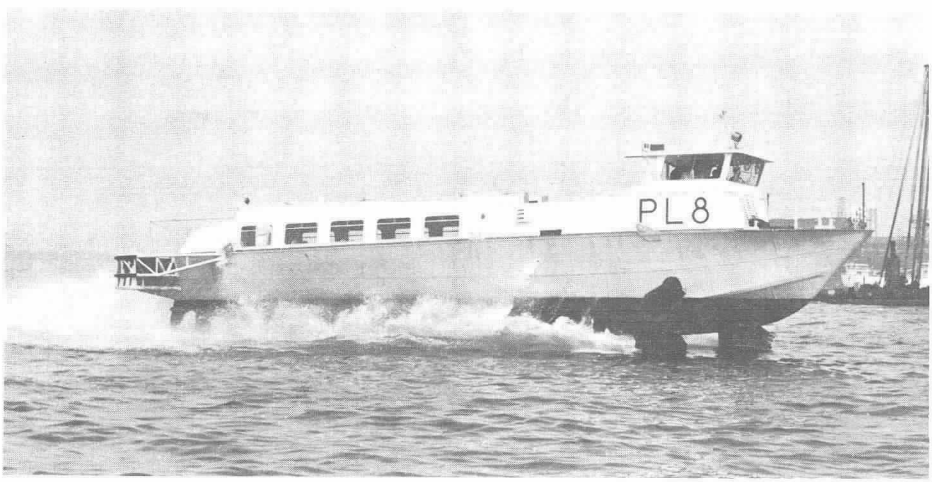

Fig. 14. A special type of PT 20 for oil-workers in tropical waters

Tropical conditions were taken into consideration in the design and installment of the engine plant, and the propeller has been placed in a specially protected position. Because passengers board and leave the boat via the aftship this part has been fitted with particularly sturdy metal guards. Because these boats are undergoing very rough handling by their native crews the requirements with regard to their performance, sturdiness, and maintenance are extremely high. Thus, for example, the boats must be able to remain foilborne even when sudden full rudder is applied at full speed. Four boats of this special 29-ton type have been constructed at the Gusto Shipyard in Schiedam (Holland) for the Shell Petroleum Company in Maracaibo.

Continued successful and profitable operation with the PT 20 stirred up sufficient interest in a larger type of boat to be used in open waters farther away from the coast and suitable for interisland services. The prototype of the PT 50 was constructed early in 1958, again by the Rodriquez shipyard in Messina (Fig. 15).

In this 60-ton boat, passengers are placed below the main deck. Thus that deck contributes considerably to the strength of a hull, allowing structural weight savings. The machinery consists of two of the same type of Diesel engines tried out with great success during a period of over 4 years in the PT 20 boats. Shafting is simplified as compared with the smaller craft by eliminating the V-drive. Both rear and forward foil are rigidly attached to the hull, but the lift of the forward foil can be modified by hydraulically operated flaps.

Fig. 15. The PT 50 hydrofoil boat

Figure 16 shows the general arrangement. The passenger room is divided into two compartments which are separated from each other by the engine room. The forward cabin contains a bar, and a little saloon is provided on the upper deck, aft of which there are baggage compartments. Two PT 50 vessels which have been delivered to Venezuela are fitted with air-conditioning installations.

Figure 13 also shows the power curve $N_{e/2}$ of the PT 50 for comparison with the PT 20. It reveals that the power is somewhat higher, especially at increased speeds, which must be attributed to the twin shaft and twin rudder arrangement and to the not very favorable location of the propeller chosen in order to give better protection.

Technical Data for the two types are as follows:

	PT 20	*PT 50*
Length overall	68 feet	89 feet
Displacement fully loaded	28 tons	60 tons
Payload	6.8 tons	15.0 tons
Number of passengers	75	140
Max. power	1350 hp	2700 hp
Max. speed	42 knots	40 knots
Cruising speed	38 knots	36 knots
Power at cruising speed	920 hp	1000 hp
Range	300 naut mi	300 naut mi
Power/ton	48.2 hp/ton	45 hp/ton
Power at cruising/Payload	135 hp/ton	134 hp/ton
Power at cruising/Passengers	12.3 hp/pass.	14.3 hp/pass.

The Supramar company is working on the design of some larger and faster types of hydrofoil boats intended for use under heavier, open-sea conditions and over longer distances. A 110 multiple-purpose type with a carrying capacity of at least 200 passengers will be provided alternatively for Diesel and gas turbine propulsion. With two Mercedes-Benz engines of 3000 hp each, a speed of 47 knots is expected, which will be

