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THE HYDROFOIL BOAT; ITS HISTORY AND FUTURE PROSPECTS

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ead in London at the Spring Meeting of The Institution of Naval Architects on March 26, 1958, *Professor E. V. Telfer, D.Sc., Ph.D.* (*Vice-President*), *in the Chair.*

Summary

The history of hydrofoil boats is traced from the earliest days of their development, and the main systems that have been invented are considered in their original and present-day versions. The advantages of this type of craft, compared with high-speed planing boats, are described. These comprise in particular lower resistance and better and more comfortable behaviour in rough water.

It is argued that serious application of the hydrofoil principle had to await the development of analogous design concepts in the field of aeronautics, and of suitable structural methods and materials. The ground work necessary for the successful design and construction of passenger ferries carrying up to 70 people, was not available until the 1940's, and even so the aftermath of the war delayed practical achievement until the early 1950's.

The problems of designing such ferries, work boats, sports boats and so forth of up to, say, 50 tons displacement, and having cruising speeds of around 40 knots, are now considered to be solved. These craft can operate satisfactorily in comparatively rough seas (e.g. up to 6-ft. waves, depending on boat size) and also at high speed on inland waterways. It is expected that many such vessels will be built and will give excellent service in the next few years, and that the present rather limited disposable load (a fuel and payload together of about 25 per cent of all-up weight) will be improved. This improvement will come in part from a decrease in percentage structure weight arising from further developments in the techniques of constructing the hydrofoils.

It is shown that an outstandingly new field of marine craft performance is open to any vessel that can travel at, say, 70 knots, with a lift-to-drag ratio of 15 and a propulsive efficiency of 65 per cent. Special purpose designs using hydrofoils and having speeds of at least 60 knots are possible now, but disposable load is small. Serious consideration of hydrofoil craft designs capable of speeds in the 50 to 100 knot range awaits the development of efficient practical supercavitated hydrofoils.

Descriptions are given of the major detailed design considerations that determine the hydrofoil configurations. They are in particular, cavitation, static and dynamic stability, and structural requirements.

Some model tests made by Saunders-Roe, in connection with the Canadian *Bras d'Or* research hydrofoil boat, are discussed.

Introduction

Several papers presented before The Institution in recent years have been concerned with subjects which lie rather outside the main stream of naval architecture. Even so, these subjects have a substantial history, involving theoretical and practical developments of considerable interest, both in their own right and in relation to some orthodox ship design problems.

Examples include: "Yacht Testing" and "The Planing Performance, Pressures and Stresses in a High-Speed Launch," both given in 1956.

The present paper is another in the same category; it extends consideration of the design problems of high-speed craft to one of the least familiar solutions, the hydrofoil boat.

Craft mounted on wings which fly just under or penetrating the surface of the water, have attracted the attention of inventors for over fifty years, the period of development of the aeroplane. This interest has arisen from one or more of several potential advantages, in comparison with other high-speed marine craft. These are a reduced resistance, a greater maximum speed for a given power, a more comfortable ride, and an ability to maintain speed in severe sea conditions.

An admittedly rather cursory examination of the TRANSACTIONS has revealed one previous contribution in which hydrofoils were the centre of interest. This was given by R. L. Townsin(1) in 1954. It was concerned only with towing tank tests on a particular laminar flow hydrofoil section, the results of which are of interest in connection with hull resistance and propeller, rudder, appendage, and stabilizer design, quite apart from hydrofoil boats.

There is, however, a S.N.A.M.E. paper by Buermann, Leehey, and Stilwell,(2) which was presented in November 1953, and gave a valuable general review of developments up to that date. It has been drawn upon frequently in preparing the present contribution.

In view of the rather specialized interest that the subject has hitherto attracted, and the author's fairly recently acquired membership of The Institution, a few words of explanation

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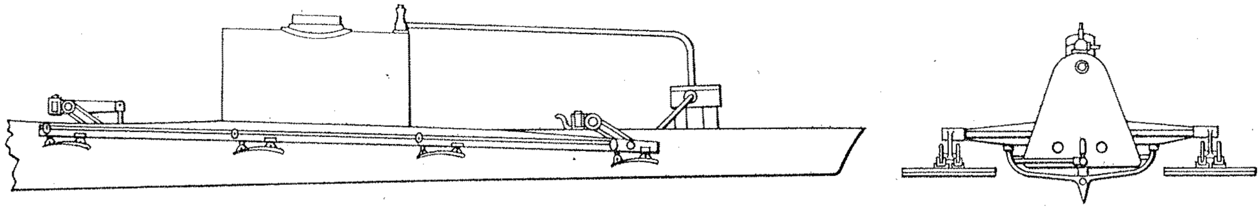
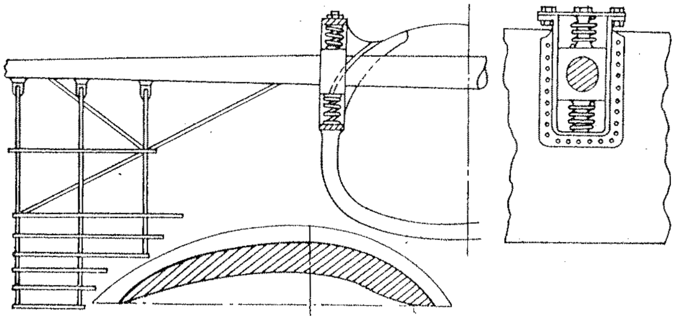
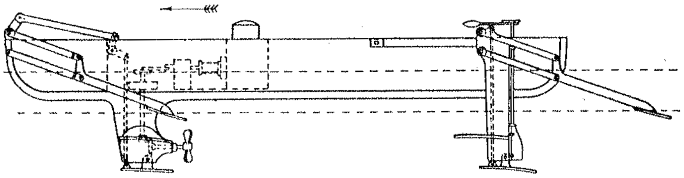


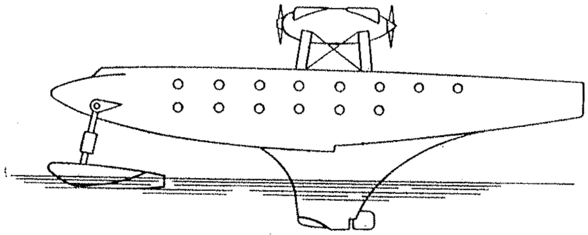
C. A. de Lambert's Hydrofoil boat as patent specification, 1891



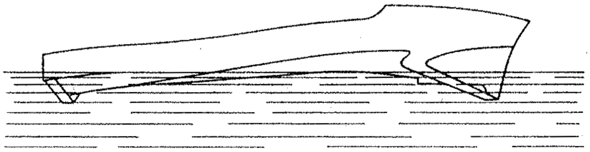
Surface-piercing ladder. Forlanini, 1898



Fully submerged incidence controlled. Meacham, 1906



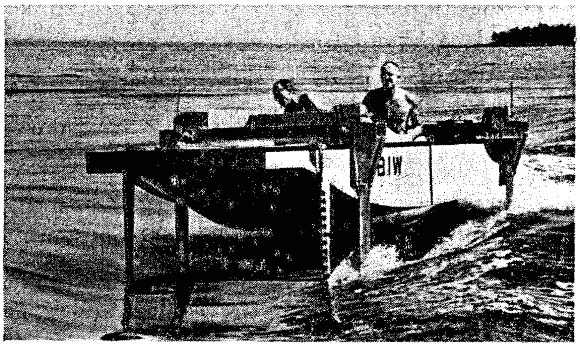
Planing support forward. Grunberg, 1934



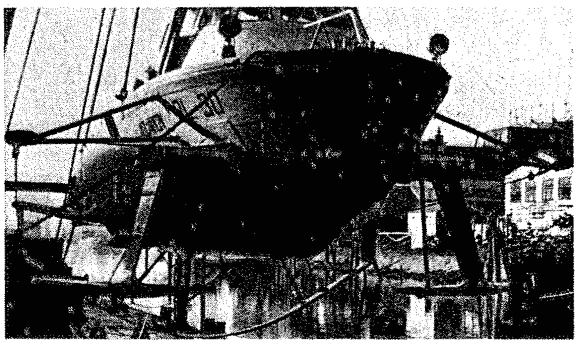
Surface-piercing hoop. Schertel, 1937

FIG. 1.—COMPARISON BETWEEN HISTORICAL AND CONTEMPORARY EXAMPLES OF FOUR BASIC HYDROFOIL CONFIGURATIONS

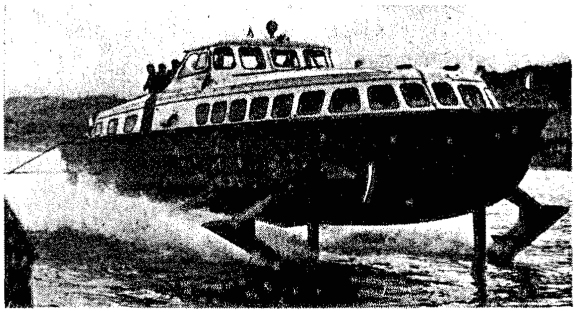
U.S.A.: Carl XCH–4



U.S.A.: Research craft



Europe: Aquavion *Aquastroll* 24/40



Europe: Supramar 70 passenger ferry

oncerning the technical experience underlying the paper may be n order.

In 1951 the Canadian Defence Research Board was seeking British collaboration in their hydrofoil boat research programme. The successful design of a hydrofoil craft has been found to equire a combination of naval architectural and aeronautical principles and experience, concerning hydrodynamics, structure, and powering.

The Saunders-Roe group of companies has for many years been concerned with the design and construction of fast marine raft and of aircraft, in particular flying boats. In view of this xperience the firm was requested to carry out a survey of the practical possibilities of hydrofoil craft, as a result of which several design studies were produced under contract. All this work, with which the author was associated, led to the design and construction for Canada of the *Bras d'Or*, which was aunched at Beaumaris, Anglesey, in April 1957.

An extensive series of model tests was made, in support of he work, by the staff of the company's test tanks. This programme of experiments was contracted for by the British Admiralty.

Since 1951 the author has had the opportunity of physically examining, and in most cases attending demonstrations or trials of, about a dozen hydrofoil boats in Europe, Canada, and the United States. These had eight basically different hydrofoil configurations, representing independent solutions of the design problems.

When preparing this paper the choice lay between giving a detailed account of work leading to the design and construction of the *Bras d'Or*, or attempting to extend the general survey given in the S.N.A.M.E. paper already mentioned.

In view of the growing interest in the practical possibilities of this type of craft, and the difficulties that the non-specialist has in appreciating the significant differences between the various hydrofoil systems that are competing for public attention, it was concluded that an overall survey would be the more valuable at the present time. Several operational craft have been launched in Europe since the S.N.A.M.E. paper was written, and some of the possibilities then indicated have now become actualities.

A multiplicity of design approaches is common in the early stages of any form of transportation, since the problems to be solved are not then fully appreciated, or developments in other ields, such as metallurgy, have not yet reached the stage where the simple aesthetic solution can be employed.

At a mature stage, a diversity of types will in general still exist because of the requirements of different operational roles. The primitive structural features and complexities of earlier concepts will, however, have disappeared. An example of such development can be seen in fixed wing aircraft, virtually all of which are now monoplanes.

Hydrofoil development in many respects is still in the "biplane" stage, but already a number of the differences between systems can be justified in terms of suitability for different roles. This paper does not, therefore, need or seek to advance the claims of one system above all the others. It discusses the advantages of each.

The Historical Roots

The Earliest Years

The first patent concerning a boat fitted with "hydrofoils" of which the author has found evidence is in the name of C. A. de Lambert, and is dated 1891. The inventor, who was of French birth but Russian nationality, is said to have demonstrated a steamboat, so equipped, on the Seine during that year. The hull did not lift clear of the water, but according to press reports it had a quite remarkable speed. Stability was inadequate, however. In France in 1897 the Comte de Lambert drove a catamaran fitted with four transverse "hydroplanes" [Ref. (2)]. Whether this was, in fact, the same craft has not been ascertained. A sketch from the specification is shown in Fig. 1. Although the "hydroplanes" were of aerofoil section, their vertical location relative to the hull would suggest that they behaved as planing surfaces at speed. This appears to have been true of a number of applications of hydrofoils to potential aircraft and successful planing craft made at the turn of the century.

In 1907 Wilbur and Orville Wright made some experiments at Dayton, Ohio, on a catamaran supported by hydrofoils [Ref. (2)]. It is interesting to speculate on the possible results of their having concentrated on the development of this idea, rather than on the aeroplane.

Fig. 1 also shows early patents and current examples of four basic and fundamentally different conceptions of a hydrofoil system. All the other types that will be referred to in this paper can be treated as variants, some of them very significant variants, of these four.

The patents will be discussed first.

Inherent Draught Control of Area using Ladder Foil Units

Hydrofoils may be completely submerged at all design operating conditions, or may pass through the water surface with change in operating condition, in which case the draught may be said to control the area used for producing water lift. Ladder hydrofoil units vary area with draught in this way.

The original ladder unit appears to have been developed by the Italian Enrico Forlanini in the years 1898 to 1905, with application to seaplanes in mind, and several patents in his name have been examined. A marine craft of 1·65 tons displacement was demonstrated on Lake Maggiore in 1906. It lifted clear of the water and reached a speed of 38 knots, using a 75 hp engine. It is said to have been stable in small waves, but the patents show a history of increasing complexity, clearly arising from attempts to overcome defects in behaviour. These included adjustment of the ladder in height and attitude relative to the hull, modification of the ladder construction, introduction of auxiliary ladders which were to be retractable at high speed, introduction of safety ladders intended to enter the water only in emergency, and use of aerodynamic damping surfaces.

The hydrofoils forming the rungs of the ladders all had their spans horizontal, in conditions of zero heel, so that their individual contributions to lift must each have fallen suddenly to zero as they passed through the water surface, causing a jerky change in draught with speed. This is overcome, in modern ladder systems, by providing the rungs with considerable spanwise angular setting to the horizontal, dihedral angles in the range 20-40 deg. being commonly used; and arranging their vertical spacing so that the lower end of one rung leaves the water surface as the top of the next below comes through it. There can then be a smooth variation of lift with draught.

Nevertheless, the original Forlanini system had the essential ladder characteristics. It gave a variation of hydrofoil lift with draught over a large draught range, allowing the hull to be exceptionally well clear of the water at high speed. It provided much less immersed hydrofoil area at high speed than at low, permitting the use of near optimum lift coefficients in the former condition without prejudicing the minimum foilborne speed.

The first extensive successful application of hydrofoils generally used ladder systems having appreciable dihedral, and was achieved by Guidoni in Italy. Between 1910 and 1921 he employed foils under the floats of many seaplanes, to reduce impact loads and pounding, and improve landing characteristics in rough water.

The aircraft had all-up weights ranging from about 1,500 lb. to 55,000 lb., but successful flights were only made up to about 13,000 lb. The craft were usually airborne well below 50 knots, and even so the greater part of the aircraft weight was supported by the wings at the higher waterborne speeds, so that the speeds of operation and hydrofoil loadings were comparatively low. Loading values of between 300 and 800 lb. per sq. ft., on the submerged areas, are quoted.

The original foils were built of steel, this giving place to wood, and finally aluminium alloy.

Guidoni developed a special hydrofoil section which will stand comparison with modern designs, although for structural reasons its small ratio of thickness to chord, limits its load-carrying ability. He claimed to have achieved hydrofoil system lift-to-drag ratios of between 7·0 and 8·0.

Usually each float had two ladders in tandem, one well ahead of the craft centre of gravity, and the other just behind it. This is an unusual arrangement for surface craft, but is appropriate to aircraft, since it allows aerodynamic control forces to lift the front hydrofoils clear, at a reasonably low speed, thus giving the increased craft attitude necessary for take off. It was also claimed to reduce the danger of diving.

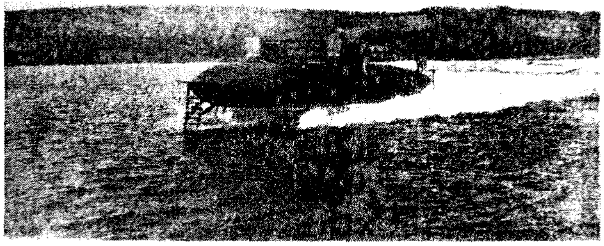
Longitudinal stability seems to have been quite satisfactory but, as might be expected, directional instability was common, especially with twin float designs. Vertical fins were attached aft on the floats to alleviate this.

The work of Guidoni is understood to have developed from that of his fellow-countryman, Crocco, who experimented with a marine craft supported by simple monoplane dihedral foils, about 1907. This is said to have attained a speed of about 48 knots, but aeronautical applications which were his main interest were not very successful.

The Italian efforts apparently ceased when increasing take-off speeds accentuated problems of cavitation and stability. The last patents of this period that have been noted were in the name of G. Pegna and the Piaggio Aircraft Company. The applications made in Britain on these patents are dated 1928. They contain the most interesting idea of using simple monoplane hydrofoils of large anhedral, having their tips much lower than their root attachments to the hull sides. This gives a high degree of inherent stability in roll. Planing surfaces are shown at the tips, for use above 50 knots where aeration and cavitation of the foils would occur. Pegna was also a co-patentee of a much earlier specification dated 1913.

The next major step in ladder hydrofoil development was made by Dr. Alexander Graham Bell and Mr. Casey Baldwin. They are understood to have bought the Forlanini patents in 1907, and thereafter they designed a series of craft called by them Hydro-Dromes, and designated HD-1 and so on. They were joined by Mr. Philip L. Rhodes, now well known as a consulting Naval Architect, practising in New York. This phase of activity culminated in 1918, in the construction of a revolutionary craft, the HD-4, and its operation on the Bras d'Or Lakes in Canada. The Bell-Baldwin system, incorporated in the HD-4, was patented at that time. Its further development, although broken by considerable periods of inactivity, has continued until today. It has the longest history—forty years—of any proprietary system, and is of particular interest to The Institution since it has been the main Commonwealth contribution to the subject.

In order to include pictures of "Bell-Baldwin" craft in operation, not only today but also in the early years, this development has been illustrated separately in Fig. 2. The HD-4 is shown at speed in Fig. 2. A number of details have been obtained from Ref. (3). The hydrofoil units were of ladder type, rather similar to those of Forlanini, but with a slight dihedral. The steerable rear foil unit, also of ladder type, which acted as a rudder, is of particular interest. This feature, which reduces the tendency of the struts to aerate or cavitate at high speed, has been retained on virtually all craft fitted with the Bell-Baldwin system.



HD-4, 1919

Bras d'Or, 1957

FIG. 2.—DEVELOPMENT OF BELL-BALDWIN SYSTEM

Another important feature was the suspension of the main foil units from a steel tube which was carried through the hull. This has been repeated in recent Supramar craft. In the HD-4 case the foil units were attached off centre relative to the tube axis, so that at high speed, when the lift moment exceeded the drag moment, the lower ends of the ladders were deflected forward and put the rearward sloping restraining struts in tension.

The design included a safety ladder at the bow, which came clear of the water at high speed, and aerodynamic surfaces to give additional damping in choppy water, as originally proposed by Forlanini.

The craft was powered by two Liberty engines of 350 hp each, driving pusher airscrews, and is said to have reached a top speed of 61·5 knots, at an all-up weight of 11,000 lb. The foil sections were developed empirically by Baldwin and Rhodes in extensive experiments, and were claimed to have given a lift-to-drag ratio of 8.

In Ref. (3), Wm. Washburn Nutting wrote:—

"... Then you notice that you are travelling over waves 1½ ft. in height, waves that would take the bottom out of an ordinary hydroplane travelling at such a speed. There is no pounding or jolting of the kind with which everyone who has ridden in a racing hydroplane is familiar. A slight undulation like that you feel in a Pullman car is the only sensation. Another noticeable thing is that when hitting a wave there is no retarding of the machine as would be the case with a surface plane.... Then Baldwin gives you the wheel ... and you find that she steers with the ease of an automobile.... If you have ever flown you know that flying is a dull business compared to skimming over the water at 60 knots, and for this reason there undoubtedly will be a future for the type of sport as well as for the more serious things at which Dr. Bell and Mr. Baldwin have been aiming."

This description is closely applicable to the performance of a number of the hydrofoil boats in which the author has ridden in recent years. Some of the technical reasons why Mr. Nutting's prediction of future development should have taken some thirty-five years to be made good are considered in this paper.

Three patents on the Bell–Baldwin system were filed in Britain in 1920, and included modifications to deflect debris and reduce the shock when hitting obstructions; these modifications were not incorporated in the actual craft.

A British patent in the name of Marks, and dated 1921, describes a "locomotive" boat on ladder foils which hauls a train of foilborne cars! This patent was communicated to Marks by Baldwin.