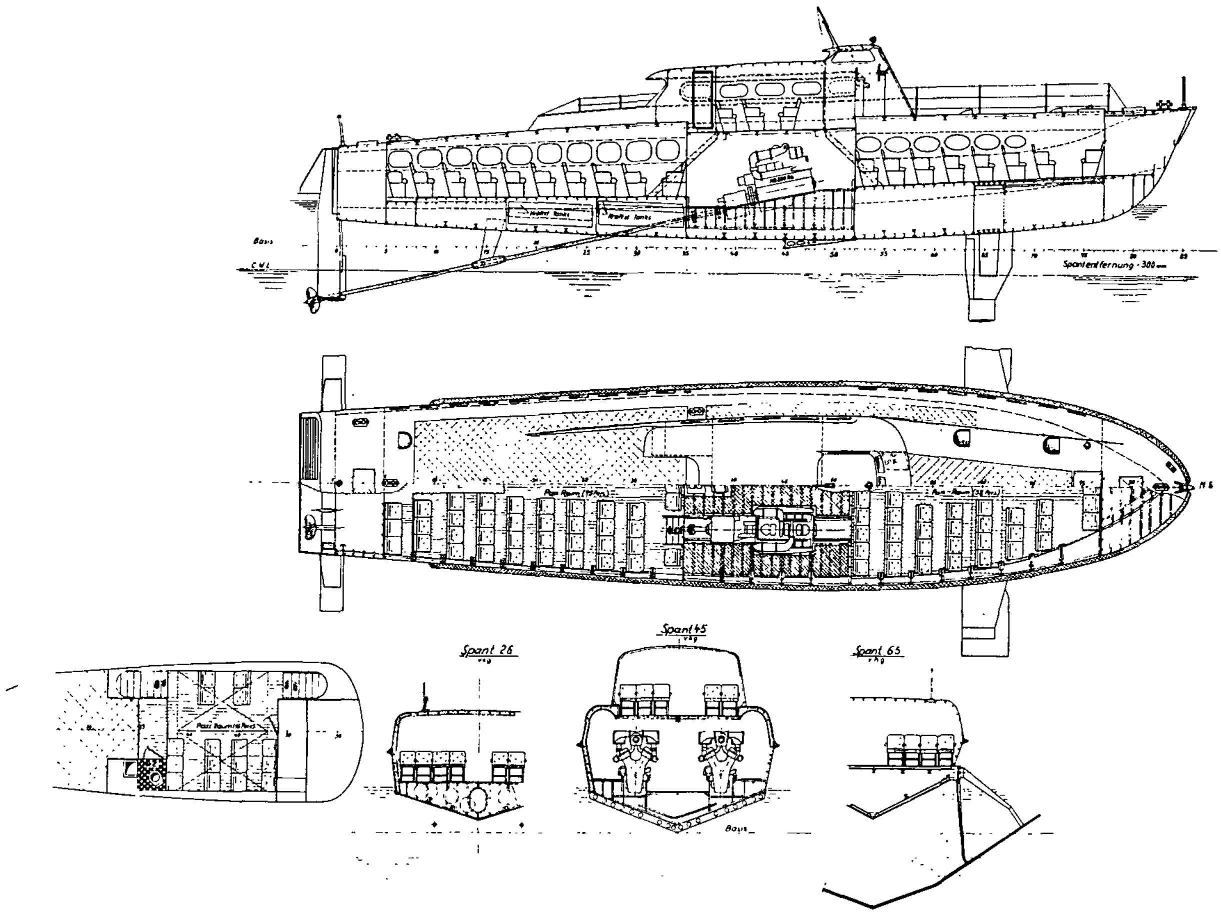

Fig. 16. The PT 50 hydrofoil boat

increased to 53 knots if the Diesel engines are replaced by two 4200-hp Bristol-Proteus turbines.

The next larger type was originally planned with a displacement of 120 tons but this was later increased to 160 tons. With accomodations for 400 passengers over short distances or 320 baggage-carrying passengers and four motor cars, a top speed is expected of 50 to 60 knots, depending on the type of turbine.

The project of a 300-ton boat with supercavitating foils to carry about 550 passengers will be discussed in a subsequent section with regard to its economical and attainable speed and to the limits of its application. It is proposed to power this craft with two Bristol Siddeley-Olympus turbines with a continuous output of 17,500 hp each. The cruising speed is estimated to be 70 knots, thus reaching the technically possible limit, as we shall see later on, but still representing from the commercial point of view a very profitable speed under favorable conditions.

Depending on the area of application either the surface-piercing foil or the new type of fully-submerged foil, now in development, will be employed in these future craft.

DEVELOPMENT OF COMMERCIAL PASSENGER SERVICE WITH HYDROFOIL BOATS

For the introduction of hydrofoil boats in public service, Supramar in 1952 constructed a 9-ton boat (PT10) with a seating capacity of 28 passengers and powered by a 500-hp Mercedes-Benz Diesel engine located in the stern. Soon after her first demonstration on Lake Lucerne, Italian and Swiss navigation companies chartered this boat for passenger services between the Swiss and Italian part of Lago Maggiore under the technical management of Supramar. Thus the first scheduled hydrofoil boat service in the history of shipping was inaugurated on May 16, 1953 (on the same lake, incidentally, on which Forlanini succeeded in getting his hydrofoil test-boat "foilborne" for the first time 55 years ago).

Interest in the new "flying boat" became widespread and in many cases took on enthusiastic proportions. In a surprisingly short time travellers became accustomed to this rather strange means of transportation. With 27,000 nautical miles covered during this testing period, valuable experience was gained on the technical as well as on the commercial side of the business. By the middle of 1956 the first 28-ton boat (PT20) had completed several demonstration runs along the Italian coast and a round trip of 1600 nautical miles from Italy to Greece. It had proved its seaworthiness on many occasions and in waves up to 13 feet high. On the initiative of Mr. Rodriquez a shipping company named Aliscafi was established in Sicily and the first scheduled sea service inaugurated between Sicily and the Italian mainland in August 1956. Cutting the port-to-port time from Messina to Reggio di Calabria down to one-quarter of that of the conventional ferryboat and making 22 daily trips the boat thus set an example for the operation of other hydrofoil services. The results of this service after four years of operation are noteworthy: With a seating capacity of 75 passengers one boat alone has carried a record number of some 31,000 people in a single month. The average daily number of passengers is today between 800 and 900. To date the boat has carried a total number of approximately 1,000,000 passengers. The boats operating around Sicily have covered a combined distance of approximately 465,000 nautical miles, which is more than the round-trip distance to the moon.

After the establishment of the Messina-Reggio line other services have been organized between the following localities:

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1957	Messina-Taormina	PT 20
1957	Messina-Liparian Islands-Palermo	PT 20
1959	Venice-Trieste	PT 20
1958	Lake Garda	PT 20
1960	Naples-Capri-Ischia	PT 50
1959	Maracaibo-Cabimas (Venezuela)	3 PT 20
1960	Stavanger-Bergen (Norway)	PT 50
1960	Stockholm-Mariehamn (Sweden-Finland)	PT 50
–	Buenos Aires-Montevideo	2 PT 50

The most prosperous services exist between Maracaibo and Cabimas and between Naples and Capri. On the first mentioned line two PT 20 boats carry an average of nearly 1700 passengers daily and over 600,000 per year over a distance of approximately 20 miles. The shipping company was able to amortize the two vessels within one year. On the Naples-Capri line, operated with a PT 50, passenger fees had to be raised on account of an excess of passengers. A second PT 50 has been ordered and two PT 20s have been sent to Naples in the meantime to assist in operations during the season. A second PT 50 was also requested for the Stavanger-Bergen line only two months after its inauguration.

On many occasions Supramar boats had the opportunity to demonstrate their seariding qualities under very severe weather conditions. Soon after establishment of the PT 50 line at Naples a heavy storm caused the 500-ton ferryboats to discontinue their trips between Naples and Capri. The PT 50, however, maintained its service in an overloaded condition carrying 170 passengers instead of the regular number of 140. On another occasion a PT 20, passing through the Straits of Otranto was forced down by waves of an estimated height of 13 feet but short length. It was still possible to maintain an average speed of 15 knots. In the Caribbean Sea another PT 20 got caught in the fringe of a hurricane and was able to continue her journey in half-foilborne condition in long waves averaging 16 feet in height.

As regards maintenance, inspections are undertaken at regular intervals of about 2 to 3 months, including cleaning of hull, bottom, and foils. In a tropical climate, where intensified growth of barnacles affects the drag of the foils, more frequent inspection and cleaning is indicated. If the foils are not retractable, this work is usually carried out by aqualung divers. Disregarding major machinery overhaul, which is normally due after 5000 operating hours, the maintenance of the foils requires about 25 percent of the maintenance work of the entire boat.

Strength and reliability of the foil system was several times demonstrated when boats ran aground and were still able to continue operation. A boat colliding with a pier caused considerable damage to the latter while suffering only minor deformations of the plating around the foil suspension point that did not interrupt service.

PROBLEMS OF ECONOMY IN COMMERCIAL HYDROFOIL OPERATION

Six years of experience in public passenger service with hydrofoil boats proved that the commercial application of this type of craft is very profitable in areas with an adequate passenger frequency. Similar to air transportation the comparatively high speed of hydrofoil boats in relation to other waterborne craft results in a high earning power. Since the present foilborne craft usually operate at speeds up to 3 times that of other boats, their potential carrying capacity is up to 3 times greater. In other words, a hydrofoil boat can be considered to be equal in capacity to a ship up to 3 times its size.

Figure 17 presents an analysis of actual commercial experience for the type PT 20 (assuming 2 boats in service) based on prevailing European conditions and a price of 6 cts/kg for Diesel oil and 53 cts/kg for lubricating oil. The graph indicates the yearly net return to be expected over ticket price (cents per nautical mile) multiplied by the load factor (number of passengers per available seats) . As a function of three parameters the graph thus enables anticipation of whether commercial application of hydrofoil boats would be profitable under given local conditions. Assuming a fare of 8 cents per nautical mile, a load factor of 0.5, and 1500 operating hours per year the graph shows a yearly net profit of slightly more than 30 percent of the invested capital.

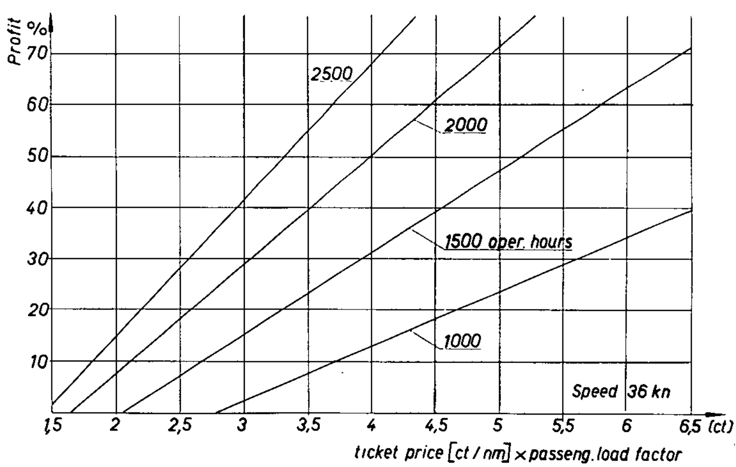

Fig. 17. Commercial experience for the PT 20

The diagram is based on a cruising speed of 36 knots. In order to determine the influence of speed on profits and also the economical speed of the vessel at which the most favorable relation between costs and revenues is obtained the curve depicted in Fig. 17 was computed under the following suppositions:

Load factor:	60 percent	
Fare:	8 cts/naut mi	
Diesel engine	specific weight:	4.3 kg/hp
	specific fuel consumption:	166 g/hp/hr
	price of engine:	$26/hp
Turbine	specific weight:	1.3 kg/hp
	specific fuel consumption:	320 g/hp/hr
	price of engine:	$44/hp.

The engine weights include gears and all auxiliaries as well as ducts, pipings, etc. The highest profit is obtained with either Diesel or turbine propulsion at a cruising speed of 40 knots. Although the engine output at that speed is nearly 60 percent higher than at 30 knots the remarkable profit is obtained by 33 percent higher revenues in accordance with the equal increase in passenger-miles. On account of the higher price of the engine and its higher fuel consumption the interest on the invested capital earned with a turbine-driven boat is only 85 percent of that of a Diesel-powered vessel. However, the fact that the modest space requirements for turbines permit the accomodation of additional passengers has not been taken into consideration. The conditions will be changed if prices and consumption figures for turbines can be further reduced in the future.

We shall now consider the field of application for the commercial hydrofoil boat within the framework of modern transportation and with regard to any competing craft. We will also investigate its limitations as far as technical practicability, speed, and economy is concerned.

Table 1 presents the principal data as they affect the economy of the hydrofoil boat and its three competitors: the conventional displacement boat, the airplane, and the helicopter. The data are based on an assumed distance of 100 nautical miles. For an estimate

Table 1
Comparison of Prices and Operating Costs

	Type	Block-speed V (knots)	No. of seats	Price ton ($)	Price seat ($)	Price seat V_r* ($)	Operat. costs passeng. mi (¢)
Passenger Boat	26.5 tons	12	92	3,600	700	700	1.4
Hydrofoil	PT 20	36	75	9,300	2,800	900	1.6
Airplane	Convair	150	44	43,000	18,000	1,500	3.4
Helicopter	Sikorsky S-55	72	10	~130,000	~40,000	6,700	12.0

* $V_r = V/V_{pass.\ boat}$.

of economy the two last columns are the most interesting. They indicate price per seat divided by block-speed (port-to-port speed) and the direct operating costs per passenger mile (expenditures less cost of ground organization). It appears that the foilborne craft is very economical compared with the other means of transportation and under the assumed conditions. In spite of the slightly lower "initial capital expenditure per passenger mile" and operation costs of the displacement boat, the attainable revenues within a certain operation period are higher for the hydrofoil boat because it travels three times as fast. It must also be taken into consideration that the public is generally willing to pay higher fares for faster transportation. The comparison with the commercial airplane reveals that its initial costs are higher and its total operation costs very much higher if the expenditures for the ground organization are taken into regard. With total operating expenses estimated to be at least 7 times those of the hydrofoil craft, the helicopter cannot be considered to represent an economical instrument of transportation at present.

In order to find the speed ranges within which the hydrofoil boat and its competitors can be successfully employed we have already shown in Fig. 1 the power coefficient for the craft in question over speed. First of all the earning power for a hydrofoil boat with

550 passengers was calculated as a function of speed in order to determine the limit from a commercial point of view. In doing this the following conditions were assumed:

Load factor:	60 percent (330 passengers)
Ticket price per nautical mile (in correspondence with the average economy class fares for airplanes):	7 cts
Operating hours per year:	2000
Range:	500 nautical miles
Total weight of turbine including gear and accessories:	1.55 pounds/hp
Specific fuel consumption:	0.6 pounds/hp
Purchasing price of turbine including gear and accessories:	$42/hp.

For the fixed costs the same assumptions as in Figs. 2 and 17 were made. The specific power requirements shown are based on measurements in various boats of the Schertel-Sachsenberg system. It turned out that the power coefficient $N_e/\Delta^{7/6}$ given on a logarithmic scale over the Froude number $V/\sqrt{\ell}$ (ℓ = foil distance) lies on a nearly straight line for all hydrofoil boats constructed, so that reliable figures are available. Values of a much lower order given in other theoretical treatises, which neglect the fact that after a relatively short operating time the foils are no longer hydraulically smooth, are not realistic.