Between 1918 and 1939, Baldwin repeatedly made unsuccessful attempts to interest the American Navy department in the project, and in ref. (2) it has been suggested that this might have been due in part to a tendency to porpoise in a seaway.

During this period about a dozen small sporting and pleasure craft, ranging in length from 12 to 35 ft., were designed under the direction of Mr. Rhodes, usually for private clients. These are said to have given their owners good service, but systematic performance figures were not, of course, obtained. Details of some of the craft are understood to be approximately as follows:—

The HD–12 had a round bilge hull, some 30 ft. long, fitted with chine strips, and reached a speed of about 50 knots.

Miss U.S. 3 was a racing craft, with a round hull, some 35 ft. long, employing a 650 hp engine, at a displacement of 6,500 lb. The craft is claimed to have achieved a speed of 80 knots. Unfortunately it was destroyed by fire after two runs.

Both the above craft had pointed sterns.

There was also an interesting small outboard craft with a square transom, which had the main foils aft and the rudder foil forward for *CG* reasons. It behaved normally.

Classified work was undertaken in Canada during the last war, and this has led to current activity, involving developments of the Bell–Baldwin system, such as the production of the *Bras d'Or*, already mentioned.

During the 1930's, the John Samuel White Company of Cowes, Isle of Wight, in association with Captain Hampden and Mr. H. C. Carey, filed about five patents for craft fitted with ladder foil units. A vessel is known to have been built and run in the Solent, and is said to have become foilborne, but the author is not aware of any detailed published information on it.

The patents show a number of interesting variations on the ladder principle. These include cantilever suspension of the hydrofoils from a single central strut, which has since been employed by Mr. W. Carl in America. There are also swept-back struts and hydrofoils, with and without dihedral, and a braced girder construction which, together with the hull shell, forms a beam to carry the hydrofoils. The hull may be attached to the girder by vibration damping fastenings. The patents show as many as fifteen rungs on a ladder; such a number would be likely to give a high resistance and to suffer from serious cascade interference. Fixed multi-rung rear ladders and not steerable rear foil units are illustrated. An advantage of the latter has already been mentioned in connection with the Bell–Baldwin system.

Having discussed the early work on the ladder system in detail, the next basic design principle will be considered. See Fig. 1.

The Control of Variation of Incidence with Draught by means of Mechanisms

In 1906 a British patent application was made by an American citizen, W. M. Meacham. From the modern standpoint, the system was remarkable, not for employing ladders, which were in the circumstances unnecessary, but for the system of controlling the incidence of zero dihedral foils. In this a planing "skid" or hydroski as it would now be called, lying above or behind the foils it controls, is linked to them in such a way that if at a given speed the hull height above the water changes, the foil attitudes are varied so as to offset the change. A particular merit of incidence control is that the craft can be made to travel in a path which follows the wave contour, so that the hull remains effectively above the water, without having to provide so large a clearance between it and the hydrofoils as would otherwise be necessary to cope with correspondingly critical wave conditions. Meacham's patent provides for fixed foils also.

In 1911 a Captain Richardson, U.S.N. (ret.), and a Mr. White, fitted a dinghy with fully submerged foils employing manual incidence control for stabilization and manœuvring. This craft is illustrated in Ref. (2).

Inherent Draught Control of Incidence, without Mechanisms

The system due to the Frenchman, V. Grunberg, is shown next. It was patented in Great Britain in 1934. Support is supplied by planing floats forward and a completely submerged hydrofoil aft, which is fixed relative to the hull. The planing bodies must follow the surface of the sea provided that conditions are not so severe that they bury or skip off at high speed. For example, if at a given speed the foil sinks, the craft pitches about the planing bodies and increases the incidence of the hydrofoil which is fixed to it, so that a restoring increment of lift is generated.

The system thus has an inherent incidence control feature without the employment of any mechanisms or special sensing devices. Model tests made in the Saint-Cyr tank, and published in 1937, demonstrated its feasibility, but French development seems then to have been discontinued.

Since then there have been several independent instances of the idea being studied and improved upon by other investigators. Such research was prompted by the simplicity of the system which provides the most straightforward control of incidence and inherent stability in pitch. Also planing bodies can behave better than forward hydrofoils in following sea conditions.

An objection to the system as shown in the patent is that the hydrofoil provides no stability in roll and it has been found that the front planing bodies must then have a track width almost equal to the longitudinal distance between them and the hydrofoil. This requires a large overall width and prevents the bodies being located beneath a conventional hull.

Another, and perhaps somewhat perfectionist, argument is that hydrofoils largely eliminate the pounding sustained by high-speed planing craft, and that it is therefore objectionable to retain forward planing bodies, which are likely to have pounding and skipping tendencies associated with them, and which also have poorer lifting and resistance characteristics than hydrofoils. In the Grunberg system, however, only about 10 per cent of the all-up weight is supported by the planing bodies, and the patent shows them mounted on shock absorbers.

In 1938 a patent was taken out by the late Dr. Allan and William Denny Brothers Limited, which referred to a scheme employing planing support forward and a hydrofoil aft. This scheme had a number of resemblances to the Grunberg system. As far as the author is aware there has been no publication of any information that would indicate any further British interest in the principle.

Inherent Draught Control of Area, using "Monoplane" Foils

The particular advantage of "draught control of area monoplane" configurations is the low resistance obtained by using simple high aspect ratio hydrofoils throughout.

The appropriate patent, illustrated in Fig. 1, is that of Frhr. H. von Schertel (Baron Hans Schertel von Burtenbach), published in Great Britain in 1937. He started experimenting in 1927 and, following tests with seven different boats, achieved his first practical solution in 1936. The most characteristic feature is the employment of two simple hydrofoil units, of about equal area, placed one at the stern and the other close to the bow. The units are of "hoop" type, in which there is a single member whose dihedral varies laterally, giving stability in roll, and whose ends are turned back to attach to the hull. The turned-back ends, having anhedral, resemble the high roll stability Pegna foils, already referred to, which were proposed at about the same time. The hydrofoil chord, section shape, and setting may also vary laterally, partly for structural reasons. Longitudinal stability is provided by change of foil lift with attitude and with the variation in immersed foil area, that occurs with change of draught, at a given speed. This latter feature provided by monoplane hydrofoils, instead of ladders, characterizes the craft described in this section. Foils that immerse more area as draught increases are often described as "surface-piercing."

Until near the end of the last war, Schertel and the German shipbuilder Sachsenberg collaborated in the design and construction of a number of boats. Research and design work were directed by Prof. Weinblum. The foils were, in general, made of steel, and in some cases were fitted with hydraulically controlled ailerons. The following vessels were tried out over a period of seven years on lakes, rivers, and in the Baltic, and many improvements were introduced.

Type	Length, ft.	Displacement, tons	Speed, knots
—	23	1·2	30
KoBo	32·8	2·8	38
TS 1–5	38·1	5·6	40
VS 6	52·5	17·0	48
VS 8	105	80·0	43
VS 10	92	45·0	60

Ref. (2) contains photographs of both the 17-ton patrol boat VS–6 and the 80-ton tank transport VS–8, in foilborne condition. The performance figures are as provided by the Supramar Company, Lucerne, Switzerland, of which Schertel is now a director.

None of the German craft was used operationally, undoubtedly in part due to non-technical considerations. The VS–8, which was apparently under-powered, fell off the foils in some following sea tests, but was very stable in head seas. Owing to malfunctioning of the steering gear, it was damaged by hitting a sandbank and was beached.

It was decided to concentrate development on the VS–6, and a modified stern foil was recommended to improve stability and perhaps to overcome troubles experienced in following seas. It has been suggested that any craft having the front and rear foils about equidistant from the centre of gravity will experience serious difficulties in following seas. The very successful post-war developments of the Supramar Company, which include a modified stern foil, show this view to be incorrect.

The location of "surface-piercing" hydrofoils about equidistant fore and aft of the craft centre of gravity is a definitive characteristic of the Schertel configurations described, but the employment of hoop foils alone is not. Dr. Otto Tietjens developed a system having a main "hoop" foil somewhat forward of the craft centre of gravity, and a smaller stabilizing foil at the stern. The latter was in general of fully submerged type, carried on a single strut, and might be steerable or carry an elevator. A small runabout using this system was built and operated in America by J. Herz in 1932, and a larger boat was constructed and tested near Berlin in 1936. Speeds of about 24 knots are said to have been attained.

During the last war, a craft, designated the VS–7, was built in Schleswig, to the Tietjens system, and tested in comparison with the Schertel VS–6. They both had the same displacement of 17 tons, but the VS–7 proved the faster, reaching a speed of about 55 knots. Its stability and manœuvrability were much poorer, however. Tietjens has claimed that both the lateral and longitudinal stability of his system were very good. To ensure the latter, the rear foil was set at a higher attitude than the front foil, and had a lower rate of change of lift coefficient with attitude, but model tests have suggested that aeration or cavitation might cause longitudinal instability. At least one of the later Tietjens foils was swept back from the hull attachments so that the attitude automatically reduced with increase in speed, and prevented the main foil rising too high out of the water. This was intended to combine high lift at low speed with good cavitation characteristics at high speed. It also helped to retain lateral stability.

As long ago as 1904 an American patent for a system, somewhat resembling that of Tietjens, was granted to a man named Thompson. As recently as 1947 a 20-ft. craft based on the same idea, but in a version due to Hampden and MacPherson, was built by the firm of Camper Nicholson and tested in Portsmouth Harbour up to speeds of about 38 knots. A considerably more distant relative of both the Schertel and Tietjens systems has been devised by the Baker Mfg. Co. of Evansville, Wisconsin, mainly for use on small pleasure craft. Simple hoop foils made of extruded aluminium alloys are employed. The hoops have straight Vee lower portions and vertical sides, and are simply supported on circular section horizontal tubes, which form the top members. Roll stability is achieved by placing hoops, not under the hull as in the systems previously described, but on either side. In the normal arrangement a third hoop is located under the hull, forward or aft of the pair, to give longitudinal stability. A 24-ft. research craft employing four such foils, arranged in two pairs, is shown in ref. (4), from which the details that follow have been obtained. The craft, called *Highpockets*, is powered by a 125 hp Chrysler Crown engine, and its maximum speed without hydrofoils is 20 knots. On foils it reaches 36 knots, and can proceed at 32 knots in waves as high as 4 ft. In 5-ft. ocean swells off Florida, it outran a 63-ft. air-sea rescue boat having the same rated speed.

Modern examples of the four basic design principles, shown in Fig. 1, will now be commented upon.

Current Examples of the four Basic Systems

It will be appreciated that only a limited amount of the information on some of the craft now to be described has been released. Published figures will be given where available.

The ladder system given in Fig. 1 is that of the Carl XCH–4. The photograph shows the large dihedral, and that the second rung is running on the surface. The single central supporting struts, the comparatively low aspect ratios of the rungs, and the sweep back, are all noteworthy. The influence of transonic aerodynamics is apparent, and the design has a most pleasing cleanliness and simplicity in appearance compared with its ancestor. The aeronautical flavour of the propulsion system, and its implication for high design speed, will not have escaped notice.

The most recent craft employing the Bell–Baldwin system is the *Bras d'Or* which, as already mentioned, was launched in ril 1957, and is seen in Fig. 2 undergoing functioning trials the Menai Straits, North Wales. This boat has now been t to Canada, and is undergoing extensive research trials re.

The craft specification required the essential features of the l-Baldwin hydrofoil system to be retained. There are three l units, the rear one of which is steerable. The front ladders ve four rungs and the rear one three, which is a considerable luction in numbers compared with the HD–4. The rungs are -shaped in front elevation with considerable dihedral, and ve relatively low aspect ratio with some sweep-back. The idence settings increase from the lower to the upper rungs. e boat is 59 ft. long and weighs 17·5 tons. It is powered by o Rolls-Royce "Griffon" engines which have been modified suit marine conditions. The hull is constructed of aluminium oy.

The recent 20-ft. United States Navy research craft, that is mpared with the Meacham patent in Fig. 1, employs fully bmerged foils whose incidence is controlled by electrical aught-sensing devices instead of mechanical ones. As the ater level at either of the two front struts rises, resistances are orted out, and a step-by-step servo actuates the corresponding ort or starboard hydrofoil unit. Disturbances in both pitch d roll are handled in this way, without the foils tending to rface. The craft will also follow a wave contour, provided at the servo system can cope with the frequency of encounter. The rear foil is also fully immersed, but is not necessarily cidence controlled in the above sense. Since the front foils e designed to follow the surface of the sea, a fixed fully-bmerged rear foil will provide the craft with inherent pitch ability of the Grunberg type.

Several methods of incidence control using mechanisms have een investigated in recent years. An altimeter has been used determine draught, and foil incidence change actuators have een controlled by an autopilot.

A modern system employing mechanical sensing devices has een developed by Mr. Christopher Hook, and given the pro-rietary name *Hydrofin.* His basic patent specification was odged in 1942. The initial development was undertaken in frica, using an old flying boat hull, continued in Cowes, Isle f Wight, and afterwards in the United States, where conversion its for small craft are marketed. One research craft employing is system is 16 ft. long, and has operated well in a bad 4-ft. hop off Miami Beach.(4) Two hydroskis are mounted on long ockey arms ahead of the craft, and these are linked, mechanically r hydraulically, to fully submerged main hydrofoils, each of which supports about one-third of the craft all-up weight, in ully foilborne conditions.

Mr. Hook has described his forward hydroskis as "anticipators" which foretell the approach of a wave from ahead, before it reaches the hydrofoils. In practice, and as in the case of other incidence control systems, in which the sensing devices are placed closer to their foils, the *Hydrofin* behaves satisfactorily at other headings to the sea. It is stated to be particularly good in following seas, presumably because the slower rate of encounter gives the hydroskis more time to respond, and there is no danger of them skipping off the wave surface, as they might do at high rates. A patent of 1945 covers the provision of damping and of a manually controlled incidence setting adjuster in the linkage. A fully-submerged fixed after foil is integral with the propulsion system, and again provides Grunberg type inherent pitch stability.

The current exponent of the Grunberg system, shown in Fig. 1, is the "International Aquavion" company's *Aquastroll* 24/40. This employs two hydrofoil-hydroskis forward, set well into the sides of the hull. They plane on the water surface at speed. Adequate rolling stability has been achieved by replacing Grunberg's fully submerged foil by a hoop. This also increases pitch stabilization by adding increase in foil area with draught to the inherent increase in foil incidence. The Aquavion system is due to two Swedish engineers, Almquist and Elgstrom, and it is understood that theirs was an independent invention made without knowledge of Grunberg's work. Activities began in Sweden and were for a time controlled by a Swedish joint stock company entitled Supermarin. The first prototype was built in 1948 to carry 17 passengers. A small aluminium alloy craft using almost the same system, but apparently with a single planing foil having some dihedral forward, has been designed and built by Marstrands Mekaniska, Werkstad, Sweden.

In 1950 a pleasure craft, using the system of Almquist and Elgstrom, 57·4 ft. in overall length and having an unladen weight of 9 tons, was built in aluminium at Lidingö. It was called the *Pilen.* The diesel engine developed 860 hp at 2,800 *rpm,* and a craft range of 300 miles is quoted. During a trial run from Stockholm to Finland and back, carrying 20 passengers, 3 crew and ballast, winds up to 27 knots and very rough seas were encountered. Even so, the average top and cruising speeds were in excess of 37 knots and 31 knots respectively. As a result of this trial the craft was accepted by the Société Franco-Khmere de Navigation of Saigon.

The *Aquastroll* 24/40 is a practical operational craft. It was demonstrated in January 1957 to representatives of various organizations. The author was one of these representatives and had the pleasure of riding in the vessel on a trip between Rotterdam and the Hook of Holland. The remarks that follow, and the relevant performance data given in Table I, are formulated from the extensive information given in the technical brochure issued by the Aquavion Company.

The steering and transmission are provided by orthodox rudders and inclined shafts of rather high angle. The hull is of round bilge form forward, but has a fairly deep step amidships and hard chines aft, to facilitate a straight shaft run from engine to propeller and assist the hull to break clear of the water when becoming foilborne.

The front "wings" carry only a little of the craft weight and are so designed that when the water is smooth a small part of a wing acts as a hydrofoil, another small part as a planing surface, and the remainder is out of the water. When the unit is pressed down into the water, the area giving planing lift is greatly increased, and finally acts wholly as a hydrofoil, in which condition the lift developed is about eight times the undisturbed value.

The craft follows the contour of waves exceeding two and a half times its length, but the front wings cut through the crests of breaking waves and waves that are shorter than the boat length. Tendency for the front wings to skip in short waves is checked by a small fully submerged stabilizer hydrofoil mounted near the stern and forming part of the shaft and rudder bracket system. Vibration and shocks are alleviated by special construction and rubber mounting of the front wing system. The craft will sit down in high waves of between one and one and a half times its length, but the surface following characteristics of the front wings cause an immediate increase in incidence and restoration to foilborne conditions. Quartering and beam seas have no special effect.

The Société Générale de Surveillance S.A. of Geneva made a trials inspection during January 21, 1957, on the rivers Nieuwe Waterwey and Oude Maas, in Holland. This inspection justifies the figures shown in Table I.

Maximum speed with two 250 shp diesels (the craft is designed for two 300 hp engines) was 32·16 knots.

Distances to stop from full speed, with and without the use of reversing engines, are about 0·9 and 1·7 boat lengths, respectively! This extraordinarily high "braking power" is a feature of many hydrofoil boats due to the large attitude and consequent resistance that can be obtained as the craft sits

TABLE I

SOME DETAILS OF CURRENT OPERATIONAL HYDROFOIL CRAFT

Craft	Aquavion *Aquastroll* 24/40	Supramar *Freccia d'Oro*	Supramar P.T. 10 or POT. 10	Supramar P.T. 20 or POT. 20
Length overall, L (ft.)	47·08	46·6	51·0	68·0
Maximum beam of hull, B (ft.)	12·50	10·2	11·2	15·8
L/B	3·77	4·58	4·55	4·31
Width over hydrofoils (ft.)	19·70	14·9	19·4	25·6
Draught, floating (ft.)	6·25 unloaded 6·73 fully loaded	5·5	6·6	8·5
Draught, cruising (ft.)	3·28	2·4	3·0	3·9
Passenger capacity (approx.)	27 (normal load)	28	36	70
Engines	2 × 300 hp diesel	550 hp diesel	600 hp diesel	1,350 hp diesel
Shaft angle, deg. (approx.)	10	—	12	10
Maximum speed (knots)	38	45·8	42	43
Cruising speed (knots)	—	37·8 at 350 hp	35 at 480 hp	38 at 1,100 hp
Construction material, hull	Aluminium alloy	Aluminium alloy	Aluminium alloy	Aluminium alloy
Construction material, hydrofoils	Aluminium alloy	Special steel	Special steel	Special steel

down stern first. The time from rest to full speed is about 45 seconds.

The diameter of the turning circle at full speed is 7 boat lengths. The craft does not heel appreciably in these conditions. The craft can turn on its own centre with one engine half ahead, and the other full astern. The longitudinal and transverse stabilities were extremely good when running close to a number of sea-going vessels in waves up to 4 ft. high. The craft requires no special training to handle it, and can be manœuvred better than ordinary boats in crowded waters and dock basins.

On the occasion when the author attended a demonstration of the *Aquastroll*, the following facts and figures were obtained:—

The Dutch Instituit T.N.O. voor Werktuigkundige Constructies, Delft, has made measurements of craft weight and speed. The maximum speed at a weight of 15·83 tons was 30·9 knots (average of six runs). The hull lifted clear of the water, at an engine *rpm* of 1,600, in 18 seconds from a "standing start," when the weight was 15·16 tons, while a speed of 30 knots, at an *rpm* of 2,000, was attained in 34 seconds. The weight in a condition ready for service, with full tanks, but without passengers, was found to be 13·46 tons. The maximum additional load (payload) at which foilborne conditions could be obtained without labouring was 3·24 tons. This payload is 20 per cent of the maximum all-up weight of some 17 tons. The engines used were said to be heavier than a suitable alternative, which would have permitted a payload of 25 per cent. On the other hand, the hydrofoils were made of aluminium alloy, and hydrofoil craft designed for speeds of about 40 knots generally require steel hydrofoils, which are heavier. The fuel weight with tanks full is 0·8 tons, which is enough for about 10 hours' endurance or 300 miles range. The total disposable load of payload and fuel is thus 25 per cent.

The best speed obtained in timed runs at a displacement of 15·6 tons was 31·8 knots at 2,100 *rpm*. Assuming that the engines were operating at their full rated power, totalling 500 shp, corresponding to 2,100 *rpm*, the corresponding value of η (L/D)* is 6·82.

Thus if propulsive efficiency = 0·5, 0·6, lift to drag ratio, L/D, lb. per lb. = 13·6, 11·4, so that an L/D of about 12·5 would seem to be achieved.

The largest waves encountered were about 2 ft. high and 35 ft. long. The front "wings" appeared rather lively when the craft ran across a regular chain of waves, and threw up a considerable amount of spray, which should not, however, be a serious matter.

The Aquavion Company is now offering a new design 27 ft. 7 in. long and 9 tons all-up weight, in which the hydrofoils only extend a little way outside the hull beam of 11 ft. 11 in., while the front wings are entirely within it, and can easily be removed and replaced in case of damage by collision.

This account of the *Aquastroll* can best be concluded by a quotation from the technical brochure of the Aquavion Company:—

"The Aquavion is based on the only possible system, which makes any readjustment of its wing superfluous because the angle of attack of the wings and their lift adapt themselves automatically to the situation of the moment, as a result of the slight change of the 'trim' of the Aquavion itself."

The present author would agree that the Aquavion conception is a very promising, simple, and robust one, but absence of mechanical controls should not be regarded as too much of a virtue. Aeroplanes require elevators and ailerons, and it seems reasonable that effective incidence adjustment of hydrofoils should be admissible for various operational roles and conditions.

In any case the claims of the other very promising current developments must also be considered. The last picture on Fig. 1 shows the Supramar *Freccia del Sole* (Arrow of the Sun), Type P.T. 20, 70-passenger ferry operating in the Straits of Messina. Before considering this craft in more detail, it is well to mention the earlier post-war achievements of the Supramar Company.

The Schertel–Sachsenberg system, as it is officially called in the informative Supramar technical brochure, has a long and continuous history of improvement, with which the original inventor, Frhr. von Schertel, has been associated throughout. The first phase from 1927 to 1945 has already been described. At the end of the war, the Sachsenberg shipyard at Dessau-Rosslau passed into Russian hands. Immediate post-war conditions prevented commercial development of the system for some seven years, at the end of which a new company, with both German and Swiss directors, was created in Switzerland.

A new boat, the *Freccia d'Oro* (Golden Arrow), was designed for passenger service on inland waters. It incorporated the company's latest ideas and results of research, and was a considerable advance on the technical achievements of the previous craft. After extensive tests and demonstrations on the Lake of

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* The L here refers to Lift, not length, of course, and will always do so in this paper when written in the expression L/D. The commonly used notation for lift to drag ratio in lb. per lb. has been used since test results on isolated hydrofoils are almost always presented in it.

Lucerne, the boat joined the fleet of the official Swiss and Italian teamship Navigation Company of Lake Maggiore, where it was used in the daily international passenger service between Locarno–Pallanza and Arona. This is believed to be the first ime in the history of shipping that a hydrofoil boat has been used for regular passenger transport.

Some details of the *Freccia d'Oro* are included in Table 1. Other figures of interest are as follows:—

Displacement, fully loaded	9·5 tons	
Economical speed, at 170 hp	26·7 knots	
Range at economical speed	324 nautical miles	
Heeling moment (lb. ft.)	6,500	9,030
Maximum angle of heel (deg.)	8·35	9·15
Speed for maximum angle of heel (knots)	18·0	18·8

Speed (knots)		10	20	30	40
Craft lift/drag ..	at a displacement of 8·8 tons	11·9	12	11·6	8·5
Propulsion efficiency, per cent		50	67	70	66
Diameter of turning circle, in boat lengths		4	5·2	10	35
Approximate maximum wave height in which operation can continue at full engine power (ft.)		3·0			

When turning, the craft banks inwards, which is the natural but not the conventional direction.

The author had the good fortune to attend demonstrations of the *Freccia d'Oro* on Lake Maggiore in early December 1954, and was greatly attracted by the smooth performance, the ease of handling, the lightness of the spray from the hydrofoils, and the flatness of the wake. The craft approached and edged into landing stages without fuss, bringing the hydrofoils neatly in between adjacent piles. Unfortunately the calm weather prevented any assessment of performance in heavy waves.

The Messina ferry shown in Fig. 1 has a displacement of 28 tons; other particulars are as the P.T. 20 given in Table 1. The transmission system comprises a vee drive and inclined shaft. The propeller is ahead of the shaft bearing, which is carried at the centre of the rear hydrofoil, and is combined with the lower pivot of the rudder. The hull has sharp chines with a small breaker step amidships, ahead of the station where the shaft enters the keel. The hydrofoils are manufactured from special steel by Deutsche Edelstahl, Krefeld. Similar arrangements were used on the *Freccia d'Oro*.

During the summer of 1956 the *Freccia del Sole* ran for several months in continuous service as a ferry across the Straits of Messina. On another occasion it travelled the 50 miles from Messina to the Island of Stromboli at a speed of 39 knots. Waves about 8 ft. high were encountered. These can be taken from ahead, while 5-ft. waves are said to be acceptable at any heading. The hull is light and flexible, but this does not appear to be a disadvantage. It permits a payload plus fuel of about 25 per cent of the all-up weight. The stability in heel is very good, and passengers can crowd to one side of the craft without serious effect.

The author travelled on the craft in the Messina straits early in July 1956. Continuous speeds up to 38 knots were employed, but unfortunately waves did not exceed about 2 ft. in height.

A recent Russian hydrofoil boat was described in the September 27, 1957, issue of *Engineering*. A quotation of particular interest from the article states: "The air cushion under the hull serves to minimize pitching, rolling and other disturbances." At the end of the last war, information and some personnel who had been connected with the Schertel–Sachsenberg system came into Russian hands; the Russian boat appears to be based upon the German ideas. The craft is said to have carried 66 passengers a distance of 200 miles, along the river Volga, at a speed of nearly 43 knots.

Economic Considerations

During the summer seasons 1953 and 1954, the *Freccia d'Oro* travelled more than 27,000 nautical miles and carried well over 25,000 passengers. The Supramar company publish an interesting cost assessment for a passenger service, covering a daily distance of 150 nautical miles in 4 working hours, for 8 months (240 days) of the year. Two P.T. 10 craft are assumed, and these, as Table 1 shows, are a little larger than the *Freccia d'Oro*. Utilization is taken to be 60 per cent of capacity payload, giving an average of 23 passengers. The depreciation period is only 8 years for both boats and engines.

The economics based on Swiss conditions are:—

Operating cost	70 per cent that of a comparable conventional craft
Investment capital	800,000 Sw.fr., say £65,300
Fare per passenger mile	0·37 Sw.fr., say 7¼d.
Profit before subtraction of taxes	211,000 Sw.fr., say £17,210,

which is 26 per cent interest on investment capital.

During August 1956 the *Freccia del Sole* is said to have carried 31,000 passengers in the Straits of Messina, and earned a profit amounting to 4 per cent of its initial cost.

The Aquavion brochure gives some cost figures also, and states that in spite of the manufacturing requirements for the hydrofoils, the purchase price is not more than 15 to 20 per cent higher than a conventional boat of the same size, and stresses the economic advantages of comparatively low resistance at high speed.

Summing Up

There are a number of performance characteristics which nearly all successful hydrofoil craft of whatever system will possess, in virtue of the inherent properties of hydrofoils. Some important features claimed for both the Aquavion and Supramar craft are given below. They provide a suitable link between the historical and descriptive matter, so far discussed, and the technical remarks that are to follow.

In comparison with conventional fast boats, hydrofoil craft have much less resistance, especially at high speed. The retarding effect in waves, not exceeding the design height, is almost entirely eliminated, and speed can be maintained virtually unchecked.

Response in disturbed water is not serious, and once foilborne, conditions improve with increase in speed. The ride is considerably more comfortable than in an orthodox high-speed craft. The Supramar brochure compares the behaviour to that of an aircraft in bumpy air, whereas a displacement craft is like an airship buffeted by every gust.

The acceleration is high and the stopping power remarkable. The hull rises gradually and quite smoothly out of the water with increase in speed.

Stability is unusually good. At low non-foilborne speeds the hydrofoils act as stabilizing fins.

The hydrofoil boat is easy to handle, and even at maximum speed there is so little wake that narrow, relatively shallow and congested waterways can be traversed without any danger to other craft at moorings, or under tow, or to embankments.

Since the hull is out of the water at high speed, the length-to-beam ratio can be varied within wide limits to suit different roles.

The author accepts the general validity of these claims from personal observation and study, but certain qualifications must be made. He has, for example, never had the opportunity of experiencing behaviour in limiting rough sea conditions.

Much of the remainder of this paper is concerned with the technical "facts of life" to which all the designs need to conform. Other qualifications will emerge in the course of it.

The Special Advantages of Hydrofoil Craft

Introductory Remarks

Hydrofoil units by themselves are found to have appreciably higher ratios of lift to drag than the best high-speed hulls, and unlike a hull they generally have a resistance in waves which is not greatly in excess of that appropriate to calm water conditions. Hydrofoil boats will thus achieve the resistance and seakeeping advantages mentioned in the previous paragraphs if the hull can be lifted well clear of the water at intermediate and high speeds.

A systematic understanding of the technical reasons underlying the advantages, and of the detailed design features necessary to achieve them, requires a discussion of the hydrofoil lift and drag, the minimum speed at which fully foilborne conditions are obtained in calm water, and the fundamentals of behaviour in waves.

Since Ref. (2) gives a lengthy discussion of these points, only a summary, directed particularly to performance aspects, will be given here. Associated technical problems such as cavitation and stability are considered in later sections of the paper.

Finally, the sample resistance and design wave height curves of Figs. 3 and 4, respectively, will be discussed. They refer to two particular types of craft. A quantitative comparison between all the four systems shown in Fig. 1 has not been attempted through lack of suitable published or unclassified information.

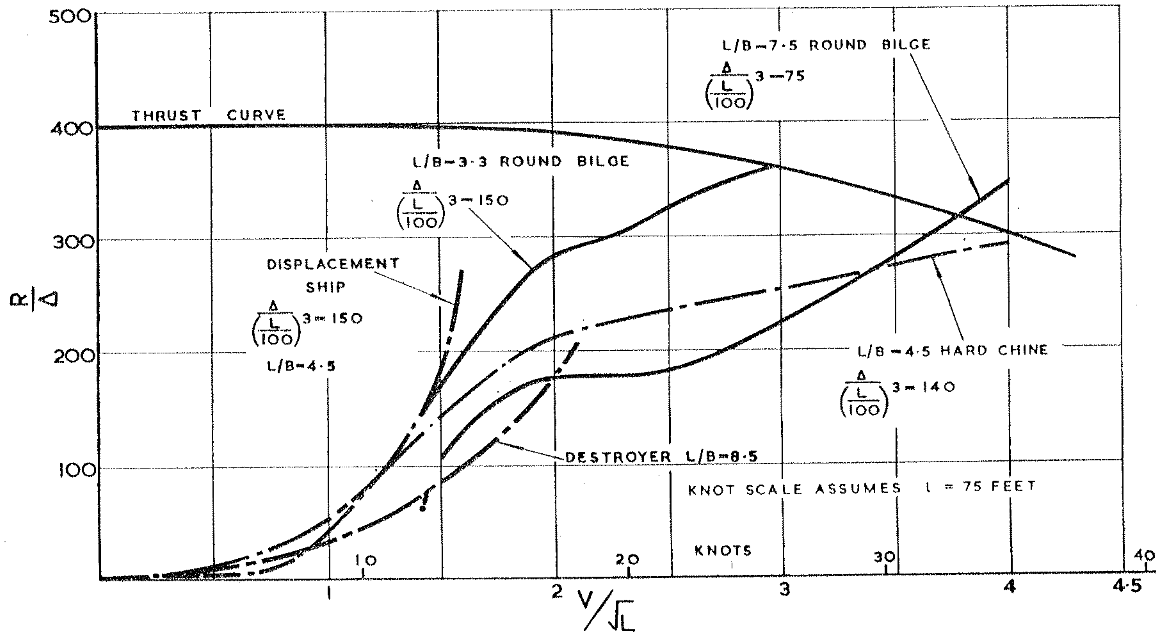


FIG. 3A.—DRAG CURVES OF ORTHODOX DISPLACEMENT AND PLANING CRAFT

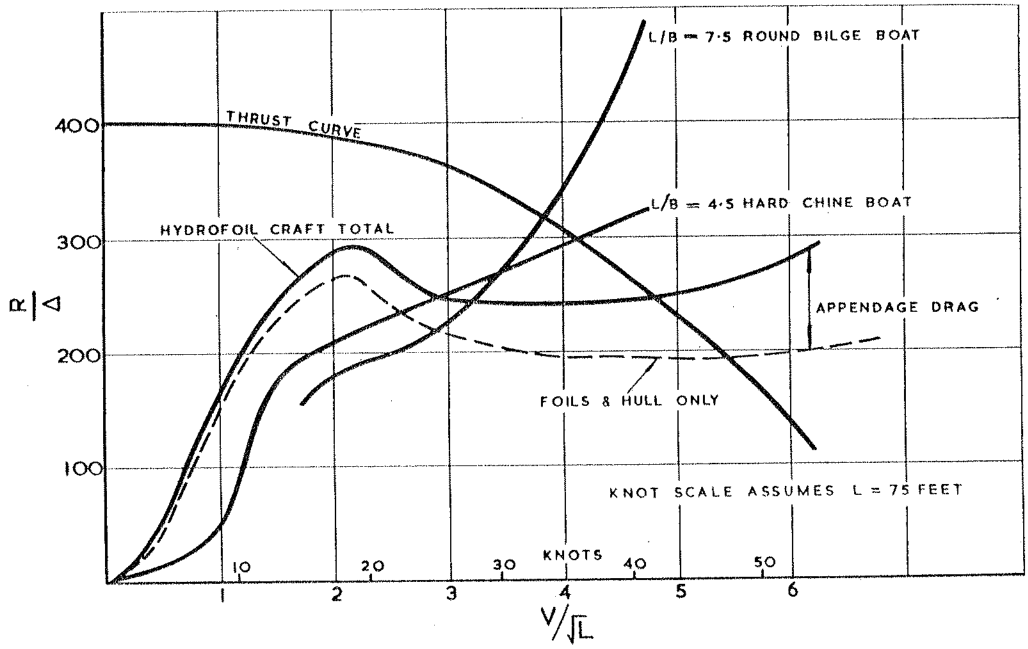


FIG. 3B.—COMPARISON OF THE DRAG OF A HYDROFOIL BOAT WITH ORTHODOX CRAFT OF APPROXIMATELY THE SAME LENGTH

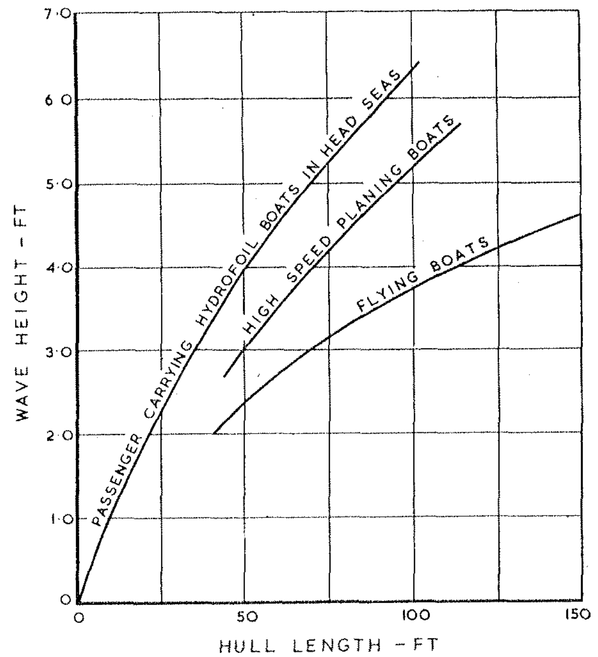


FIG. 4.—VARIATION OF DESIGN WAVE HEIGHTS WITH HULL LENGTH FOR VARIOUS WATERBORNE CRAFT

Some Fundamental Aspects of the Lift and Drag of Hydrofoil Units

The range of variation of lift that can be generated by a hydrofoil unit is of basic design importance. Since boat hydrofoils are only aerofoils "flying" just below or intersecting the surface of the water, aerodynamic theory can of course be employed to calculate many features of the lift and drag. The general considerations are stated here, without formulae, since the latter are given in any good textbook on aerodynamics. The most striking difference between the air and water behaviour is the much smaller area required to generate a given force in water. At a given speed this is decreased in the ratio of the densities of water and air, approximately 800 to 1.

Special allowance must be made for the presence of the free surface, and for cavitation and aeration effects (see page 17). The influence of the former on lift and induced drag can be allowed for by the usual image vortex methods, treating the surface as a horizontal free boundary of constant pressure. In the case of ladder foils there will also be some "cascade" interference effects, especially on lift and induced drag, which will vary with draught. Cavitation has many analogies with conditions occurring in transonic aerodynamics.

The design lift coefficients employed for hydrofoils should be as near as possible to the values giving maximum L/D, and should allow for the generation of a good reserve of lift, when incidence increases above the design value, so as to provide stability and adequate response in waves. Since foils that intersect the free surface also provide reserve lift by increase in submerged area with draught the variation of design C_L with speed can differ from that necessary for fully submerged foils. Whatever the system, a reserve lift of two or three times the craft all-up weight irrespective of speed has been found necessary. In very general terms, the stalling lift coefficient of a hydrofoil, based on submerged area, is of order 1·0. Lift coefficients in the range 0·2 to 0·3 are thus the highest that can be used at low speeds. At very high speeds cavitation limitations demand lower values still.

As will have been gathered from the historical section, and will be considered in more detail later, hydrofoil boats do not normally exceed speeds of 40 to 50 knots nor lengths of, say, 70 ft. Thus the $V/\sqrt{L}$ of a large craft will be about 6, whereas a small runabout 20 ft. long and travelling at 30 knots has a a value of 7. To avoid the disadvantageous effects of hull immersion at high speed it is necessary to become fully foilborne at a $V/\sqrt{L}$ of 3 at the very most. This is illustrated by the resistance curves for craft given in Fig. 3. It follows that the "take-off" speed, as it is sometimes called, must not be greater than about half the maximum speed. Representative values that have been quoted for a Supramar craft are: take-off, 28 knots; cruising, 43 knots; maximum, 49 knots. Since lift varies with speed squared at a given lift coefficient it is clear that at take off the immersed area must be about four times that employed at high speed if constant C_L is to be used, whereas in a fully submerged system four times the lift coefficient must be used.

Ladder systems can meet the first condition, but simple hoops of the Supramar or Aquavion main foil type tend to require excessive span unless the change in immersed area between take-off speed and cruising speed is about 2 to 1. Thus they employ C_L's at the two speeds which are also in about the same ratio.

The resistance of a hydrofoil unit is made up of induced, wave, profile, and parasite drags, the two latter have both frictional and form components. The induced drag and profile drag of a hydrofoil vary directly and inversely with C_L at a given lift, so that a moderate variation of C_L around the value for maximum L/D will not greatly affect the lift to drag ratio. A large increase in C_L can, however, appreciably increase the total drag from this source. The induced drag is inversely proportional to the effective aspect ratio, including the end plate effect of end struts, so that immersed foil areas of large span relative to chord are particularly efficient. Vertical struts have profile drag, and if they are inclined to the stream they will also sustain induced drag related to the sideforces they produce. Parasite drag includes interference drag of strut and foil intersections, and spray drag of struts.

Spray and wave drag cannot be estimated by standard aeronautical techniques. A number of tests have been made to determine strut spray drag, including the effect of profile and rake angle. Some results have been published, as for example by Coffee and McKann.$^{(5)}$

Wave drag of hydrofoils was investigated by Keldysch and Lavrentiev$^{(6)}$ in 1934. It is only important at low speeds, and especially around $V = 6{\cdot}7\sqrt{C}$ knots, where C is the hydrofoil chord in feet.

The power available at full speed is usually considerably greater than that required for take-off, but unless a controllable pitch propeller, with its attendant complications, is used, the latter resistance may be critical. It is important that the reserve thrust available at take-off shall be sufficient to give a good acceleration in rough seas, in which condition the hull contribution to resistance is considerably increased. Otherwise the time and distance from rest to take-off will be inconveniently long, and a craft that can proceed at speed in a seaway will not get up again if it ceases to be foilborne.

If the design speed appreciably exceeds 40 knots, cavitation considerations demand hydrofoils of very thin section, which causes both structural and hydrodynamic difficulties that can be overcome by the employment of hydrofoils of lower aspect ratio or the introduction of additional struts. High-speed operation in rough water introduces asymmetric loading conditions which also demand additional structural members. One solution is to adopt a ladder arrangement, but in any case drag is increased, especially at the lower speeds even in calm water and when cutting through a wave crest, since a relatively large strut area and a number of strut hydrofoil junctions are submerged.