In Fig. 3 the curves of profitableness and of the boat's power in consideration of the increasing displacement (turbine and fuel weight) are plotted against speed. The number of turbines to be installed was based on the Bristol Siddeley Olympus turbine with 22,700 hp maximum and 17,500 hp continuous output. Under the assumptions made, the best profit is obtained at about 50 knots. With increasing speed earning power reduces and one may consider 85 knots as the utmost limit at which the boat can still render a profit under otherwise favorable conditions. The limit of technical practicability, however, can probably be expected at 75 knots at the present stage of the art when observing the requirements of the classification committees and the regulations of the London Ship Safety Convention, especially with reference to electrical installations, auxiliaries, and safety installations. Apart from the fact that a larger engine plant can hardly be properly installed, the amount of fuel necessary for greater speeds increases at such a rate that the number of passengers necessary for obtaining a profit can no longer be maintained.

Figure 1 shows that 38 knots was chosen as the lower limit of application of the commercial hydrofoil boat of the given size (160 feet) and 80 knots as the upper limit. Exceeding this limit under economically acceptable conditions, for the case in question, seems possible only if hydrofoil boats with better lift/drag ratios or lighter engines with less fuel consumption are developed in future. In the speed range beyond 80 knots the superiority of the airplane – as far as power requirement is concerned – increases continuously with the speed.

The diagram also contains the dotted curve of the "flown" values of ground effect machines (hovercraft) which operate at an altitude of about 5 percent of the craft's diameter. Because only scant results are available, this curve does not pretend to be correct. Data of projects which have not yet been completed or power figures at altitudes of less than 0.05 diameter are not represented. A comparison between the hydrofoil boat and the hovercraft is justified only if the flight altitude of the latter would be great enough that both types can manage the same height of waves. However, it can be assumed that the respective curve will be considerably improved in the course of development.

The length of a route between two points which can still be operated advantageously in competition with an airline is also dependent on the economic maximum speed of the hydrofoil boat. Preference obviously will be given to the airplane if it requires much less time for the trip and if both the airplane and the hydrofoil company charge the same prices. Assuming a maximum speed for the hydrofoil boat of 75 knots and for the medium-distance airplane a block speed of 360 knots, it can be safely predicted that for all distances beyond 300 nautical miles, for which the hydrofoil boat needs more than four hours, travellers will prefer the airplane with its 50 minutes of flying time, even counting the time lost getting to and from the airports.

It can be expected that under the existing circumstances the longest economically favorable distance for the hydrofoil boat lies between 300 and 400 nautical miles. Although quite a lot of publicity has been given to the idea of a future Atlantic hydrofoil service it appears very improbable, if not impossible, that hydrofoil boats will ever be suitable for this task which can be much better accomplished and with better economic results by modern airplanes.

NOTATIONS USED

a = vertical acceleration
b = span of hydrofoil
c = chord of hydrofoil
h = submergence below water surface
ℓ = foil distance
w = weight
v = speed in ft/sec or in knots
q = $0.51\rho v^2$ = dynamic pressure
A = b^2/S = aspect ratio
B = fuel consumption
C_D = D/qS = drag coefficient
C_L = L/qS = lift coefficient
D = drag of hydrofoil
L = lift of hydrofoil
L_W = wavelength
F = Froude number
H = wave height
N = motor power
S = projected foil area
W = orbital sensitiveness
Z = wing characteristic
Δ = displacement
α = angle of incidence
γ = weight density of water
ϑ = dihedral angle
δ = wave slope
ρ = γ/q = mass density

DISCUSSION

Christofer Hook (Atlantic Hydrofin Corportation, Villeneuve le Roi (S&O), France.

Baron von Schertel gave the example of phase shift in the case of following waves for the surface-piercing system but he neglected to point out that the main advantage of the submerged foil is the opportunity it provides for correcting this out-of-phase effect by application of an advance or prediction signal to the incidence changes. Ideally, this would lead us to a telescopic sensing device whose advance position with respect to the controlled foil would be adjusted to suit different ratios of hull to wavelength. In practice, a simplified compromise in the form of a fixed advance length is perfectly satisfactory since only relatively short waves are significant.

It is also feasible to incorporate into such a sensing device a wave-height measuring system, coupled to powerful damping, so that all waves up to a given maximum (corresponding roughly to the height clearance) may be filtered out, resulting in practically level flight over waves up to this size. For larger waves the aforementioned size may be subtracted as a constant so that, for example, a wave 6 feet high may be dealt with as if it were only 3 feet high.

It is too often assumed that a given hydrofoil system must be restricted to a given severity of sea and that beyond this some disaster must follow. The impression given is not improved by the fact that the details of the type of disaster are left to our imagination! This is, however, somewhat unfair since a similar restriction should also be placed on normal boats, which should then also be sold with a "sea severity tag" attached – which is not done. A good hydrofoil can perform in seas well beyond the capacity of a crash boat to follow, as has been shown in U.S. Navy reports, and when failure to follow is eventually arrived at it is not followed by any kind of disaster but merely by a sitdown, and the ship can always continue in a half-foilborne condition; in fact, pitching is so severely damped by foil action that a light hull fitted with foils will survive where the same hull with foils removed will break up. The matter of wave filtering becomes so important at sea that fine comparisons of relative lift/drag ratios of the two methods becomes pointless.

Finally, I think that the purely mechanical method cannot be lightly dismissed as bulky and vulnerable since its reliability is unquestionable. Since an increase of C_L is obtained by incidence instead of by carrying reserve foil area we can offset the gain in weight consequent in the elimination of this weight against the added hardware required to manipulate the prediction method and we fill find that there is no added weight. On the basis of cost, if I may be excused, I may perhaps point out that for a sport boat or 4-passenger size the cost of the hardware does not exceed $100. I think that all hydrofoil men here today should realize that we are very much riding on the wave created 25 years ago by the Schertel-Sachsenberg group and that, had it not been for the commercial successes of this group, hydrofoils would never have got going again after the fizzle out that followed the Bell experiments in about 1920.

H. Von Schertel

Mr. Hook is right when he points out that the description of phase shift for a hydrofoil boat travelling in a following sea, given in the paper, refers to the surface-piercing foil system, and that the behavior of a boat fitted with fully-submerged foils controlled by a predicting sensor would be different. I tried to give the advantages of fully-submerged foils as far as I could in a paper of the present length.

L. S. Snell (The De Havilland Engine Company Limited)

Baron Von Schertel makes certain assumptions in Fig. 17 when comparing the performance of the Diesel engine and gas turbine. He goes on to say that "conditions will be changed if prices and consumption figures for turbines can be further reduced in the future."

It must be remembered that though the specific fuel consumption (S.F.C.) of the Diesel engine can be taken as generally constant at about 0.4 lb/b.h.p.-hr, a wide variety of gas turbines with equally widely differing performances can be produced. The S.F.C. quoted in the paper has already been improved upon, though unfortunately at the expense of cost and bulk. Figure D1 shows schematically three engine types recently evaluated for a small high-performance craft. That on the right utilizes a simple open cycle and its design owed much to aero engine practice. The efficiency of this simple cycle can be improved by raising the turbine inlet temperature and increasing the compression ratio, if this can be associated with an increase in compressor efficiency. Modification to this cycle is desirable if good economy is the main aim. The center illustration shows the addition of a heat exchanger which recovers some of the exhaust heat previously lost, while the remaining diagram depicts a quite sophisticated arrangement using three stages of compression with inter-coolers and exhaust heat regeneration.

Figure D2 shows the performance expected from each of these arrangements compared with that obtained from the conventional Diesel engine. The component efficiencies and maximum cycle temperatures used in these calculations are quite modest and are those liable to be encountered in a marine engine rather than an aero engine. Examination of these curves indicates a most significant point, that is whereas the Diesel engine has a consistently good specific fuel consumption over a very wide load range, the simpler gas turbines markedly worsen as the throttle is closed.

The author said that after using practically full power to get on the hydrofoils, cruise then takes place at about 55 percent maximum power. Cruise economy at this point is, therefore, the main consideration in the choice of prime mover. Unfortunately the choice of a simple open cycle working on high compression ratios and high turbine inlet temperatures can be most misleading as, although the S.F.C. is considerably improved at near 100 percent full power, at 55 percent the S.F.C. is not materially better. This state of affairs might well be more of a problem for the present generation of hydrofoil craft as it would appear that as cruising speeds increase so the cruise power will proportionately increase.

A near ideal solution would be to evolve a variable-mass-flow engine fitted with an exhaust heat regenerator. With decreasing throttle, mass flow would similarly decrease, and if a near-constant pressure ratio and turbine inlet temperature was employed, the thermal ratio of the heat exchanger would be markedly improved and, coupled with reduced ducting losses, would give an increasingly better S.F.C. with closure of the throttle.

During the course of the analysis previously referred to, account was taken of the additional space available not only for the gas turbine compared with the Diesel engine but for the varying amounts of space which could be saved with the different gas turbine configurations and their associated fuel tanks. Surprisingly enough, the higher fuel consumption