The rough water potentialities of a hydrofoil boat naturally depend upon keeping the hull clear of all but occasional contact with green water. It will not behave well if the bow comes squarely into impact with a wave slope.

If waves are sufficiently long, any hydrofoil craft will follow them without difficulty, and if they are considerably shorter than the craft length it does not respond sufficiently rapidly to follow them and so cuts through the crests. In either case the behaviour is satisfactory. Critical conditions occur when the waves are of order once or twice the hull length, and may be particularly serious in following seas since the craft speed relative to the crests is so low that it has ample time to adjust its attitude to the wave slope, and so reach a condition of maximum nose down pitch, at which the margin of reserve moment opposing diving is at a minimum.

The orbital motion of fluid particles which occurs in waves is also of significance. The motion is upward and downward on the forward and rear wave slopes respectively, defined relative to the direction of wave motion. A head sea, or a following sea which catches up with a craft, thus increases the effective incidences of the hydrofoils, as they attempt to rise to a wave, and assists them; whereas a following sea moving slower than a craft reduces the effective incidence and tends to make the foil plunge in to the facing wave slope. Once the crest is passed the incidence changes continue to assist the craft to follow the surface contour in the former case, and ride away from it in the latter.

If the hydrofoil system chosen is not one that follows the wave contour closely, the responses in heave and pitch can be comparatively low. This allows the craft to be designed to travel along an almost horizontal path such that the irregular surface of the sea is located between the hull keel and the lowest points of the hydrofoil units. However, the parts of the foils required to remain in the water at design speed must in general be positioned rather far below the hull to ensure adequate water clearance.

If, on the other hand, a wave following system is employed, the foil depth below the hull can be reduced but response can be greater. These remarks apply particularly to the medium-sized and larger craft. Wave length to height usually exceeds 15 or 20 to 1, and waves shorter than 100 ft. in length are comparatively rare unless the wind is just beginning to rise or the fetch is less than 100 miles. Thus small hydrofoil pleasure or research craft, of about 20 ft. overall length, will rarely encounter waves of greater relative mean height than would be possible for larger craft.

The hydrofoil boat resistance shown in Fig. 3 is appropriate to a craft designed for a speed of over 50 knots, and for this reason lies somewhat above the minimum obtainable. Fig. 4, on the other hand, gives a variation of design wave height with boat length for a family of craft designed for speeds up to about 40 knots, and having very competitive resistances.

Fig. 3A does not refer to hydrofoil craft. It is intended to provide a basis for judging the hydrofoil resistance of Fig. 3B in terms of the characteristics of orthodox vessels. Nevertheless, Fig. 3A has a considerable interest on its own account. It will be observed that the three conventional high-speed hulls whose resistances are shown vary both in length to beam ratio and in displacement length ratio, $\Delta/(L/100)^3$, as follows:—

L/B	3·3	7·5	4·5
$\Delta/(L/100)^3$ ..	150	75	140

They are, nonetheless, considered suitable for comparing with one another and with a hydrofoil boat, since they represent common practice for the respective types of design. Furthermore, $(L/B) \times \Delta/(L/100)^3$ has the values 495, 562, and 630 respectively, so that for a given displacement $L^2 B$ does not vary very greatly. This is the rule followed closely by the forebodies of modern flying boat hulls, and is determined by conditions around the hump speed where the attitude is a maximum and planing forces become predominant.

The resistance curves are plotted against $V/\sqrt{L}$. For illustrative purposes, an equivalent in knots for an L of 75 ft. is shown also, but the results equally apply for other lengths under conditions of dynamic similarity. The thrust curve, on the other hand, should be taken with the scale of speed in knots, and is included merely to illustrate a representative variation for a craft of moderately high speed. Its intersections with the resistance curves do not have a special significance.

To obtain comparative maximum speeds for the various hulls, two assumptions are necessary. A reasonable assumption, for example, is that each craft can achieve the same maximum value of ehp/Δ, by suitable choice of propeller, irrespective of the corresponding speed. Now

$$\frac{\text{ehp}}{\Delta} = \left(\frac{1}{326}\,\frac{R}{\Delta}\,\frac{V}{\sqrt{L}}\right)^{\sqrt{L}} = \left\{\frac{1}{32\cdot6}\,\frac{R}{\Delta}\,\frac{V}{\sqrt{L}}\left[\frac{(L/100)^3}{\Delta}\right]^{1/6}\right\}\Delta^{1/6}$$

so that for a given ehp/Δ, V follows from the curves once $\sqrt{L}$ or $\Delta^{1/6}$ have been fixed. Comparison of a number of craft all having the same displacement is in general significant, comparison at constant length much less so.

Let ehp/Δ equal 32, Δ = 60 tons, then

L/B	$\Delta/(L/100)^3$	L, ft.	$V/\sqrt{L}$	V, knots	R/Δ, lb. per ton	(Lift/drag), lb./lb.
3·3	150	73·6	3·25	27·9	374	6·0
7·5	75	89·5	3·62	34·2	299	7·5
4·5	140	75·3	4·07	35·3	295	7·6

whereas for L = 75 ft.

L/B	$V/\sqrt{L}$	V, knots	R/Δ, lb. per ton	(Lift/drag), lb./lb.
3·3	3·21	27·8	370	6·1
7·5	3·78	32·7	320	7·0
4·5	4·08	35·3	295	7·6

(The intersections shown on Fig. 3A, taking L = 75 ft., give

L/B	3·3	7·5	4·4
V, knots ..	25·5	32·5	35·5)

Thus the hard chine craft has just the best maximum speed at constant displacement, and appreciably the best at constant length. As $V/\sqrt{L}$ increases above 4, the hard chine hull becomes increasingly superior, due to the rather rapid increase in resistance of round bilge hulls associated with their lower attitudes. This is shown more clearly in Fig. 3B.

At $V/\sqrt{L}$ of, say, 2·5 or less, the long, narrow, round bilge hull has the lowest resistance per ton because of its high length-to-beam ratio, but even there the hard chine hull has the better resistance at a given length-to-beam ratio, in the neighbourhood of 4. There is a considerable difference of opinion as to how generally the last result is true, and systematic model tests are required to resolve it.

It is interesting to observe how the resistances of the high-speed craft are bracketed by ship curves at the upper end of the displacement range, around a $V/\sqrt{L}$ of 1·0. The ship and the hard chine hull, both of L/B 4·5, have almost the same resistance. The destroyer at L/B of 8·5 lies below the round bilge hull of L/B 7·5. At higher speeds ship curves rise above those for high-speed craft because of the great wave resistance due to the squat produced by streamlining aft, and associated low pressures. At the very lowest speeds the same streamlining gives the lowest resistances, of course.

Turning to Fig. 3B, the better round bilge boat and the planing boat from Fig. 3A have been shown again in comparison with a hydrofoil boat whose foil system has been designed for a speed of about 50 knots. The hydrofoil boat resistance may for the moment be taken with the $V/\sqrt{L}$ scale, but this will be qualified later. Taking ehp/Δ and Δ at 32 and 60 tons respectively, as before, the speed can be calculated when L is known. From Table I an L/B of about 4·0 is commonly used on hydrofoil boats, as would be expected since their hulls tend to be of at least semi-hard chine form to facilitate take-off. Thus 75 ft. is a reasonable length for comparison purposes, and gives a V of 41·8 knots. This is over 6 knots or 18 per cent better in speed than the conventional craft, in calm water, and will in general be proportionately better still in a seaway.

The hydrofoil system design speed of, say, 50 knots is not, however, achieved. To do so with a craft 75 ft. long requires an ehp/Δ of 41·7. This value gives the conventional hard chine hull a speed of 41·8 knots, so that the hydrofoil boat is now 20 per cent better.

The value of $(L/B) \times \Delta/(L/100)^3$ at 75 ft. and L/B of 4 is 568, while values for the *Aquastroll* 24/40 and *Freccia d'Oro* are 600 and 384, respectively. Thus the former has a conventional ratio of displacement to hull size, but the latter has a large hull. This is consistent with the roles for which the craft are intended. The hull sizes of Fig. 3A are suitable for naval applications, for example, whereas the *Freccia d'Oro* is a passenger ferry and needs a large volume for economical operation.

If the lower coefficient value of 384 is assumed for a 60-ton craft and L/B remains at 4·0, the length becomes 85 ft. The ehp/Δ then required to achieve 50 knots is somewhat reduced to 39·8.

The general shape of the hydrofoil craft resistance in Fig. 3B is typical of configurations which do not use ladder hydrofoils, and clearly shows the source of the higher speeds that can be achieved for a given power. The component of resistance due to the hydrofoils and hull peaks at a "hump" $V/\sqrt{L}$ of about 2·0, and then as the hull comes clear of the water falls back to an almost constant value (less than one-eleventh of the lift in the case shown) which continues unchanged up to, say, 40 knots. The resistance is better than that of any conventional craft, in fully foilborne conditions above $V/\sqrt{L}$ of 3·0.

At speeds above 40 knots and not usually exceeding 55 knots, depending upon the details of the design, the hydrofoil resistance may show some increase due to cavitation. Care must therefore be taken in accepting estimates from curves of, say, R/Δ against $V/\sqrt{L}$ that turn out to lie in this speed range. As will be explained in more detail later, the hydrofoil resistance per ton of displacement is in general a function of absolute speed, and not of speed coefficient. Thus at low speed, where the hydrofoils are unimportant, the behaviour does to that extent obey laws of dynamic similarity. At high speeds only the appendage drag continues in part to do so, and resistance may best be referred to a scale of speed in knots. In the discussion of hydrofoil craft drag previously given the length taken gave speeds that were in any case appropriate.

The appendage drag of the rudder shafts and shaft brackets and non-lifting struts tend to increase faster than the first power of speed. However, reduction in wetted area, as hydrofoil draught continues to decrease, should make the appendage component increase more slowly than the square of speed. Even so it accounts for the greater part of the change of hydrofoil craft resistance that occurs in the practical fully foilborne speed range.

Craft such as the original Bell–Baldwin HD–4 and the Carl XCH–4, which employ air propulsion, have the important resistance advantage that appendage drag is almost eliminated. It is thus not surprising that unusually high speeds, even for hydrofoil boats, have been obtained with them. A disadvantage is the low efficiency of air propulsion at low speeds, which demands an auxiliary marine power plant if extensive low-speed running is required under operational conditions.

Although it has been stated earlier that hydrofoil craft hulls are usually of hard chine form, general shape may be influenced by the design take-off $V/\sqrt{L}$. If this lies well into the displacement region a displacement type hull, but having a breaker step and side strips, might be used. In any case high deadrise or U-sections are necessary in the bow region, to cope with occasional wave impacts, and rapid descent from the foils. The hull determines craft attitude up to take-off, so that the hydrofoils must be carefully set in relation to it, if they are not of controllable incidence type.

This discussion of resistance may be concluded by referring to Table II, which collects together and presents in a suitable form various items of information concerning hydrofoil craft resistance, many of which have been mentioned in earlier sections of this paper.

Examination of the results of Table II emphasizes a number of points already made. The maximum $V/\sqrt{L}$'s obtained tend to decrease as the size of the craft increases since there is an absolute rather than a coefficient speed limitation.

The Supramar craft have higher values of bhp/Δ than the Aquavion *Aquastroll*, and thus achieve higher speeds where the values of L/D and η L/D are smaller. Thus it is probably not of great significance with regard to resistance that the η L/D of the Aquavion craft is better than the Supramar values, in fact the former lies between the Supramar values, at maximum speed and at speed for max. L/D respectively, as it would do if the resistance per ton variations against speed for the two craft were in general similar.

In the same way, the very low η L/D of the HD–4 ladder system is probably due, at least in part, to the very high associated maximum speed.

The Tietjens VS–7 is to some extent an exception to the above remarks in that it is sizeable and yet has a high $V/\sqrt{L}$. Like the HD–4, it attained a high speed by employing a large power-to-displacement ratio. Consider the η L/D's in order of speed.

	V, knots	η L/D
Freccia d'Oro, max. η L/D	25	8·7
Aquastroll 24/40	30	7·4
Aquastroll 24/40	35	7·5
Highpockets	36	5·9
Forlanini, 1·65-ton craft	38	5·8
Freccia del Sole	43	6·2
Freccia d'Oro	46	4·9
VS–7	55	4·3
HD–4	61·5	2·96
Miss U.S. 3	80	2·46

If these are plotted they will be seen to lie in a quite narrow band about a line described by

$$\eta\, L/D = 12{\cdot}9 - V/6$$

The only exception is *Miss U.S.* 3. The extremely high speed quoted for this craft requires verification. If true, it suggests a most interesting flattening off of the demand for increasing power, once extensive cavitation has been established!

The Supramar performance results quoted in some detail earlier indicate η's of between 50 and 70 per cent, depending on speed. Taking 50 per cent, which is reasonable near the usual maximum speeds, the L/D range corresponding to the above table would be 5 to 17. In fact the values appropriate to isolated high aspect ratio foils can be between 15 and 25, but the best foilborne craft values rarely exceed $12\frac{1}{2}$, and at 40 knots 10 to 11 is exceptional.

Fig. 4 indicates how hydrofoil craft can withstand higher

TABLE II

Craft	Foil system	Length, "L" (ft.)	L/B	V max. (knots)	$V/\sqrt{L}$	Δ (tons)	$\frac{\Delta}{(L/100)^3}$	$\frac{L}{B} \times \frac{\Delta}{(L/100)^3}$	hp	$\frac{\text{bhp}}{\Delta}$	η L/D.‡ lb./lb.	L/D.‡ lb./lb.	Wave height (ft.)
Forlanini, 1906	Monoplane foils			38		1·65			75	45	5·8†		
Crocco, 1907				40÷									
Guidoni, 1910–1921	Ladders											7 to 8*	
HD–4, 1919	Bell–Baldwin ladders	60	10·4	61·5	7·8	4·9			700	143	2·96†	8*	1½÷
Bras d'Or, 1957	,,	59				17·5							
Hampden–Macpherson, 1947		20		38	8·5								
Highpockets	"Baker"	24		36	7·3	2·8			125				5 ÷ swells
Research craft	"Hook"	16											Bad 4 ft; chop ÷
Tietjens, 1932–1936	Tietjens			24									
VS–7	,,	46		55	8·1	17	174		1.500	88	4·3†		
—	Schertel-Sachsenberg	23		30	6·3	1·2	99						
KoBo	,,	32·8		38	6·6	2·8	80						
Ts1–5 1939–1945	,,	38·1		40	6·5	5·6	101						
VS–6	,,	52·5		48	6·6	17·0	117						
VS–8	,,	105		43	4·2	80	70						
VS–10	,,	92		60	6·3	45	58						
Freccia d'Oro	,,	46·6	4·58	—	—	9·5	93	425	550	58	8·7*	12·5*	
Freccia d'Oro	,,			45·8	6·7	8·6	84	385	550	64	4·9†	7·5†	
Freccia del Sole	,,	68	4·31	43	5·2		89	383	1,350	48	6·2†		
Supermarin *Pilen*, 1950	"Aquavion"	57·4	4·37	37	4·9				860				
Aquastroll	,,	47·1	3·77	32·2	4·7	16·7	159	600	500	30	7·4†		
Aquastroll	,,	47·1	3·77	38	5·5				600	35	7·5†		
Comparative conventional craft as Fig. 3	Round bilge	73·6	3·3	27·9	3·25	60	150	495			6†		
	,,	89·5	7·5	34·2	3·62	60	75	562			7·4†		
	Hard chine	75·3	4·5	35·3	4·07	60	140	630			7·6†		

* Maximum value.

† At V max.

‡ In these columns L is lift in lb. See note at bottom of page 8.

waves than planing hulls of the same size. The foil boat limitation shown is a conservative one, appropriate to passenger-carrying craft proceeding in a condition of reasonable comfort. The values for craft 16 ft. and 24 ft. in length are only about 1⅓ ft. and 2 ft. respectively, whereas, as shown in Table II, research craft of these lengths have behaved well in 4-ft. seas!

When considering the possibility of operating in a given area, the probable durations during which high winds will continue to blow steadily are, of course, important. For example, a 35-knot wind persisting for 4 hours will produce a mean maximum sea height of about 7 ft. in conditions of unlimited fetch, whereas if the wind continued blowing unabated a wave 9 ft. high would be generated.

The Merits of Various Hydrofoil Configurations

Classification of Systems

Earlier in this paper, and in Fig. 1, a broad classification into four main types was made and can be re-expressed as in Table III.

So far it has been tacitly assumed that ladder foil units are only of "surface-piercing" type, as the blanks in the Table show. This is obviously not logically necessary. A ladder with rungs of zero dihedral all fully submerged and some or all incidence-controlled could be employed, and Hook is believed to have experimented with such arrangements. Again, a surface-piercing ladder could be designed to have a bottom rung which always ran fully immersed, in a particular application, but this does not introduce a practically important difference of principle. A surface-piercing unit with some mechanical incidence control would be a more significant variant.

Since the Grunberg system, with a fully submerged main foil, can be discarded in practice for lateral stability reasons, there are really three main types, each of which could occur in monoplane or ladder form. Mixed types are also possible, but are considered less likely to be successful, because of the additional complications involved.

Effect of Size and Speed on the Choice of Ladders for Main Foil Units

The merits of various hydrofoil configurations will now be considered, and the comment in the previous section that cavitation and structural requirements may favour the use of ladder systems on high-speed designs will be illustrated first. The upper part of Fig. 5 shows the weights and design speeds of a number of craft, distinction being made between those that

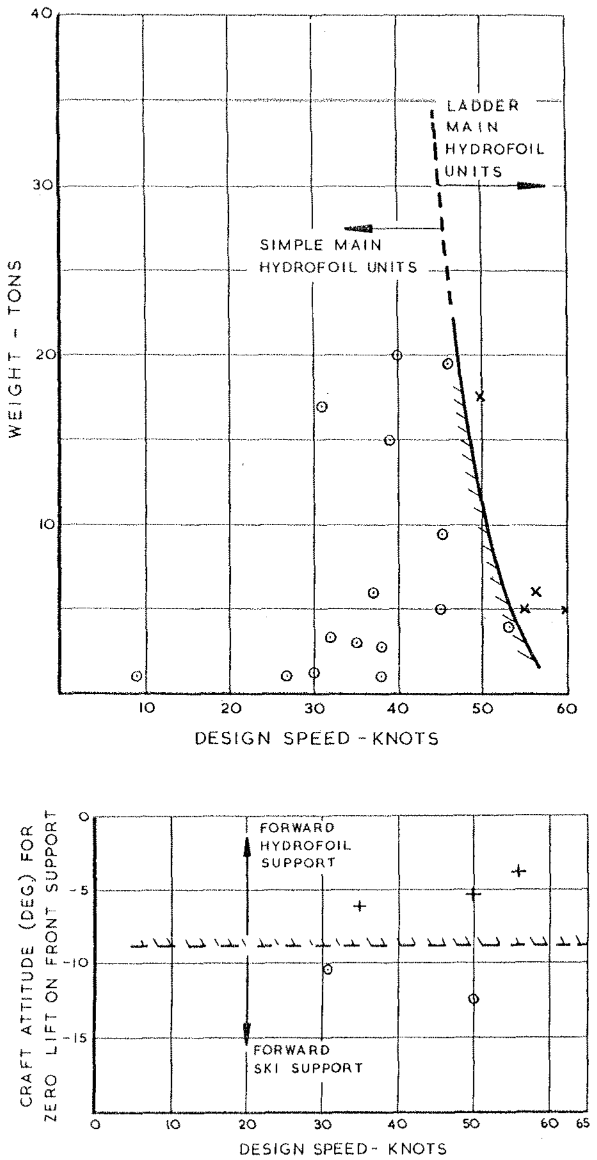


FIG. 5.—CLASSIFICATION OF HYDROFOIL SYSTEMS BY DESIGN SPEED AND BEHAVIOUR IN PITCH

TABLE III

CLASSIFICATORY SCHEME FOR HYDROFOIL SYSTEMS

	SURFACE-PIERCING FOILS		FULLY-SUBMERGED FOILS	
	Control of area by draught			
		Control of incidence by draught "incidence control"		
		Without use of mechanisms		With use of mechanisms
Monoplane main foil unit	e.g. Supramar	e.g. Aquavion	e.g. Grunberg	e.g. U.S. research craft
Ladder main foil unit	e.g. *Bras d'Or* Carl XCH-4	—	—	—

do and do not have main foil units of ladder type. A simple boundary divides the one type from the other. This boundary goes to higher speeds as displacement decreases.