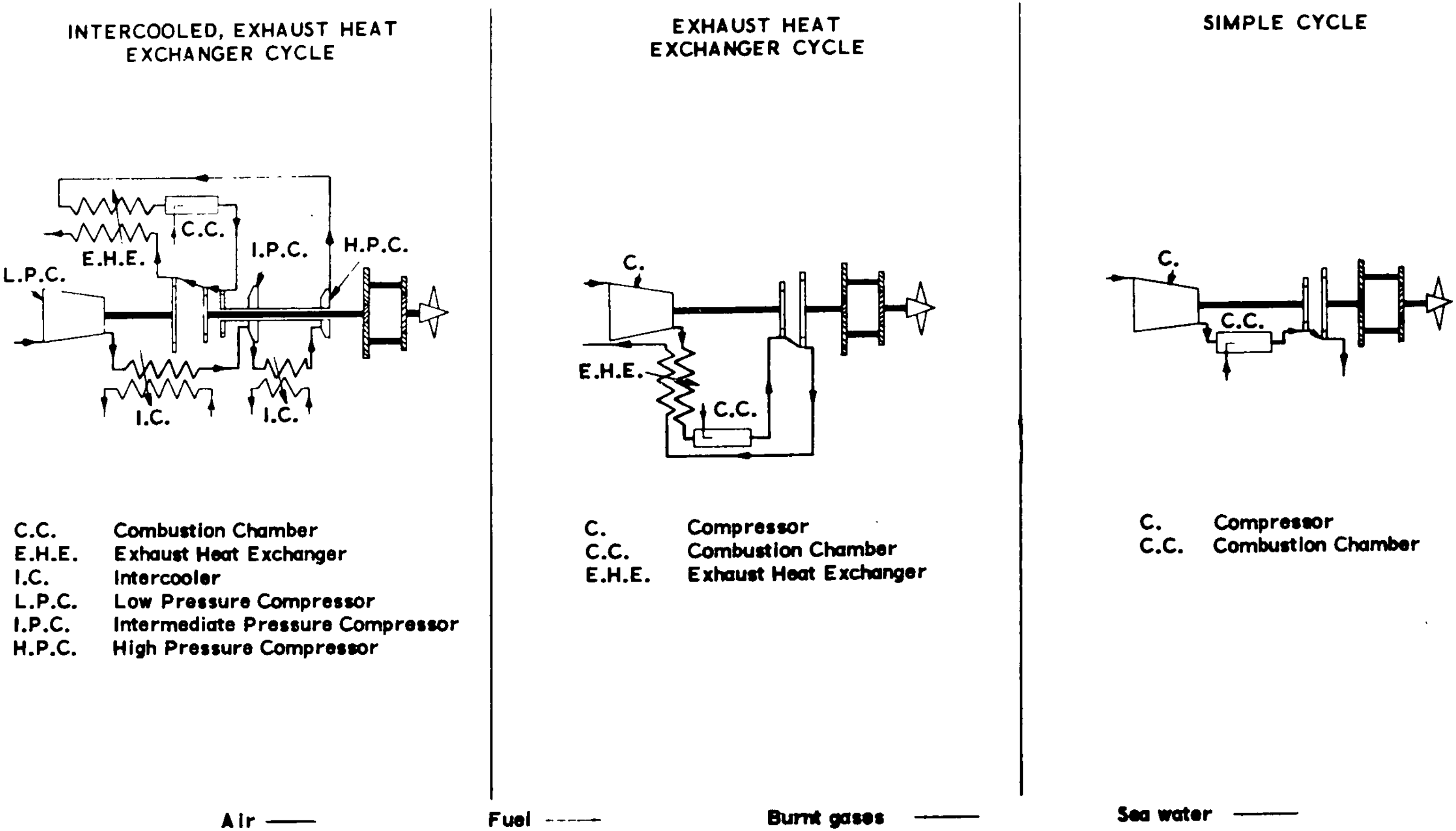

Fig. D1. Air-breathing gas turbine cycles

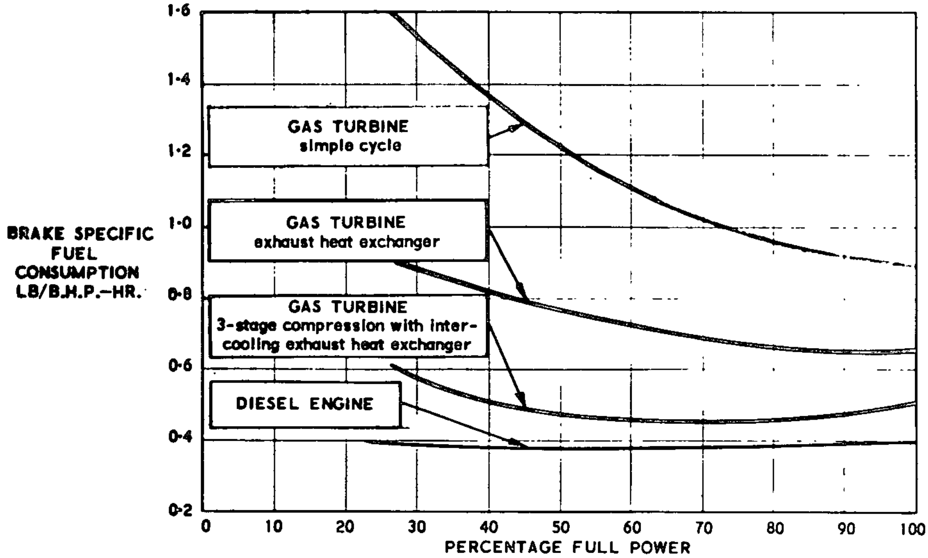

Fig. D2. Surface performance of air-breathing engines

of the simpler cycles was just about offset by the engine room volume and weight saved, so that for ranges of up to 1000 nautical miles there was little to choose between the installations; above this figure the more sophisticated units showed to advantage. However, in this design evaluation the installational size of the Diesel engine concerned cut the payload so much that its use could not be considered.

This raises a further point, very much to the forefront of the engine designer's mind, that above a certain size, Diesel engine specifics – both weightwise and volumewise – greatly increase as high duty materials and associated workshop practices can no longer be employed. One British engine, for instance, uses 36 pistons and 3 crankshafts in order to get the largest engine size which can be made from the better class materials and precision methods of manufacture. It would, therefore, seem that apart from small, highly specialized or experimental craft, the gas turbine should really come into its own at shaft horsepowers of, say, 4000 and above for the type of craft the author discussed.

Speaking very personally, I feel that no real progress will come with the adoption of the gas turbine for high-speed marine craft until units are designed expressly for this purpose, not merely rehashes of aero engines. The knowledge and facilities exist for designing and developing these units; the engineer should be given the opportunity of doing this at the earliest possible date.

R. N. Newton (Admiralty Experiment Works)

I would like to refer to two specific points arising from Baron Von Schertel's excellent paper which bear directly upon the general comments I made concerning hydrofoil craft and GEMs in the discussion of Mr. Oakley's paper on high-performance ships.

Near the end of the section titled "Present Types of Commercial Passenger Boats" Baron Von Schertel listed particulars of the PT 20 and PT 50 Supramar craft. While the figures quoted leave no doubt as to the economical performance of such craft in calm weather, i.e., their relatively low horsepower for a given speed, it should be noted that the maximum speeds quoted are not really high in comparison with modern planing forms and the range, in particular, is very limited.

Now there can be little doubt, I think, that higher speeds will be achieved with the larger craft which the Supramar Company are contemplating, but one is left to wonder whether they will have the range for open sea voyages as claimed, or the ability to operate in heavy sea conditions.

After listing the existing services the paper states that the craft have demonstrated their sea-riding qualities and then goes on to quote three occasions upon which a craft was forced down by the waves. In other words it is at least admitted that this type of craft is limited by the sea condition. Unfortunately the paper does not say at what speed the craft were able to proceed in waves, nor is there any proof of the heights of waves quoted – as much as 16 feet in one case. One of the most difficult quantities to estimate, without the use of apparatus only now coming into use, is the height and length of waves. I venture to suggest that the heights quoted in the paper are heavily exaggerated.

To emphasize the point I would like to quote an extract from a recent report of David P. Brown, President of the Board of Managers of the American Bureau of Shipping:

"After months of study of plans and design criteria as well as inspection during construction, the first of several hydrofoil passenger craft is about to be submitted to the committee for classification. Requests to class this type of craft were considered favorably by the technical committee last autumn, subject to appropriate limitations as to the area of operation and indication in the classification symbols that the craft is of special design and not comparable to a normal vessel in respect of scantlings and certain machinery details. Hydrofoil launches are now being built for use in Lake Maracaibo and in the Caribbean."

In conclusion may I repeat the plea I made in the discussion on Mr. Oakley's paper for more research into the seaworthiness of this type of craft.

H. Von Schertel

Mr. Newton expressed the view that hydrofoil boats can get into sea conditions in which they have to come down onto the sea. The behavior of hydrofoil boats in a seaway depends, of course, on the length of the waves, and on the direction of travel of the craft relative to the waves. Our experience over more than 10 years shows that the hydrofoil craft can run in almost any sea condition, occasionally, of course, with reduced speed (as is the case with any type of boat) and in a half-foilborne condition. Also I would like to add that in this condition hydrofoil boats have proved to have superior sea-riding qualities over planing boats, owing to the damping action of the foils. This fact has also been stressed by Mr. Hook. Concerning speed in waves, comparison runs which have been made between our commercial boats and several Navy craft showed that the higher the waves encountered the more the difference in speed was in favor of the hydrofoil boat.

Mr. Newton emphasized that the range of 300 miles given in the paper for our hydrofoil boats does not bear any comparison with fast planing craft. May I draw the attention Mr. Newton to the fact that the paper only deals with rather short-distance commercial boats with a high passenger load. In the case of a planing boat and a hydrofoil boat of equal speed and displacement, the range of the hydrofoil craft will be considerably higher on account of the much lower motor power and the associated low fuel consumption.

A. Hadjidakis (Aquavion Holland N.V.)

There are many things wherein I fully agree with Baron Von Schertel, for instance: that the efficient speed for a hydrofoil craft lies between 40 and 50 knots; that the required engine power per ton displacement is about 40 b.h.p.; and that seaworthiness increases with size (it would be terrible if we disagreed on this point). Our thinking was very much in the same direction. Compare for instance Baron Von Schertel's Fig. 7 with Fig. 7 in my paper.

However, there are some points where we differ. In the first place, I wonder why the foil incidence of your hydrofoils is such that a lift coefficient of only 0.22 is obtained. Is this so chosen to prevent cavitation at full speed or perhaps to get better takeoff characteristics, or is there some other reason? We use lift coefficients of up to 0.45 at top speed. In the second place, it surprised me that a gas turbine engine gives a lower profit if used in the PT 20 type, as is indicated in your Fig. 2. In my opinion it should be contrary. Let the specific weights be 4.3 kg/hp for the Diesel engine and 1.3 kg/hp for the gas turbine, which gives a difference of 3 kg/hp, or for 1375 hp a weight decrease of say 4 tons. Because of double fuel consumption, fuel weight will increase say 1.5 tons. But there is still 2.5 tons left, which means at least some 25 extra passengers; that is to say an increase of income of one third, as the PT 20 carries 75 passengers normally. Furthermore, only a small engine room would be required, so there would be more space left for other things.