The maximum speed of satisfactory sizeable craft with monoplane foils has hitherto been about 48 knots, extending to 55 knots for small runabouts of 3 tons or less displacement. The Schertel-Sachsenberg VS-10, a 45-ton craft with a maximum speed of 60 knots, appears to be an exception, but very little information is available on it, and it is not known whether the hydrofoils were structurally and hydrodynamically satisfactory for regular operation at this speed. The Tietjens VS-7, a 17-ton craft attaining about 55 knots, is another apparent exception, but the craft was unsatisfactory for other reasons, and so again it does not provide very significant evidence in refutation of the boundary shown in the figure.

It is considered that with present materials and structural techniques, ladder units are suitable for design speeds above 50 knots, especially if the craft displacement is appreciable. Relevant cavitation and stress conditions will be discussed later. The likelihood that structural developments have not yet reached the stage when hydrofoil craft can enter fully into the "monoplane" era, may be offered as a major reason for their slow rate of evolution compared with the aeroplane.

On the other hand, it is important to emphasize that craft required to operate regularly only at speeds less than 50 knots can be designed, in a refined form, and built now, using existing structural techniques. Some examples have already been given in this paper. A speed of 40 to 45 knots is quite adequate for many purposes, including practically all civil applications.

Resistance, Seakeeping and the Effect of Centre of Gravity Location

The fundamental considerations given in the previous section of this paper lead to the following conclusions concerning resistance and seakeeping.

If simple hoop foils such as are used in the Supramar system are not to have an excessive span, the hull water clearance tends to be less than in ladder configurations. Since the Supramar system is not of surface-following type, its rough water behaviour will suffer some limitation, if not in height of wave acceptance then in maintenance of low resistance, since the hull will more often encounter green water. The simple high aspect ratio foil units, with few struts, have an exceptionally good resistance, however, both in calm and rough water. Behaviour in head seas should be good because the growth of lift with draught is not very great, thus limiting the response.

The Aquavion system has a basically low resistance, because of its main high aspect ratio hoop foil. The forward ski-foils are relatively more resistful, but the effect of this is limited by only allowing them to carry about 10 per cent of the total load. Since the system is of surface following type, the hull clearance obtained with a hoop foil of acceptable span is adequate. The planing surfaces are insensitive to orbital motions of the fluid particles, so in that respect the following sea behaviour should be good. They may tend to skip off in critical wave conditions, but a small damping foil at the rear of the craft is claimed to check this. The lower curve of Fig. 5 shows a boundary, dividing craft of Grunberg or Aquavion type, having ski-foils at the front, from those that have pure hydrofoils. The former can pitch to a more negative attitude, before the front support ceases to give lift. This supports the Aquavion Company's claim that their system is particularly free from any tendency to dive. It will be appreciated, however, that a large permissible nose-down attitude might be associated with a tendency to assume such attitudes, so that further evidence is required to justify the claim.

The fully submerged incidence controlled system has a high induced drag at take-off speed and rather large movements in critical waves having a high rate of encounter, but the hull water clearance can be kept relatively low. Following sea behaviour is good since the system has ample time to provide

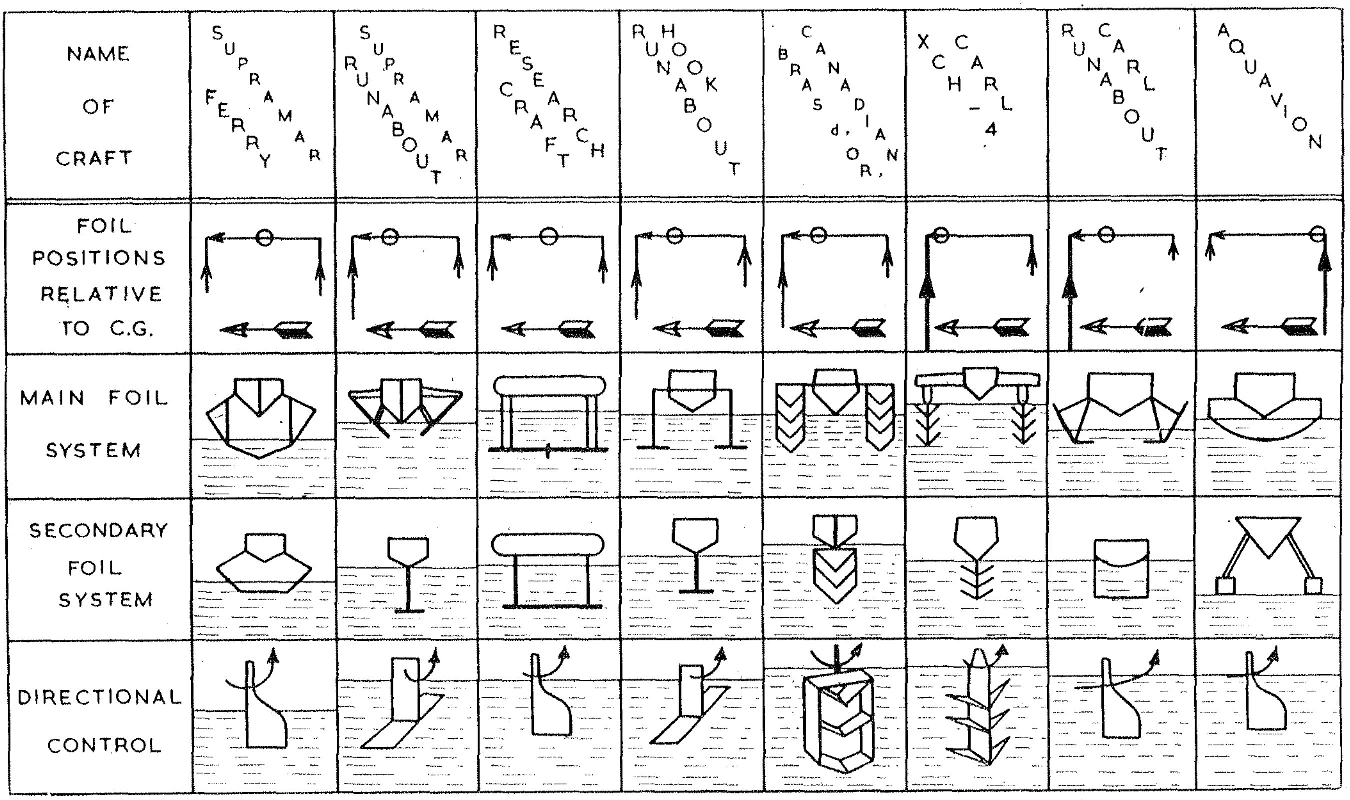


FIG. 6.—FOIL CONFIGURATIONS OF A NUMBER OF CONTEMPORARY HYDROFOIL CRAFT

orrective forces. It looks very attractive on a small experiiental craft, but the complications of the incidence control ystem are not lightly to be set aside, and larger craft would not e so simple structurally. High speeds are likely to demand nacceptably high rates of response.

Surface-piercing ladder systems can employ optimum C_L's ver a wide speed range, but any reduction in individual drag is ffset by added strut and interference drag, and cascade effects. ince the systems are not of surface following type, but can have large hull water clearance, the seakeeping qualities at high peed can be good, with limited response. The upper rungs of ie ladders can be set at increased incidence to assist behaviour n following seas, at some cost in resistance.

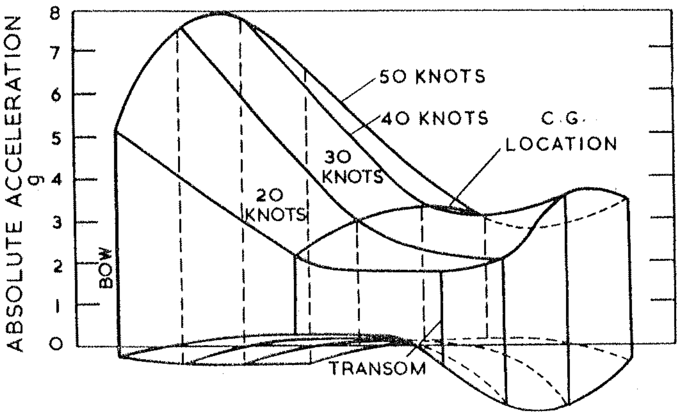
The location of the centre of gravity relative to the main ydrofoils is very important and has considerable effect upon eakeeping behaviour. Fig. 6 introduces, in diagrammatic form, ome important sub-classifications of various contemporary ydrofoil configurations.

The *CG* location is shown first. It is almost at 50 per cent of ie "wheel-base" in the Supramar ferries and the research craft aving a fully submerged incidence control system. This allows articular freedom in varying the load distribution, a very esirable feature for a passenger or cargo-carrying craft. Some chertel–Sachsenberg boats have carried as much as threeuarters of the total load on the front foil, and the fully submerged ystem can employ two foils of different areas, but in either case ie bigger foil tends to have an inconveniently large span. This particularly important on big craft since, for reasons to be xplained later, foil area increases approximately as displacement nd not as the two-thirds power of displacement. It is the latter iat would give a family of vessels possessing geometrical imilarity. A small forward foil ("Canard") fully submerged ystem has been tried, but the use of two units of equal area llows the spans to be contained entirely within the hull beam, hich is excellent for handling and prevention of damage.

The Aquavion craft has the *CG* just ahead of the main foil o as to obtain the small loads on the front ski-foils that are esirable with this system. The Carl XCH-4 has the *CG* at the ont foil so as to achieve stability similar to that of an aeroplane. n other cases the *CG* is about one-third of the wheel-base ehind the front foils, which in consequence carry two-thirds of ie load. If there are two front foil units, one on each side of ie hull, and a single tail foil unit, then the load is equally istributed among all three.

Model tests made in various tanks, including those of the aunders-Roe Company, on non-surface following systems show iat when the *CG* is almost over the front main foils pitching esponse is very small, but heave response can be large. Aftward iovement of the *CG* towards mid-wheelbase causes increased itch and reduced heave response. The behaviour, however, is lmost the same for *CG*'s one-third and one-half the wheelase aft.

Fig. 7 shows a typical carpet of envelopes of vertical accelerations, recorded on a towing tank model having two forward and ne rear surface piercing foils, with the *CG* at one-third of the heelbase aft. The conditions shown are appropriate to regular ead seas of critical length, one and a half to twice that of the ull, and a length-to-height ratio of 30 to 1. Quite high ccelerations are sustained. They are less in larger waves of the ame length-to-height ratio. Such tests are considered to be essimistic because of the extreme regularity of the waves, which acilitates the development of resonance conditions. They are, owever, simple to perform, and are useful in comparing different onfigurations, and for providing a guide as to the load factors be used in designing the craft structure.



CG at 1/3 of wheelbase aft of front foils

FIG. 7.—IMPACT ACCELERATIONS SUSTAINED IN WAVES

A complicating factor is the effect of bow overhang. If the ull bow extends well ahead of the front foils, it can impact a ave before these foils have had time to lift to the wave. A system such as that of the XCH-4, with the *CG* near the front foils, will be particularly prone to this tendency unless an unorthodox hull form, with buoyancy concentrated forward, and distributed laterally, is employed. The Supramar and Aquavion systems, having the front foils well forward and ahead of the *CG* are particularly good with regard to bow overhang.

Following sea behaviour also needs to be considered in relation to *CG* position. It is necessary that the stern should lift to a wave sufficiently to avoid pooping, but not so much that the front foil goes to an effectively negative attitude and buries, nor that the craft broaches to. Thus the further forward the *CG*, the more important it is to reduce stern buoyancy, which in any case should if possible be less than in a conventional hull.

Type of Rear Foil Unit and Method of Steering

Considering the seven cases of Fig. 6, in which the secondary foil unit is at the rear, it will be seen that there are majority choices, both for a fully submerged monoplane rear foil and for a steerable rear foil unit. These are the best characteristics for manœuvrability and dynamic longitudinal stability, as will be explained more fully later, but in some cases other considerations may predominate. The Supramar ferry system, for example, retains some surface piercing dihedral outboard for increased roll stability and to combine low resistance with adequate strength, but has the centre span flatter than in the case of the front foil, so that it acts more like a fully submerged unit. The strength consideration is more serious in the Supramar ferry than in the much smaller Supramar research runabout, which has a single fully submerged rear foil.

Cavitation and Aeration

The reasons why cavitation causes structural difficulties in the case of hydrofoil craft designed for high speeds will now be considered.

Cavitation of hydrofoils is of course similar in principle to propeller cavitation, but is somewhat simpler to study theoretically since it depends upon a streaming velocity which is almost uniform and equal to the speed of the craft, instead of upon a rotational velocity which varies across the span.

The general nature of true cavitation will, of course, be familiar to the readers of these TRANSACTIONS, but a brief descriptive account is included here to clarify the technical comments that follow.

When a body moves through water, the relative velocity of the latter is increased adjacent to the body sides, so that the same quantity of water can pass there as in the unrestricted stream.

This increased velocity causes a pressure drop. If the body is moving symmetrically, the pressure drop is the same on opposite sides as, for example, in the case of an unyawed strut. If it is at an effective incidence to the direction of motion, a circulatory flow occurs also, and this increases the relative velocity on the "back" and decreases it on the "face" so that the pressure is further reduced on the former and increased on the latter. The pressure difference provides a transverse force, which may be lift or side force or a combination of the two.

As speed increases the pressure on the "back" reduces as the square of speed, until it falls to the vapour pressure of water at some point on the contour. Bubbles of water vapour then form, and with further increase in speed the area of cavitation spreads until the "back" is completely covered by a single developed cavity.

It has so far invariably been the practice to design for the prevention of cavitation, since in partial cavitation conditions behaviour can be very unsteady, the ratio of lift to drag may decrease seriously, and the foil surfaces are attacked by cavitation erosion.

Cavitation commences at a point which is at draught d below the free surface, when the local velocity v satisfies.

$$(v/\mathrm{V})^2 - 1 = (p_0 - e + \rho g d)/\tfrac{1}{2} \rho \mathrm{V}^2 = \sigma, \text{ say}$$

where V is the speed of body, p_0 is atmospheric pressure, e is water vapour pressure, ρ is density, and g gravity, in consistent units.

σ is, of course, the cavitation number of the flow.

When $d = 2\frac{1}{2}$ ft., $\frac{1}{2} \rho \mathrm{V}^2 \sigma = 2{,}240$, so that then $\mathrm{C_L}/\sigma = (\mathrm{L/S})2{,}240$ = lift force in tons per sq. ft. of surface. At the same draught $\mathrm{V} = 28/\sqrt{\sigma}$ knots.

The values will be a little different from this at other draughts of present interest, but not sufficiently to affect general arguments.

Given a hydrofoil of thickness t and chord c, then cavitation commences when $\sigma = (\mathrm{C_L}/2) + 2\,(t/c)$ approximately, so that cavitation speed $\mathrm{V}_c = 28/\sqrt{2\,(t/c) + (\mathrm{C_L}/2)}$ knots. Thus the lower the lift coefficient $\mathrm{C_L}$ and the thinner the section, the higher will be V_c. The maximum non-cavitating speed obtainable at a given (t/c) occurs at zero lift, as for example on struts in symmetrical motion, and is about $28/\sqrt{2\,(t/c)}$ knots.

The general relationship may also be written $\mathrm{C_L} = 2\,\sigma - 4\,(t/c)$, so that loading in tons per sq. ft. $= 2 - (\mathrm{V}^2/196)\,(t/c)$, and a limitingly thin hydrofoil gives the maximum possible loading, which is 2 tons per sq. ft. In general, a hydrofoil section has a limiting curve of maximum $\mathrm{C_L}$ against σ, from which maximum $\mathrm{C_L}/\sigma$ and thus maximum loading follows. Values in excess of $1\frac{1}{3}$ tons per sq. ft. have been obtained in two dimensional experiments, but tests on hydrofoils of practical thickness and relatively low aspect ratio give limiting values of a little less than 1 ton per sq. ft., almost independent of speed. These may be compared with the 80 to 100 lb. per sq. ft. (0·036 to 0·045 tons per sq. ft.) maximum loadings obtained on aircraft wings in steady flight. Wing top surface pressures do, however, reach near vacuum conditions locally at transonic speeds.

Some results calculated by means of slightly more refined formulae than those given above are:—

These results show how rapidly the cavitation speed drops as loading, $\mathrm{C_L}$ and t/c rise. Practical behaviour will be rather more severe than these ideal cases.

Fig. 8 is based on experimental evidence, and gives variation with attitude instead of $\mathrm{C_L}$. The $x = 0$ curve in Fig. 8A refers

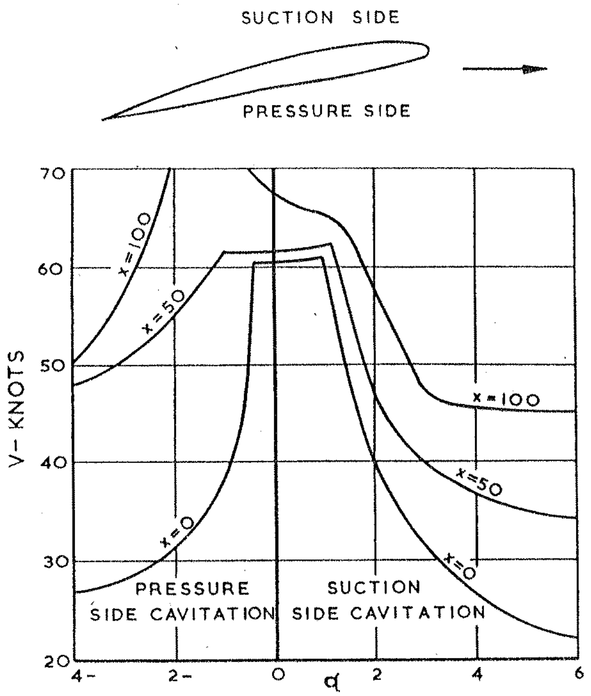


FIG. 8A.—REGIONS OF CAVITATION WITH VARYING ATTITUDE AND SPEED FOR A 3·50 PER CENT t/c PROFILE

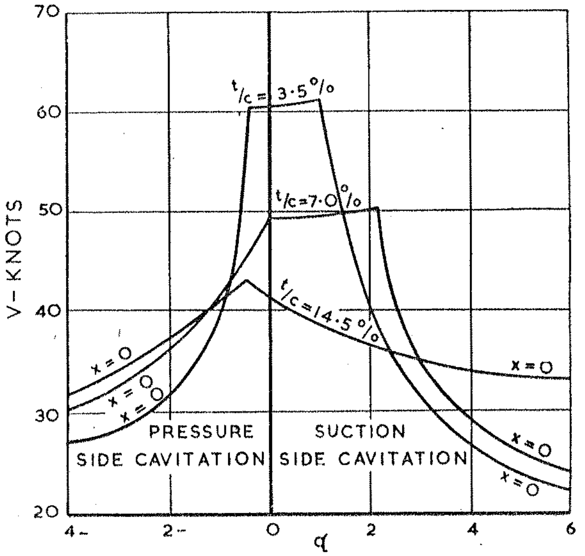


FIG. 8B.—EFFECT OF t/c ON START OF CAVITATION AT LEADING EDGE

t/c	0·05				0·10				0·15			
Loading, tons/sq. ft. ..	0	0·5	1·0	1·45*	0	0·5	1·0	1·28*	0	0·5	1·0	1·15*
Vc, knots	88	75	59	32	61	52	39	24	50	41	30	21
Corresponding $\mathrm{C_L}$ ..	0	0·07	0·22	1·09	0	0·14	0·51	1·77	0	0·23	0·87	1·89

* Maximum possible loading at given t/c.

to start of cavitation at the leading edge, $x = 50$ and $x = 100$ give the speeds at which cavitation has spread to mid-chord and reached fully developed conditions respectively. The foil section concerned was specially designed to obtain a relatively constant cavitation speed over a range of incidence near zero lift angle. The rapid fall away in speed, at higher positive and negative angles is due to a departure from the simple theory given above, arising from local suction peaks forward on the back and face of the section, respectively. This aspect is illustrated further by Fig. 9. The pressure coefficient C_p is $p/\frac{1}{2}\rho V^2$, and it is clearly advisable to keep it as large as possible. The N.A.C.A. 0·0010 section has a value at zero lift, which varies considerably along the chord. The anti-cavitation section on the other hand is almost "flat" over the forward portion, so that although the area under it, determined by t/c, is the same as for N.A.C.A. 0·0010, the minimum value of C_p is appreciably larger. It will be seen that the change in section shape required to give the pressure difference is small, and this emphasizes the manufacturing care that must be exercised in making hydrofoils.