H. Von Schertel

The lift coefficient in the example given is only 0.22 because a speed of 45 knots was assumed, so that the lift coefficient must be kept rather low to minimize or avoid ventilation and cavitation. A certain margin must be left between the lift coefficient at which ventilation occurs and the C_L value actually used in order to allow for the orbital motion in the waves.

As to the question of operational economics with turbine propulsion for the type PT 20, it has to be taken into consideration that the number of passengers is limited by the available space in the boat. The turbine-driven boat will be lighter and require a smaller engine power, which however does not compensate for the high initial cost and consumption of turbines. In my paper I remarked that economy would improve with the turbine boat if passenger space could be gained by reducing the engine room size.

E. V. Telfer (Institute for Shipbuilding, Trondheim)

As a simple naval architect listening to your deliberations I have been a little puzzled as to how to present your thoughts nondimensionally so far as these exciting craft are concerned. At the moment it appears to me that you prefer to think entirely dimensionally round each particular problem and in so doing do not necessarily see the picture as a whole.

For example, in Mr. Wennagel's paper there is one very interesting diagram (here Fig. D3B) given in dimensional form which can with advantage be re-presented in nondimensional form. Normally in ship work we use a resistance coefficient based on a speed-squared relation associated with a relative speed. One such combination is the Froude Ⓒ and Ⓚ presentation; and so long as resistance does vary approximately as speed squared, the corresponding Ⓒ value is substantially constant. When the performance of a fast vessel is so presented, however, we see (Fig. D3A) that the speed-squared relation required for nondimensionality is no indication at all of the power of the speed with which the resistance is actually varying. Actually, for speeds beyond the maximum Ⓒ, the resistance is more nearly varying directly as the speed. In this case it is better to use a nondimensional presentation which respects this fact, and this is easily obtained by plotting values of

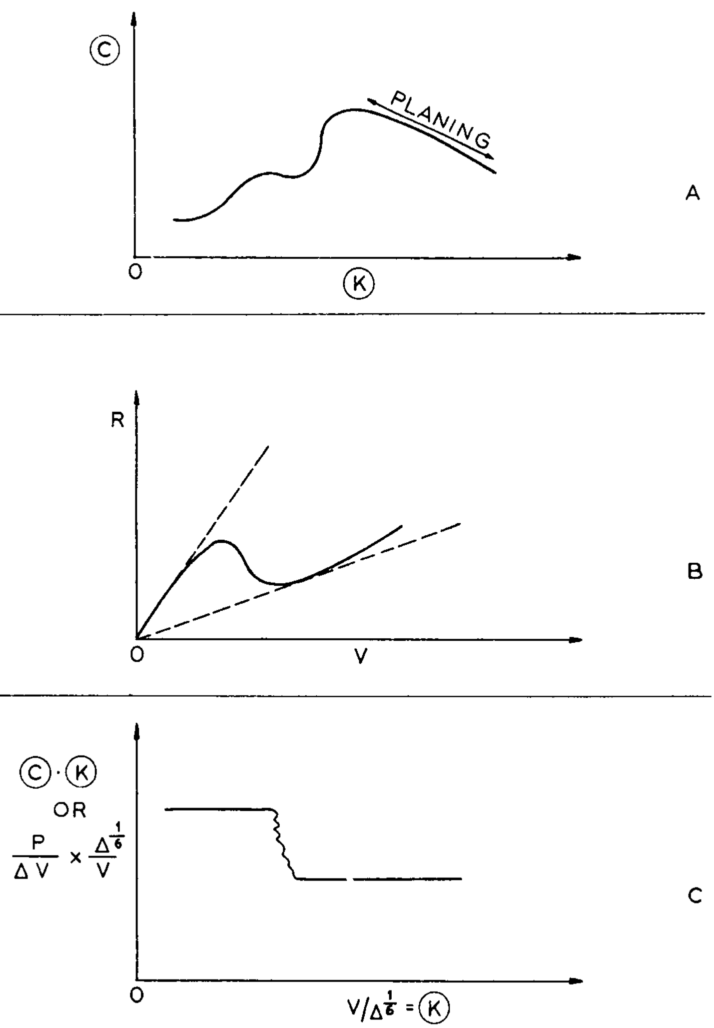

Fig. D3. Comparisons of dimensional and nondimensional presentations

Ⓒ · Ⓚ against Ⓚ. This would convert Mr. Wennagel's diagram from B to C. From the latter we see most clearly that the conditions imply two regimes of broadly constant but different Ⓒ · Ⓚ values. What is the significance of these two regimes? Incidentally the Ⓒ · Ⓚ product reduces to $(P/\Delta V)/$ Ⓚ. The term in parentheses, i.e., power per ton-knot, is the transport coefficient and is a direct commercial measure of the design efficiency.

Our discussions include many references to Froude number, i.e., Froude speed-length number. I doubt, however, so far as hydrofoil craft are concerned, whether we have a truly representative length to use in the Froude number. I suggest therefore, since for these craft displacement or weight is constant, that the Froude displacement-speed factor, i.e., $K = 0.5834\ V/\Delta^{1/6}$, should always be used for their performance nondimensional presentation.

H. Von Schertel

The Froude number is based on the distance between the fore and aft hulls.

Douglas Hill (Grumman Aircraft Engineering Corporation)

We continue to be indebted to Baron Von Schertel for his reporting of the operating experience of the craft of his design, as well as for his pioneering work in the development of hydrofoils and their introduction into commercial service. Those of us interested in the development of hydrofoils look to the experience with these craft as a milestone on the road leading to the large-scale introduction of hydrofoils for commercial and naval use.

There can be little quarrel with Baron Von Schertel's evaluation of the potential of commercial hydrofoils on the basis of the evidence he presents and the scope of his presentation. In the publicity which has attended the growing awareness of the potentialities of hydrofoil craft, it is perhaps true that the feasibility of future vessels—a transatlantic passenger liner, for example—has been overemphasized by the standards of today's commercial realities. Assuming that hydrofoil craft are better suited to coach than to stateroom accommodations, we can draw on the experience of other modes of coach transport to substantiate Baron Von Schertel's observations on the practical operating range of passenger-carrying hydrofoils. A comparison of the length of journeys of travelers by air, railroad coach, and intercity bus in the United States reveals that, while the average distance travelled varies substantially between the modes of transport, the average duration of the journey is remarkably consistent:

Conveyance	*Average Length of Journey (statute miles)*	*Average Speed (mph)*	*Average Time (hr)*
Airplane	577	220	2.6
Railroad Coach	110	40	2.7
Intercity Bus	79	30 (est.)	2.6

It would seem reasonable to expect that the widespread use of hydrofoils for coach transportation would likewise result in an average trip duration of about 2.6 hours.

Most journeys would be shorter than the average, some perhaps much longer. The peak trip length can therefore be expected to be shorter than the length of the average trip. On domestic United States airlines, for example, the most common trip length is of the order of

200 miles, corresponding to a flight of about 55 minutes. It is not surprising to find, therefore, that the hydrofoil routes described as the most prosperous are also the shortest, requiring runs of less than an hour. A journey of 300 to 400 miles, requiring 6 to 8 hours of travel at 50 knots, would seem to be approaching the limit of coach-passenger endurance, and we must agree with Baron Von Schertel that longer trips do not promise commercial success.

If indeed the time required for a trip is the factor limiting the number of passengers which may be attracted, it follows that faster boats will draw more passengers for a given route. In the example of Fig. 3, it is indicated that the most profitable speed of the boat under consideration is 50 knots, assuming a constant load factor. If the load factor itself increases with velocity, however, the most profitable speed will be greater than 50 knots.

This only serves to point out that the best speed of a hydrofoil craft from a commercial standpoint is influenced by market considerations as well as by hydrodynamic performance and operating costs. To arrive at general conclusions as to the characteristics of a commercial craft which will be most profitable, a more comprehensive analysis than the one presented is required. We shall have to examine the entire range of feasible speeds, sizes, route lengths, power plants, types of foil, and possible payloads. We shall have to examine not only how variations in these basic parameters affect hydrodynamic performance but how they may affect the operating costs and the value of the craft as transportation equipment. And all of these must be examined in the context of the environment — physical and economic — in which the hydrofoil is expected to operate.

Such an analysis is not made in this paper, and we must read it with this caution. It may appear to be more than it claims to be; it may seem to present conclusions where it provides illustrations. We have no reason to doubt, for example, that under the conditions assumed the most profitable speed for the PT 300 is 50 knots, or that a Diesel-powered PT 20 is more profitable than one which is powered by a gas turbine. We should not necessarily infer, however, that 50 knots is thus the optimum speed for hydrofoil craft nor that Diesel engines are generally more profitable than gas turbines.

The promise of hydrofoils would seem to justify a more searching evaluation: first, of their economic characteristics and, second, of where these characteristics may pay off. The Von Schertel boats have demonstrated that the hydrofoil may successfully perform the role of a waterborne bus. Why isn't consideration being given to the analogous — and potentially larger — role of ocean-going truck?

At present, the vast majority of waterborne commerce moves at speeds of 15 knots or less. As Baron Von Schertel points out, no other waterborne vehicle has been developed to provide higher speed service, as the motor vehicle and railroad do on land. The need for express cargo transport by water has been clearly demonstrated. Twenty-knot Mariner class ships have been able to draw traffic away from slower ships. Shippers pay premium rates to ship by fast passenger liner, at speeds of less than 30 knots. And at the far end of the speed spectrum, transoceanic air cargo has been growing at the rate of 10 to 15 percent per year.

In a great many respects, the hydrofoil craft seems to qualify as an "answer" to the cargo aircraft for steamship lines:

1. Its speed range is more than double that of displacement ships of comparable size.

2. Practical vessels can be built in much smaller sizes than displacement ships without sacrificing sea-keeping capability. Smaller ships permit faster turnaround in port and more frequent service. Delivery times of a day or two, rather than a week or two, are possible.

3. As Baron Von Schertel points out, the hydrofoil can operate from existing facilities and does not require extensive shore installations as airplanes do. It can provide a self-contained express link in the transportation networks which now exist around the ports of the world.

4. Economically, the hydrofoil is at its best at the shorter ranges where the aircraft—present and projected—is at its poorest.

Within foreseeable advances in the state of the art, the ranges for economical operation of hydrofoils will be substantially lower than those of aircraft. Carrying cargo instead of passengers will not, of course, repeal these limits but it will enable the hydrofoil to service routes where its own endurance, rather that that of its passengers, is the limiting factor. While the hydrofoil cannot now be expected to provide economical transatlantic service, there are major trade areas within its range capabilities. These include the Caribbean area, for example, and, it would seem, the seas adjacent to Europe. Furthermore, there are indications that the maritime industry, at least in the United States, is ripe for the introduction of a high-performance, high-productivity vessel. Long a labor-intensive industry, the merchant marine shows increasing signs of a transition to high-productivity capital equipment. Containerized cargo handling operations are now a reality and specially designed containerships are now in service. Attention is being given to the automation of ship operation. The trend toward faster displacement ships continues.

The possible role of the hydrofoil in cargo transport is indicated by the nature of the cargo it might carry. Cargo aircraft are generally considered to be taking the "cream" of the freight market—the highest valued commodities which can best afford the premium freight charges. Of the commodities valued in excess of $40 per pound which are imported to the U.S., for example, it is not uncommon for the entire amount to be shipped by air. On the other hand, virtually no commodities valued at less than $1 per pound are imported by air.

Hydrofoil cargo transports are not likely to recapture the very high valued cargo nor will they be suitable for the low valued bulk cargoes. There is a middle ground, however, consisting of general cargo—manufactured goods such as machinery, motor vehicles and parts, electrical equipment, and textile manufactures—which constitute a substantial portion of ocean-going commerce and for which the hydrofoil may be a suitable transport.

The use of high-speed hydrofoil ocean transports would require that they be recognized as an expensive, but valuable, piece of capital equipment. Their high cost would have to be matched by high utilization to realize their productivity potential. New concepts in ocean shipping would be required, as well as the traditional ship operating virtues: minimum crews which debark at the end of a run to be replaced by another crew in the manner of airline practice; turnaround times measured in hours or minutes rather than days; rapid engine replacement in port so that major maintenance does not tie up the ship.

The history of air transport is primarily the development of the passenger market. The passenger and his baggage have offered the highest revenues, and today's airline passengers are the heirs of the early travelers who paid premium fares for the novelty as well as the speed of air travel. Only now are the airlines turning to large scale freight transport for its own sake.

The initial commercial uses of hydrofoil craft have understandably followed the pattern of early commercial aircraft. The virtues of the hydrofoil, however, are not those of the airplane. As Baron Von Schertel points out, it will be well to recognize the pre-eminence of the airplane for passenger transport beyond the range of a few hundred miles. If commercial hydrofoils are to amount to more than a novelty, we shall have to look beyond the operating experience of today's boats. It will be necessary to recognize the unique characteristics of hydrofoils, to acknowledge their limitations, and to exploit their potentialities with vigor and imagination.

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