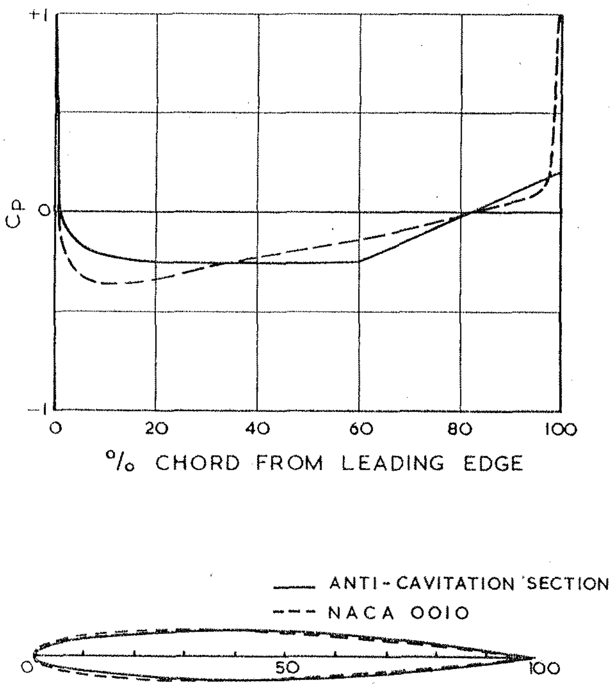


FIG. 9A.—PRESSURE DISTRIBUTIONS AT ZERO LIFT CONDITION

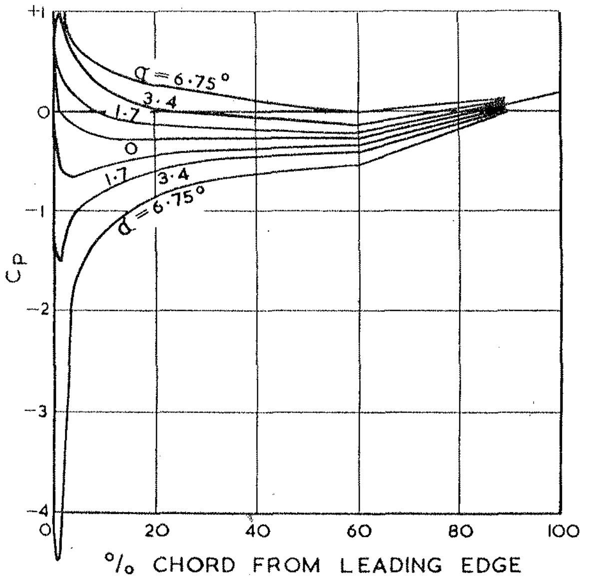


FIG. 9B.—THE EFFECT OF ATTITUDE ON PRESSURE DISTRIBUTION

Fig. 9B indicates how the pressure distributions on face and back vary with changing incidence. At the higher attitudes there are serious suction peaks which cause cavitation.

Since the lift coefficient of a section is approximately proportional to the attitude of its no-lift line, over the range of variation of interest, curves of σ against C_L are qualitatively similar to Fig. 8, with C_L as base scale and the vertical scale inverted. The minimum non-cavitating value of σ rises rapidly with increase in positive or negative magnitude of C_L, except in a nearly level region around the design C_L.

The design techniques for anti-cavitation hydrofoil sections are the same as those for subsonic wings, and it is only through comparatively recent aeronautical developments that the theory of the former has been systematically understood. This is another reason for the long period between the *ad hoc* development of the Guidoni and Bell–Baldwin sections and the production of a commercially operable hydrofoil boat.

The thickness to chord ratio of a hydrofoil has to be decreased very rapidly as design speed increases if non-cavitating operation is to be obtained above 40 knots. As Fig. 8B shows, a value of 10 per cent can be quite adequate at this speed, and introduces no serious structural difficulties. At 50 knots the value has fallen to 7 per cent, and at 60 knots to 3½ per cent, however, and the last figure presents the most extreme structural problems.

For example, if the section is more than, say, 50 per cent solid, bending stress is approximately proportional to $(\Delta/S)/(t/c)^2$. So that for a given material, loading per sq. ft. will have to greatly decrease as t/c is reduced. If, on the other hand, the section is thin walled, but not to the extent that buckling is a major consideration, stress is proportional to $(\Delta/S)/[(t/c) \times (T/c)]$ where T is wall thickness. Thus decreasing section thickness is in any case less serious and can to some extent be offset by increasing wall thickness. Really thin-walled sections, for which buckling would be an important consideration, are unsuitable for hydrofoils because of the pressures they have to withstand, and the necessity for general robustness.

The reason for the limitation of monoplane hydrofoils to design speeds below 50 knots can now be appreciated better. The excessive bending moments sustained by small (t/c) hydrofoils of large span and small chord, make it necessary to increase chord and greatly reduce span between supporting struts, relative to chord. The number of struts per foil unit can be kept to two, limiting strut drag while retaining sufficient hydrofoil area, if the latter is distributed between several rungs of a ladder. This arrangement also keeps the effective aspect ratio relatively low, and low aspect ratio foils, although in general less efficient, have been found to possess a satisfactorily smooth and continuous variation of characteristics under changing cavitation conditions.

It would, no doubt, be possible to employ multiple struts on foils of the present Supramar and main Aquavion types, but in practice ladders have been used on most high-speed designs to date, as already discussed in connection with Fig. 5. The (t/c) values that have actually been used on boat hydrofoils until now range from 18 to 4 per cent, depending upon the design speed range. The Schertel system employs 10 to 5 per cent, the latter being at the lowest portions of the hoops, and angles of incidence do not generally exceed 3 deg., for example.

The problem of cavitation limitations might be overcome by designing a hydrofoil to work reasonably efficiently under conditions of fully developed cavitation. Such a foil could perhaps be made relatively thick to alleviate structural difficulties. Some theoretical work on supercavitated foils has been published, but since it is not known to have been applied in practice to boat hydrofoils, the matter will not be pursued further here.

Another possibility might be to bleed air into the low-pressure regions to control the development of cavitation. Some tests along these lines have been made in the cavitation tunnel at the National Physical Laboratory.

Since a hydrofoil or the struts directly supporting it pass through the free water surface, air will in general tend to be sucked down to the low-pressure regions of flow on the surface of the hydrofoil at craft speeds appreciably below those at which true cavitation occurs.

This aeration can be adequately controlled by a few small chordwise plates or "fences," which project from the hydrofoil or strut surface. Some designers put them exactly at right angles to the surface, regardless of dihedral, others put the hydrofoil fences in vertical planes, so that they will break the free surface most cleanly. The fences need not extend round the whole contour, but must cover the critical low-pressure region on the forward part of the back. The aeration is checked at the fence nearest to the free surface, and if this emerges from the water it jumps to the next fence down.

Weight and Structural Design Considerations

Hydrofoil Unit Structure Weights

The absolute limit to hydrofoil loading in tons per sq. ft. imposed by cavitation introduces a "square-cube" law of development with size.

A family of dynamically similar craft has displacements and design speeds which increase with length in such a way that Δ/L^3 and $V/\sqrt{L}$ remain constant. The hydrofoil area S will then satisfy $\Delta/S\,V^2$ constant, at a given design incidence. Thus S is proportional to L^2 and the hydrofoils scale in proportion.

If, however, there is an absolute limiting speed to which all the craft must conform, Δ/S requires to be constant. It is just such a constancy of loading that cavitation imposes. The larger craft will then have relatively larger foils than the small ones.

If the foils are geometrically similar, both in external contour and structural section, then shear, bending, and torsion stresses are nearly constant when Δ/S is constant, providing that the walls of the sections are not so thin that buckling occurs. For example, section area is proportional to S, shear load is proportional to Δ, shear stress is proportional to Δ/S. This constancy of stress makes it advisable to employ the same material for construction irrespective of size. But foil weight will then be proportional to $S^{3/2}$ and thus to $\Delta^{3/2}$.

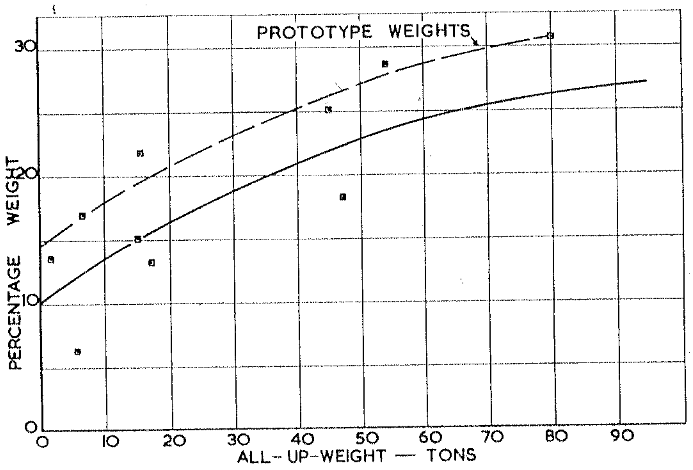


Fig. 10.—Estimates of foil and supporting structure weights expressed as a percentage of craft all-up weight

It follows, therefore, that if a 5-ton boat has its foils designed down to scantlings and has a total foil unit weight which is, say, 7 per cent of the displacements, then an 80-ton boat will have a foil weight of $(80/5)^{1/2} \times 7$ per cent, which is 28 per cent of displacement.

In practice the foils of small craft are made solid, or of simple thick-walled extruded tubes, and tend to be stronger than is necessary. Thus estimates of foil unit weights of various actual craft show a variation of the type illustrated in Fig. 10. There is a 5-ton boat near 7 per cent, and an 80-ton boat near 28 per cent, but, say, 10 per cent to 15 per cent is more normal for small craft. Nevertheless, a serious tendency for percentage weight to increase with size is indicated.

Weight Breakdown for a Typical Hydrofoil Boat

The most critical weight factor in hydrofoil craft design having been discussed, the total weight breakdown of a typical boat will now be considered. This is shown in comparison with that of a corresponding planing craft in Table IV. A service application rather than a civil one has been borne in mind.

TABLE IV

Typical Weight Breakdowns

	Hydrofoil boat, percentage of A.U.W.	Fast patrol boat (planing craft), percentage of A.U.W.
Hull structure	30	36
Hydrofoil units	18	—
Machinery	20	27
Fixed equipment, tankage, power services	8	8
Disposable load	24	29
All-up weight	100	100

Comparable design speeds have been taken, so that the lower specific resistance of the hydrofoil craft, at high speed, permits a reduction in machinery weight. The hull structure weight of the hydrofoil boat is 6 per cent of all-up weight (16 per cent of hull weight) less than that of the conventional craft, due to alleviation in hull loading design cases since the hydrofoils lift it clear of the water and cushion it against the worst direct impacts. Even so, total structure weight percentage of hydrofoils and hull together is 48 per cent, as compared with 36 per cent for the hull of the conventional craft.

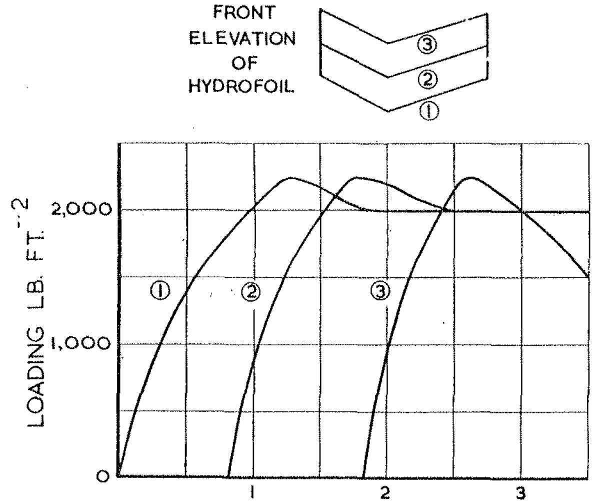
Due to saving in machinery weight the total disposable load, payload and fuel together, is 24 per cent as compared with 29 per cent for the planing boat. The importance of behaviour, convenience or novelty, as opposed to payload capacity, in choosing a hydrofoil boat is thus emphasized.

If the full line curve variation of weight with size given in Fig. 10 is assumed, then the above results apply to a 27-ton craft. On the supposition that only the foil structure weight and disposable load percentage vary with size, the latter will fall to between 15 and 10 per cent on a craft of 100 tons displacement. These are, of course, very low values that should be improved in practice, to some extent, by reduction in machinery percentage weight, but detailed studies have not shown a figure better than 15 per cent for the disposable load of a craft of about 95 tons. It is therefore considered that operational hydrofoil boats are likely to remain appreciably below this displacement for some time to come, and until further improvements in structural techniques and materials are achieved.

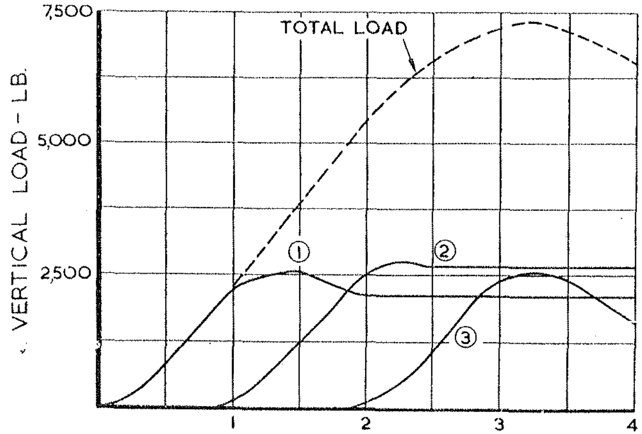
Structural Design Cases

The general structural requirements of hydrofoil boats will be illustrated by a brief discussion of typical design loadings and pressures, and the methods of estimating them used at the Saunders-Roe Company.

When a hydrofoil unit has a downward velocity v, and forward speed V, the effective incidence is increased by $\tan^{-1}(v/V)$. Values of v appropriate to the worst conditions that can be encountered in the range of sea states for which the craft is intended are taken. The critical seas are generally from ahead or in the forward quarters. The variation of lift coefficient with draught is then estimated, at the effective incidence, for each hydrofoil. The boundary curve of C_L against σ appropriate to hydrofoil section, as previously discussed in the part of this paper concerning cavitation, is used to calculate cavitation speed V_c at each C_L. The greatest loading per sq. ft. obtainable at each draught, under two-dimensional conditions, is then given by $C_L V_c^2$, or $C_L V_m^2$, whichever is the smaller, where V_m is the maximum design speed. In practice a small correction is made for the variation of cavitation speed with draught at a given C_L. Empirical allowance is made for three dimensional effects on the basis of experimental evidence. As previously explained, tests on hydrofoils of finite aspect ratio exhibit a limiting loading, which is never exceeded. Such a limit, appropriate to the aspect ratios of the system being designed, is imposed upon the two-dimensional loadings calculated as above and the curves are faired in at the junctions.



(*a*) Design loadings in lb. per sq. ft.



(*b*) Design loads, lb.

FIG. 11.—HYDROFOIL UNIT DESIGN CONDITIONS

The upper part of Fig. 11 shows the variations of design loading per sq. ft. with draught on the several rungs of the ladder whose front elevation is illustrated in diagrammatic form. The three-dimensional limitation of loading in this case is seen to be 2,000 lb. per sq. ft. Some modification to the results given by the above method may be necessary in the case of a ladder because of interference between the rungs (blanking of upper rungs by those below).

The variation of total force on the unit with draught is obtained by multiplying loading by area and, in the case of a ladder, by adding the results for the several rungs. This is illustrated by the lower curves of Fig. 11.

Asymmetric impacts on a foil unit which is heeled or sideslipping may be treated as above by suitable adjustments to effective incidence. Such impacts occur in quartering seas and in turning. The above method has been applied to the Supramar *Freccia d'Oro* and gives very similar loads to those actually used in the stress calculations for that craft. Also loads measured on a model of the *Bras d'Or*, although obtained in conditions in which cavitation was not present, are of the same order as those calculated by this "cavitation limit" treatment.

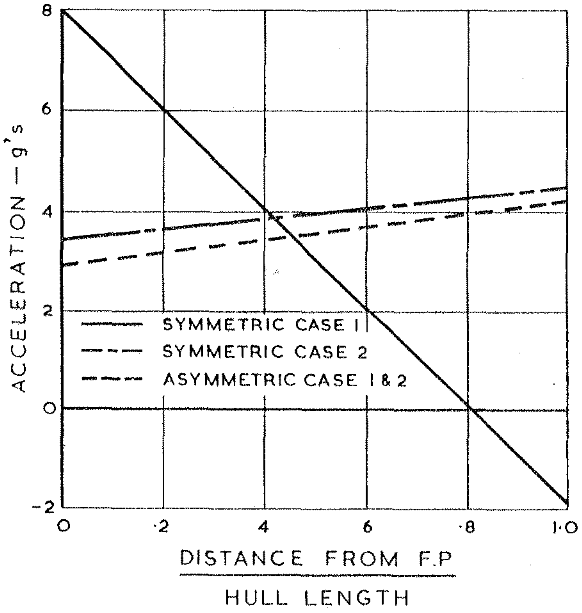
Typical vertical and transverse load factors used in designing the hull main structure of a craft intended for operations in severe sea conditions are given in Figs. 12A and 12B, respectively. The load factor shown at any longitudinal station is one and a half times the maximum design acceleration in g's sustained by a concentrated mass at that station, the weight of the mass being included in the acceleration in the vertical case. The multiplier of one and a half is an ultimate factor of safety. The loads are transmitted to the hull from the hydrofoil units and are based on assumed critical symmetrical and asymmetrical impacts of the hydrofoils with the water.

The straight line appropriate to any given case implies a translational acceleration of the craft *CG* together with an angular acceleration in pitch or yaw about the *CG*. These accelerations are chosen to provide coverage of conditions sustained in model experiments, such as those shown in Fig. 7. There are also significant cases involving angular accelerations in roll.

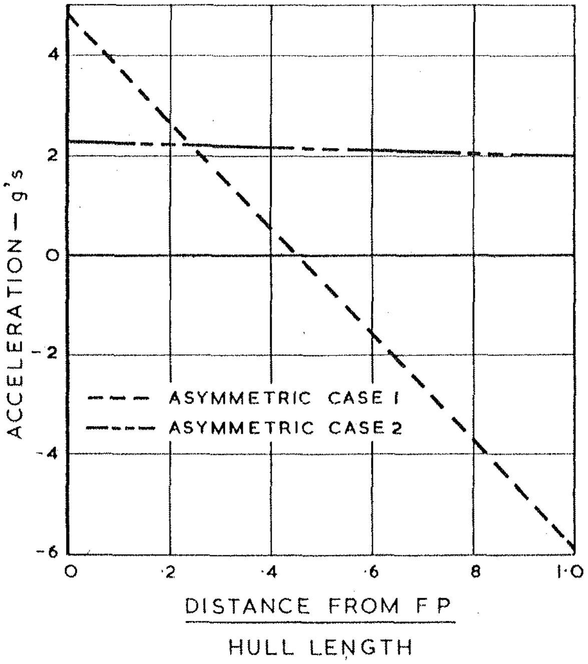
The accelerations of Fig. 7 are of similar order to those sustained by a conventional high-speed planing craft in quite moderate seas. For example, Ref. (7) quotes a forepeak acceleration of 8·36 g. obtained from measurements on a 6⅝-ft. craft travelling at about 40 knots in waves of unspecified length and 2 to 3 ft. high. Hard chine planing craft in general suffer severe pounding at high speed, even in quite small waves, and this is very uncomfortable. The pounding is associated with large local impact pressures on the hull bottom. Hydrofoil boats have a slower and smoother response, and since the impact loads occur mainly on the hydrofoils they may be transmitted directly to the hull main structure, allowing the use of lighter hull skinning.

Round bilge hulls do not pound so much as hard chine craft, but their motions are not greatly different at top speed, and resistance rises rapidly above, say, 35 knots, unless they are of large size.

The pressures used to design hydrofoil craft hull skins and framing should be based on model test results, but in the absence of such evidence a factor, to allow for the relief provided by the hydrofoils, can be applied to pressures appropriate to planing craft. Some experimental evidence on the latter is available. Alternatively, the standard methods of calculating impact pressures on seaplane hulls may be simply adapted. These are given, for example, in Ref. (8)



(*a*) Vertical accelerations.



(*b*) Transverse accelerations.

FIG. 12.—ACCELERATIONS DUE TO DESIGN LOADS (FULLY FACTORED)

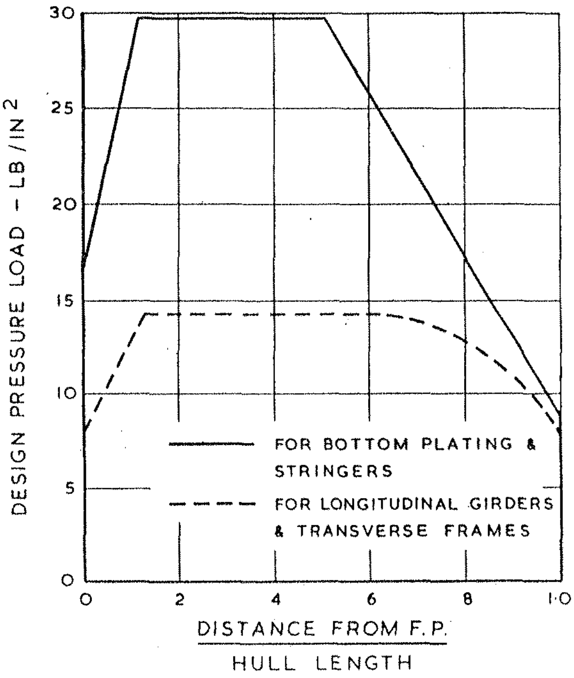


FIG. 13.—HULL DESIGN PRESSURES (FULLY FACTORED)

Fig. 13 shows some typical hydrofoil boat design pressures. The values presented again include an ultimate factor of safety of 1·5. The maximum local pressure actually sustained is 20 p.s.i. as compared with peak values of 32 p.s.i. recorded on the hulls of fast patrol boats. The pressures shown in solid line will only act over a small area, such as a panel bounded by adjacent frames and stringers, and should therefore be used for plating and stringer design. The pressures shown in dotted line occur over sufficiently distributed areas to provide design cases for main frames and longitudinal girders. In either case the pressures only act over a limited portion of the hull at any given moment, and the extent of such a portion may be assumed by comparison with the main structure load factors given in Fig. 12. The pressure summed over the portion must not give a total load lying outside the load factor envelope.

Ref. (2) quotes a case of a hull which was satisfactory for operation with hydrofoils, but failed when subjected to low-speed planing conditions.

Stability and Control

The last aspect of hydrofoil boat design that will be considered in detail in this paper is stability and control. Stability includes not only static but also dynamic aspects. Static stability is used here in the aeronautical sense as referring to conditions which apply when a craft is disturbed very slowly from a condition of steady motion. It does not mean the stability when lying at rest. Dynamic stability considers the motions that result when a craft in steady translational or turning motion is disturbed relatively suddenly, for example by encountering a wave or by a momentary application of rudder.

Control includes use of rudder to produce manœuvres, and in the case of hydrofoil craft can also involve adjustment in heel and pitch by means of ailerons on the outer portions of hydrofoil units, and by elevators on the tail units. Units which are all moving in incidence, at the will of the pilot, may also be used.

Ref. (2) states: ". . . the state of hydrofoil art, as demonstrated by the various radically different configurations presently in use, is curiously akin to that of aircraft just prior to the first World War. The underlying cause is the problem of stabilization; now as then. It is here, more than in any other particular, that emphasis on research and development must be placed if the hydrofoil is to realize its full potentialities. Modern techniques of analysis, model studies, and full-scale evaluations developed in allied fields are certainly applicable—although the problem is severely complicated by the seaway. Even a cursory examination of the reported effects of sea state on sustained speed for conventional ships, however, shows that the speed losses incurred by them are great. It is felt that the prospect of alleviating this situation, for certain size-speed ranges, by use of the hydrofoil is great enough to warrant further serious consideration."

In the author's opinion this statement puts too much emphasis on stability as the major cause of the slow progress of the hydrofoil concept between 1891 and the late 1940's. This paper has already indicated the important parts played by cavitation, hydrofoil structural requirements, and the necessity of awaiting on transonic aerodynamics for the development of aerofoil sections having flat pressure distributions.

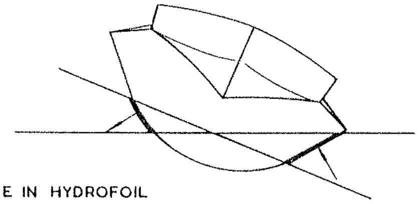
The great emphasis placed, in United States official quarters, on stabilization in a seaway, and in particular in the use of incidence control, is shown by Refs. (2) and (4), as exemplified in the quotations above. It is only in the mid-1950's that the very practical achievements of the Aquavion, Bell–Baldwin, and Supramar systems have come to be fully appreciated.

Nevertheless, stability has remained an intractable problem theoretically, because the great understanding of analogous aircraft behaviour, which was brought to completion between the wars, refers to a generally simpler mathematical situation than that applying in the hydrofoil case. Recent developments in stability and response theory, and the employment of electronic analogue computers capable of handling systems with many degrees of freedom is changing the position. Little direct information on the dynamic stability of hydrofoil systems has been published, and so in view of the relatively rare occurrence of similar problems in naval architecture, no apology is made for the simplified account of fundamentals that follows later in the present section of this paper.

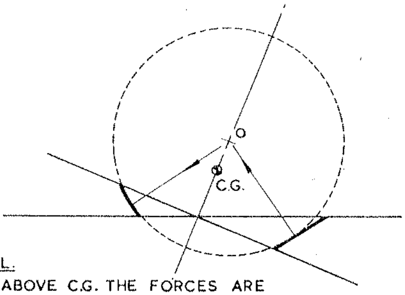
Static Heeling Stability, Turning, and Steering

The heeling and steering behaviour of hydrofoil boats presents a number of unusual and interesting features. This is not an appropriate place to develop in detail the mathematics describing the behaviour, but without it only approximate explanations can be offered.

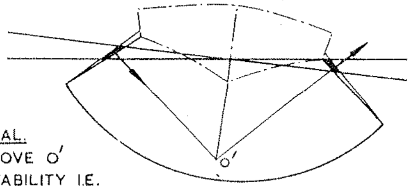
The simplest concept is that of the static heeling stability of a simple hoop foil unit. This was first explained to the author by Prof. Tietjens. Consider Fig. 14, when the craft is running fully foilborne, only the part of the hoop with dihedral is in the water, as shown in the upper part of the figure. A disturbance in heel increases the span immersed on the hull down side, and decreases it on the other, so that the change in forces acting is as shown in the middle diagram. These added forces will be stabilizing if they intersect above the craft *CG*. Thus a circle touching the foil at the unheeled waterline must have its centre above the *CG*. If the hoop has top members with anhedral, attaching it to the hull sides, these members will intersect the water surface at moderately low speeds. An argument of the above type now requires the circle, touching the foils at the waterline, to have its centre below the *CG*, which will almost invariably be the case. This provides the inherent roll stability of the Pegna system mentioned in the historical part of this paper.



CHANGE IN HYDROFOIL
LOADING DUE TO ROLL.



DIHEDRAL.
IF O IS ABOVE C.G. THE FORCES ARE
STABILISING I.E. CIRCLE TOUCHING ELEMENTS
MUST HAVE SUFFICIENTLY LARGE RADIUS.



ANHEDRAL.
C.G. ABOVE O′
FOR STABILITY I.E.
ANHEDRAL ALWAYS STABILISING IN PRACTICE.

FIG. 14.—STATIC STABILITY IN ROLL

In practice the circles, appropriate to different waterline intersections with the dihedral part of a hoop, will have different centres, but if the hoop is nearly semicircular in front elevation, as, for example, in the Aquavion system, the variation will not be very great. A circular arc elevation gives a restoring moment which is proportional to the angle of heel, θ, and is in fact $L \,.\, G\,O \,.\, \theta$, where L is the lift produced by the foil unit and G O is the height of the centre of the circular arc above the centre of gravity. In this instance no horizontal sideforce is produced by the heeling. In the case of complex foil units, and when determining the combined effect of all the foil units on a craft, the behaviour at all the intersections with a given waterline must be compounded.

It is interesting that published curves for the *Freccia d'Oro* give the following effective values for G O:—

V, knots	10	20	30	40
G O, ft.	3·53	2·48	3·42	5·97

The effective centre O corresponds to the metacentre of a conventional vessel. Values obtained by averaging the heights of circles constructed at the appropriate waterlines on the front and rear foil units, as previously described, are in a reasonable agreement with these figures. A metacentric height of 4·6 ft. has been quoted to the author in reference to the P.T. 20, by a member of the Supramar organization. Rationing by length, this would imply a value of 3·4 ft. for the P.T. 10, in good agreement with the figures previously given.

If a hydrofoil boat is turning, side force and rolling moment are produced by the effect of sideslip both on foils having dihedral and on vertical struts. If, as is usual, the craft is side slipping away from the centre of turn, the strut forces will cause an outward roll, because of their location below the craft *CG*. Dihedral and anhedral elements of hydrofoil span, so located that they are each statically stabilizing, will produce inward and outward rolling moments, respectively, in the presence of this sideslip. In both cases the sideforce is inwards.

To a first approximation a spanwise element having dihedral γ (anhedral if γ is negative), in a sideslip of positive angle β, sustains an effective increase in incidence $\beta\gamma$. The increments of force produced by the incidence changes are perpendicular to their respective elements, and approximately proportional to the increments of incidence and thus to β. They have side force components and produce rolling moments which are likewise proportional to β. Summing up over all the immersed elements, side force $= k_1\beta$, rolling moment $= k_2\beta$, say, where k_1 and k_2 are constant at fixed draught and craft attitude. If inward sideforce and rolling moment are taken positive, then k_1 is positive and k_2 is positive and negative for pure statically stabilizing dihedral and pure anhedral foils respectively. In mixed cases k_2 might have either sign.

Now suppose the craft is turning in a circle of radius r, at a speed V, and that, as is reasonable, the foil unit concerned is contributing the same proportion of total turning sideforce as it does lift. Then in fully foilborne conditions the sideforce in consistent units equals $(L/W)\,W\,V^2/g\,r$, which is $L\,V^2/g\,r$, where W is the weight of the craft. Thus the rolling moment = $(k_2/k_1)\,\frac{L}{g}\,\frac{V^2}{r}$.

If the hydrofoil is of circular arc front elevation, this moment will cause a heel through an angle θ, taken positive inward, where as before rolling moment = L . G O . θ, so that

$$\theta = \frac{k_2}{k_1}\,\frac{1}{(G\,O)}\,\frac{V^2}{g\,r}$$

It follows that pure statically stabilizing dihedral foils will cause the craft to heel inboard during a turn, and the angle of heel will be proportional to speed squared and inversely proportional to the radius of turn.

In the case of a foil which is of simple vee shape in front elevation, with apex under the craft centreline, k_2/k_1 approximately equals G O, where O is the centre of a circle through the apex of the foil and its intersections with the waterline. Thus, for simple hoop foils, $\theta = k\,V^2/g\,r$, where k is of order 1·0. A natural banking turn, like that of an aircraft, is obtained.

The extreme opposite condition is obtained when the side forces on vertical struts predominate. Consider a pair of main foil units of ladder type, having a mean track t, running at a waterline distant h below the centre of gravity, and carrying two-thirds of the total load. The variation of the lift of one hydrofoil unit with draught will be very approximately of the form $k\,W/h$, where k will vary with h and attitude, but might be, say, 2. If the vertical struts of the pair of ladders also provide two-thirds of the total turning sideforce, then their contribution is $\frac{2}{3}\,\frac{W}{g}\,\frac{V^2}{r}$, and the corresponding rolling about the CG will be approximately $-\frac{2}{3}\,\frac{W}{g}\,\frac{V^2}{r}\,h$, where the negative sign indicates that it is outboard. The heeling will introduce draught changes on the units of minus and plus $t\,\theta/2$, outboard and inboard respectively, where now θ is negative. Thus the moment due to heel is nearly enough $\frac{k\,W}{h}\left(\frac{-t\,\theta}{2}\right)t$, and since the total moment must be zero under equilibrium conditions,

$$\theta = -\frac{4}{3\,k}\left(\frac{h}{t}\right)^2\frac{V^2}{g\,r}$$

A reasonable high speed value for h/t would be 1/2, giving

$$\theta = -\frac{1}{6}\,\frac{V^2}{g\,r}, \text{ if } k \text{ is } 2.$$

Thus again the angle of heel varies with speed squared and inversely with radius of turn, but now it is outboard.

In practice, dihedral and strut effects act against one another, so that in general $\theta = K\,\frac{V^2}{g\,r}$, where K can be of either sign, and may change sign with draught, and thus with speed, for a given configuration.

The numerical values of parameters used above would suggest that a simple hoop system will heel inboard more strongly than a ladder system will heel outboard, but due to interaction of conflicting effects this does not seem to be borne out in practice. Some ladder hydrofoil boats do not heel out appreciably, but at some speeds bank inwards. A hoop foil boat can remain practically level in a moderately high speed turn.

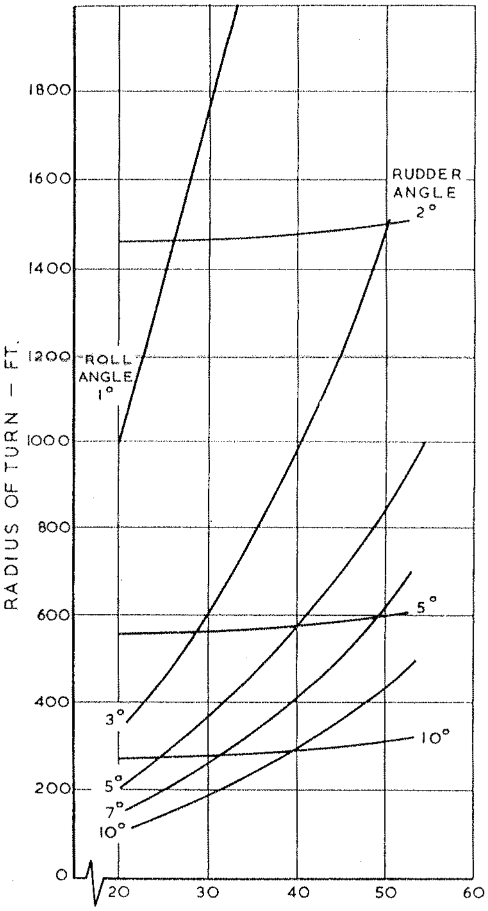


FIG. 15.—TURNING

Fig. 15 typifies the behaviour of a particular craft. In this example, a given rudder deflection produces almost a constant radius of turn, irrespective of speed. Since the angle of heel at a given rudder angle increases continuously with speed, it is necessary to decide upon a limiting design heel angle and vary the maximum allowable rudder angle with speed to suit. For example, if in the case of Fig. 15 an angle of heel of 7 deg. is chosen, the following conditions are obtained:—

Craft length, L ft., assumed ..	30			
Speed, V knots	20	30	40	50
$V/\sqrt{L}$	3·6	5·5	7·3	9·1
Max. permissible rudder angle, deg.	14	11	7	5
Radius of steady turn, ft. ..	150	275	410	615
Radius of turn/craft length ..	5·0	9·2	13·7	20·5
K ≡ heel angle/$(V^2/g\,r)$	0·52	0·42	0·35	0·34

Thus K tends to a limit of 1/3. It must not, however, be assumed that this is the best that hydrofoil craft can achieve. The turning radii could of course be reduced by, say, 30 per cent by allowing a rather larger but still practicable limiting angle of heel. Results for operational craft, already given in the historical section, are also better than those of Fig. 15. For example:—

	Aquastroll 24/40	*Freccia d'Oro*			
Craft length, ft. ..	47·1	46·6			
Speed, knots	30 approx.	10	20	30	40
$V/\sqrt{L}$	4·3	1·5	2·9	4·4	5·8
Radius of steady turn, ft.	165	93	121	233	816
Radius of turn/craft length	3·5	2	2·6	5	17·5

Comparable turning radii for conventional high-speed craft are, for instance:—

Craft length, ft.	81	81	72	68	77
Average speed, knots (approx.)	23	26	29	31	34
V/√L	2·6	2·9	3·4	3·8	3·9
Radius steady turn, ft. ..	580	465	460	150	610
Radius turn/craft length ..	7·2	5·8	6·5	2·25	8·0

The figures for the 68-ft. craft were kindly supplied by Cdr. Du Cane. It appears much more efficient in turning than the remainder and is understood to have about as good a turning performance as is possible for high-speed planing craft.

The hydrofoil boats are in general better than the conventional craft both in absolute radius of turn and in terms of boat length. The latter figures are, however, rather high in the case of the 30-ft. craft to which Fig. 15 refers. This is to be expected since it is a small boat.

It will be observed from the theory that turning radius is a function of speed, irrespective of size, for geometrically similar craft. Radius of turn will thus only vary roughly as boat length at corresponding speeds which vary as root length. If a plot of the above results is made against V/√L it will be found that all the hydrofoil craft are better than the conventional craft, the Vosper boat excluded.

From personal observation when travelling aboard hydrofoil boats, the author has confirmed that the turning behaviour is usually more than adequate, and corresponding angles of heel are low.

The type of behaviour described above, with limited rudder movement at high speed, requires the wheel to rudder gearing to have a very high reduction ratio. It is understood, for example, that the wheel of the *Freccia del Sole* makes seven complete turns in giving the full rudder travel from plus 30 deg. to minus 30 deg. This gearing causes the rudder to move 5 deg. for just over one half turn of the wheel, which is reasonable in the light of the Fig. 15 results quoted above. Only ±10 deg. of rudder is used at cruising speed, which in this case is under 40 knots. The *Freccia del Sole* has hydraulic steering.

This section on the steering of hydrofoil boats will, it is hoped, have made clear the extent to which their handling characteristics differ from those of conventional high-speed craft. It is required that the rudder of a motor torpedo boat should be capable of being put hard over at full speed in order to take avoiding action. This technique is neither desirable nor necessary when foilborne.

Static Stability in Pitch and Heave

The provision of aircraft static stability in pitch, in combination with the requirement for moment equilibrium in steady motion, causes the lift coefficients on the front and rear plane to satisfy

$$\frac{C_LF}{C_LR} \geqslant \frac{a_F}{a_R}\,\frac{1}{\left(1-\dfrac{d\,\varepsilon}{d\,\alpha}\right)}$$

where a_F and a_R are the front and rear lift curve slopes and $d\,\varepsilon/d\,\alpha$ is the rate of change of downwash at the rear plane with craft attitude. Since, in general, $a_F \geqslant a_R$, and $d\,\varepsilon/d\,\alpha$ is positive, the forward lift coefficient must be greater than that at the rear. This is the criterion for hydrofoil craft advanced by Prof. Tietjens. In the case of such craft $d\,\varepsilon/d\,\alpha$ may in some instances be nearly zero, then C_LF and C_LR should be able to have almost the same values.

The other simple aircraft requirement for pitch stability is that the static margin shall be positive. This requires merely that the overall centre of pressure of the loads on the front and rear planes shall lie behind the craft *CG*, so that a nose up disturbance which will increase the lift will at the same time cause a nose down moment, decreasing attitude and therefore lift again. A positive static margin implies that there will be a nose up moment at conditions of zero total lift on the planes.

It is interesting to extend these ideas to the more complicated combined pitch and heave conditions experienced by hydrofoil boats. Consider Fig. 16, and firstly the right-hand column.

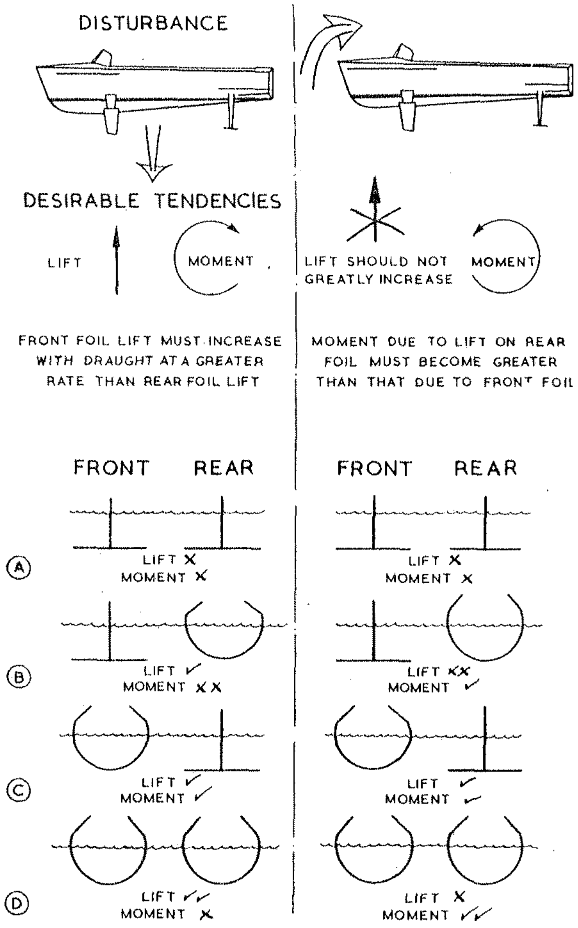


FIG. 16.—LONGITUDINAL STABILITY

By analogy with the aircraft case a nose up disturbance should cause a nose down moment, and as little additional lift as possible, to avoid the craft heaving out. Consider the possible combinations of a simple fully submerged foil and a surface piercing hoop foil. As shown in Fig. 17, the lift per sq. ft. given by the former is very insensitive to change in draught except when it is about to reach the free surface. The latter

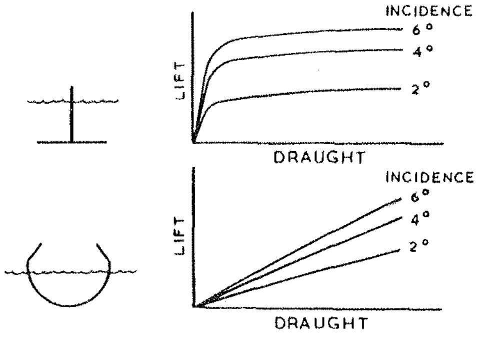


FIG. 17.—CHARACTERISTIC HYDROFOIL UNIT LIFT CHARACTERISTICS

has a lift which varies steadily with draught. In both cases lift per sq. ft. increases with incidence, but this will in general be more rapid for the fully submerged foil because of a higher aspect ratio. Returning to Fig. 16, marks can now be awarded to the different combinations.

For example, fully submerged foils both front and rear give a change of moment with incidence dependent only on the aircraft static margin considerations already quoted, while the increase in lift is considerable. A hoop foil forward in combination with a fully submerged foil aft give a substantial nose down moment, since increase in attitude reduces the draught of the hoop and counteracts the effect of incidence in increasing the lift, whereas the fully submerged foil has a lift increase which gives a powerful nose down moment. Furthermore, the total lift is not so greatly increased as in other combinations. Two hoops, for example, give a very substantial restoring moment, but the loss of lift forward due to reduction in draught is counterbalanced by an increase in lift aft associated with increased draught.

A similar argument, assuming a downward displacement in heave, is given in the left-hand column. The desirable behaviour is now a nose up moment to prevent diving and a lift to stop the increase in draught. Again a hoop forward and a fully submerged foil aft give the best compromise.

It is thus interesting to recall that current versions of the Schertel–Sachsenberg system have introduced a modified rear foil designed near the end of the last war, approximating to this condition; whereas earlier craft used hoops having considerable dihedral on their inner spans, both front and rear. Fig. 16 shows that the double hoop is particularly good in some respects but deficient in others. For example, its moment response is negligible in a heave disturbance. It will be recalled that such configurations tend to fall off the foils in a following sea.

The argument of Fig. 16 supports the current tendency, already discussed in connection with Fig. 6, of using zero dihedral fully submerged rear foils wherever structural considerations permit.

Dynamic Stability and Response in Waves

When a craft in steady motion is disturbed, it in general oscillates about the steady condition with gradually decreasing amplitude until the steady state is re-established. The craft is then dynamically stable. If the motion is stable and well damped the oscillation becomes a simple swing back, or convergence. If the damping is negligible the oscillation continues at constant amplitude. Instability causes a continuous departure from the steady condition or divergence. An unstable oscillation of gradually increasing amplitude can occur when coupling between two motions exists. This condition frequently arises in practice as, for example, in the case of control surface flutter, and design to avoid it cannot be based on simple physical principles but must involve detailed mathematical analysis.

The dynamic stability of a hydrofoil boat has many resemblances to that of an aircraft. It can be divided into two main groups of motions, longitudinal stability and directional stability.

Longitudinal stability in general involves a coupling of pitch and heave motions, defined mathematically by the equation of translational motion in heave, the equation of forward translational motion, and the equation of rotational motion in pitch. In the aircraft case, displacement in heave has no effect in itself, nor does forward distance travelled. The equation in pitch is affected by forward speed, in so far as it alters resistance. Thus a complete solution in principle gives two oscillations, one of short period, say 2 or 3 sec., and the other a long period "Phugoid" oscillation taking up to 60 sec. a cycle. If the effect of variation in forward speed is ignored, the equation of forward translational motion can be omitted and the other two give the short period oscillation only.

Although in the aircraft cases of greatest interest the motions are truly oscillatory, variation of the parameters which define an oscillation can cause it to change into the sum of two simple motions in each of which the amplitude either grows or decreases continuously. If both the components decrease a convergence back to the undisturbed condition is obtained. Otherwise the resultant effect is a continuous departure or divergence from the initially steady state. A simple divergent motion is of course usually a sign of static instability.

In the case of hydrofoil boats displacement in draught has very important effects, and the equations will in principle give two oscillations and a single component subsidence or divergence. In practice, however, the effect of change in forward speed can in most respects be neglected, and two oscillations are obtained.

So far it has been tacitly assumed that the behaviour can be considered in terms of small oscillation theory. In this the system is taken to be a conservative one, in that no energy interchange with external sources occurs, and the amplitudes are directly proportional to the magnitude of the initial disturbance. The motions are thus described by linear differential equations.

In the case of flying boat porpoising, small oscillation theory has proved valuable in explaining the approximate location of attitudes below which instability occurs, but the actual oscillations exhibit the characteristics appropriate to non-linear differential equations. There are, for example, limit cycles of definite amplitude. Very small disturbances may damp out or increase until a steady limit cycle condition is attained. Large disturbances decay until the same limit cycle is again reached. The nature of the disturbance, bow up or tail up, may affect the subsequent stability. The system is in fact non-conservative, energy being supplied from the forward motion, which exhibits a fluctuation in speed.

The stability of a hydrofoil boat in general approximates more closely to small oscillation type because in principal hydrofoil lift and moment characteristics are more simply related to attitude and draught than is the case with planing surfaces. This is especially true at high speed, but may be less true of ladders or Aquavion type ski-foil combinations than of simple hoops.

A major difference between aircraft and hydrofoil boat stability is the cut off of forces and moments imposed by the surface of the water. Once in the air the craft behaves virtually as a missile until the hydrofoils enter the water again. Fig. 18 shows a rather academic condition obtained on the electronic analogue computer of the Saunders-Roe Computer Department. A simple ski-foil is subjected to the forcing oscillation shown, representing encounter with a uniform chain of waves. Although the system is stable, impact at a critical point on the wave surface causes the ski-foil to skip, but the length and amplitude of the skip vary, tending to die away and then regenerate as a particularly unfavourable re-contact occurs. The behaviour shown arises from coincidence between a multiple of the forcing frequency and the natural frequency of the system. It will thus be seen that in periods where the skipping amplitude is building up the length of each skip equals a whole number of wavelengths. The major interest of the computation is that, although not shown here, the record contained an appreciable period subsequent to the start, in which little response occurred. When finally a critical phasing of the craft and forcing motions arose, the larger responses illustrated resulted. The quiescent period of such a run can often be equivalently greater than the length of a towing tank so that computer investigations will immediately show up conditions that may take a series of tank runs to disclose.

The example just discussed involves response in waves, not inherent stability behaviour in calm water. In the latter case, provided that instability is not severe, the motion will continue without the hydrofoils leaving the water for a sufficient period to obtain its defining characteristics. The surface cut off con-

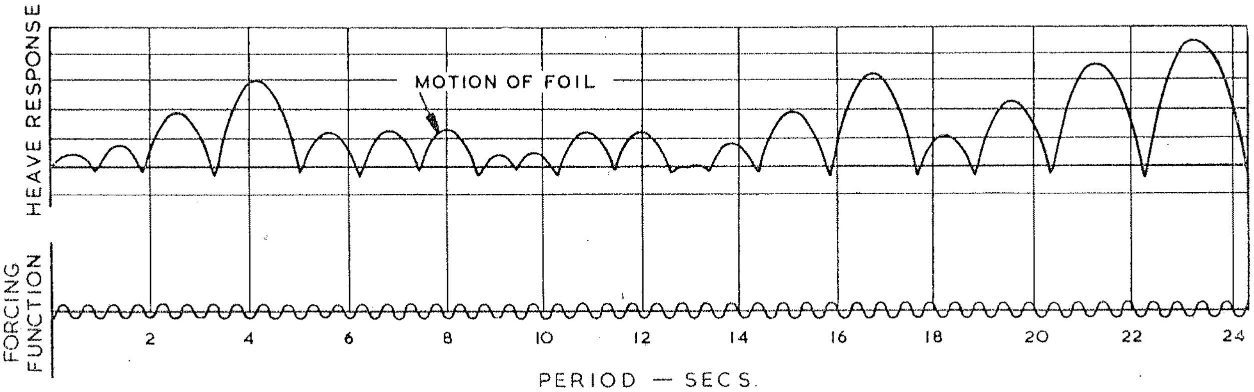


FIG. 18.—HEAVE RESPONSE OF A HYDROFOIL UNIT IN A REGULAR WAVE TRAIN, OBTAINED ON AN ELECTRONIC ANALOGUE COMPUTER

dition introduced into the computer for the previous example is then unnecessary, and simple small oscillation behaviour may be adequately descriptive.

Imlay[9] describes a number of results of hydrofoil dynamic longitudinal stability calculations, using small oscillation theory. Simple tandem systems were assumed and some cases of particular interest are shown in Fig. 19. The hydrofoils were fully submerged, but without incidence control, and had zero dihedral. There were three different distributions of area between the front and rear members. The longitudinal spacing was equal to ten times the chord that was appropriate to the case of equal area back and front. All cases had the same total area. Downwash at the rear foil due to the front foil was taken to be zero, but another calculation assuming downwash showed that its main effect was to shift the rear boundary of the stable region forward a little. Downwash is not in general as important a consideration as in the case of aircraft because of the greater chordal spacing and the effect of gravity in restoring a free level of water.

The stable range of *CG* locations extends from the front foil back for about half the "wheelbase." The natural *CG* position, giving approximately the same loadings in lb. per sq. ft., front and rear, lies most squarely in the stable range for the case where the front foil is largest. The stable *CG* positions that exist right forward require the rear hydrofoil to give a download, and this is quite unacceptable in practice, because if it comes clear of the water due to a disturbance, the craft will topple over on its nose.

The complete investigation reported in ref. 9 indicates that for stability reasons the "wheelbase" should be as large as possible. Dihedral is important for providing an adequate rate of change of lift with draught in the absence of mechanical incidence control. A low location of the centre of gravity is slightly advantageous, and reduction in the pitching radius of gyration increases the stable range of *CG* positions.

In aeronautics lateral or directional stability, as it is often called, involves a coupling of rolling, yawing, and sideslipping motions, defined mathematically by two moment equations and a translational equation respectively. Angle of yaw is angle due to rotation about an axis perpendicular to the craft planform. Angle of sideslip arises from a sideways translation in combination with a forward speed. Effects of fluctuation in forward speed are found to be negligible. The solution of the equations comprises in principle one oscillation and convergences or divergences. The oscillation is a Dutch roll with a period of about 5 sec., involving both yawing and rolling components. There is a rapid convergence in roll, called roll damping, which decays in about a quarter of a second. Finally, there is either a divergent wander off course, leading to a spiral motion, or a convergence taking, say, 30 sec. to half amplitude.

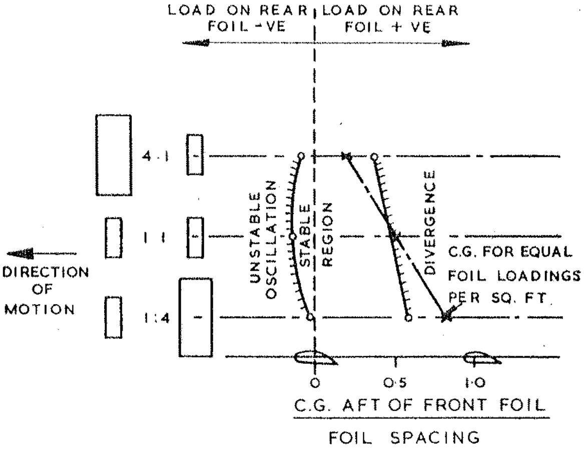
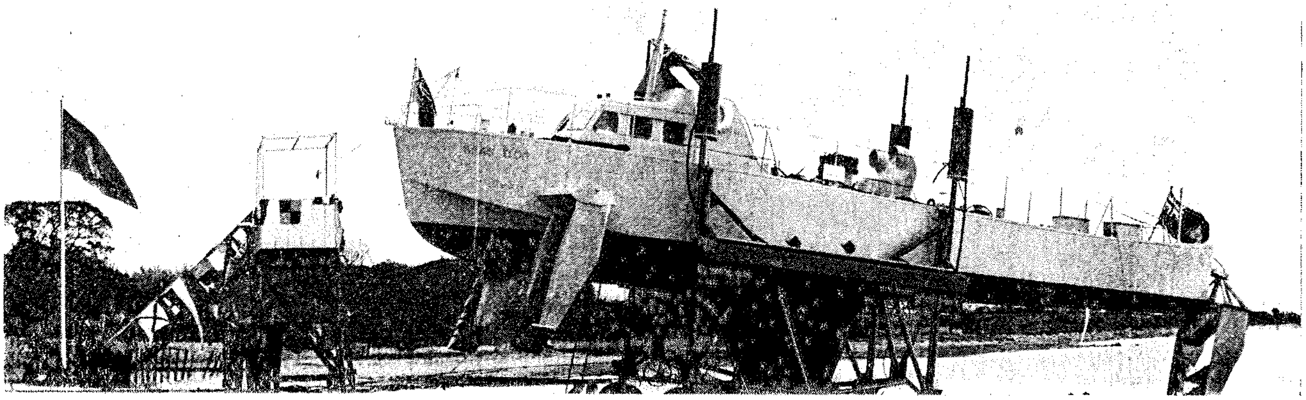


FIG. 19.—EFFECT OF LONGITUDINAL CENTRE OF GRAVITY POSITION ON STABILITY

Very little has been published on the dynamic lateral stability of hydrofoil boats. A heeling motion can occur both in full scale and in model tests, but the importance of coupling between this and yaw or sideslip has not been reported upon.

It would be very interesting to make a comparison between all the main hydrofoil systems using an analogue computer. Coupling between longitudinal and directional stability is in general unlikely to be important, and it might be possible to treat heel as an uncoupled motion in some cases. The number of degrees of freedom to be allowed for in any particular calculation are quite manageable on a computer, but can be excessively laborious by hand calculation because of the additional complication of variation of lift and moment with draught, which is absent from the aircraft case.

Aeration and cavitation will sometimes be important. In heel, for example, downward vertical velocity on the side rolling in will increase the effective incidence, and at high speed the increase can be enough to cause extensive cavitation. This will make the variation of hydrofoil lift with attitude quite non-linear. Unfortunately, model tests are not representative in this respect either, unless undertaken at full-scale speeds, which is rarely possible in a systematic way. Water tunnel tests can give basic variations of hydrofoil lift with attitude and so forth, but cannot study the motion of the complete system. Computers can allow for non-linearities, and perhaps more importantly they often indicate linear approximations which prove to be adequate for design purposes. Calculations using analogue computers where possible and the best basic information available are considered to provide the most promising systematic approach to the problem of achieving satisfactory stability in the presence of cavitation.



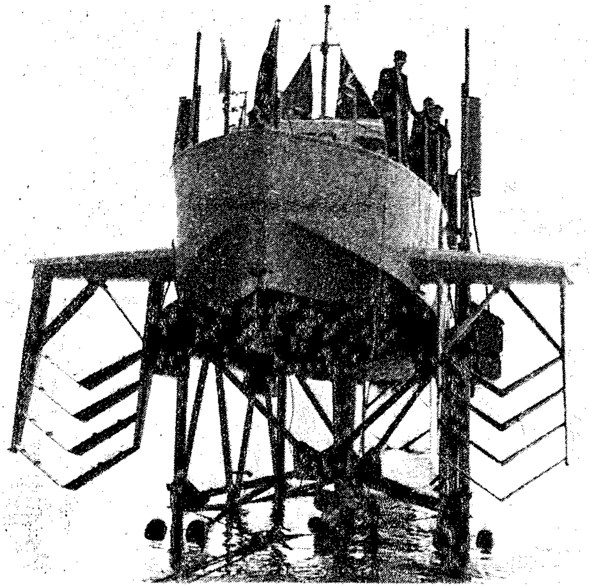


Fig. 20a.—Launching of the "Bras d'Or" at Anglesey

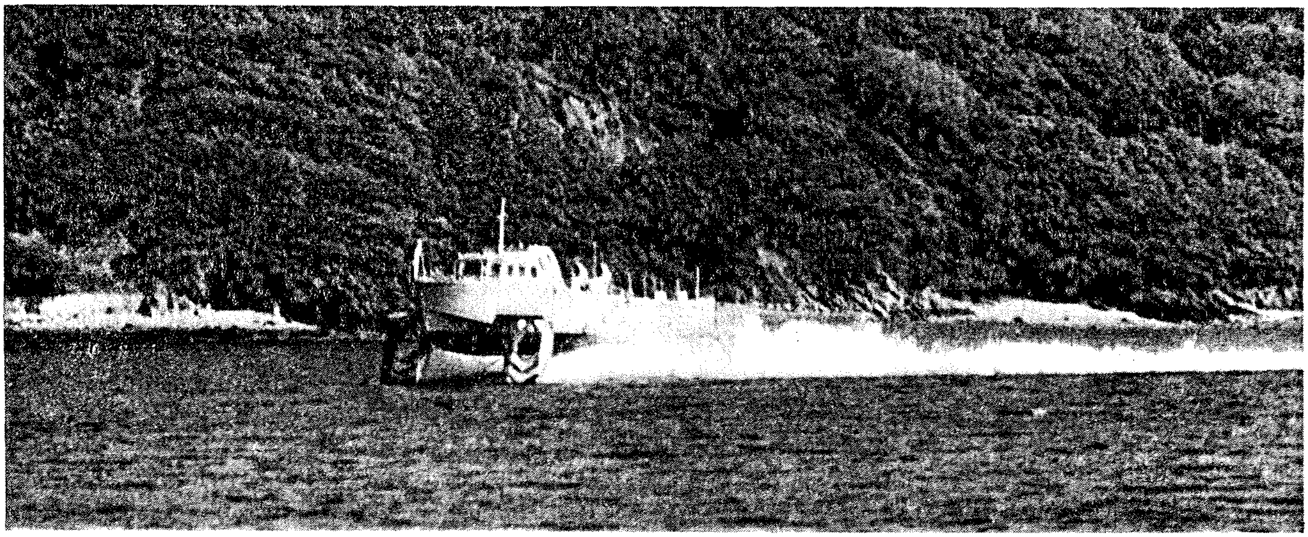


Fig. 20b.—"Bras d'Or" in Menai Straits during functioning trials

Model Test Work at Saunders-Roe in connection with the "Bras d'Or" Project

General

Earlier sections of this paper have indicated the importance of research on hydrodynamic models, for the successful development of a hydrofoil system. Such investigations can be undertaken much more economically, rapidly and systematically than is possible under full-scale conditions. The experiments are, in general, concerned not only with resistance and propulsion considerations, but with dynamic behaviour in all its aspects. Hydrofoil sections are tested in cavitation tunnels and complete hydrofoil units are run under cavitation conditions in very high speed tanks.

Although the model work is so useful, the complexities of cavitation, propulsion interference, the effects of practically obtainable hydrofoil accuracies and surface finishes, and seaworthiness in random sea conditions, require trials to be made up to full scale design speed on a craft which carries a crew.

These remarks will be illustrated in this section by reference to some aspects of the extensive model investigations made by the staff of the Saunders-Roe test tanks in connection with the *Bras d'Or* project. These tanks are located at Osborne, Isle of Wight. The work took as its point of departure extensive full-scale trials that had been made for several years previously by the Canadian Defence Research Board at its Naval Research Establishment. These trials employed a 45-ft. craft of 5½ tons displacement, mounted on Bell–Baldwin ladder foil units.

Launching and Preliminary Functioning Trials of the Full-Scale Craft

Before discussing the model tests, brief further reference will be made to the full-scale craft. In Fig. 20 it is shown prior to launching and undergoing preliminary functioning trials in the Menai Straits. Fig. 2, referred to at the beginning of the paper, includes another view of the trials.

An unusual feature of the *Bras d'Or* is the employment of a transmission system comprising a horizontal nacelle mounted at the lower end of a single large strut positioned amidships. Right-angled bevel gear transmissions, located within the strut and nacelle, drive propellers at the nacelle extremities. The aft propeller is a "Rotol" controllable and reverse pitch unit. This propulsion system was employed so as to keep separate the behaviour of the hydrofoils and the method of powering. The orthodox solution, with an inclined shaft anchored to the rear foil unit, introduces considerable interference between the shaft and propeller and the rudder hydrofoil unit.

The name *Bras d'Or* was chosen by the Canadians to commemorate the pioneer work on hydrofoil craft carried out by the Bell family. It is the name of a lake in Nova Scotia where the Bells had a permanent home and did much of the original work on the Bell–Baldwin system. It was here, in 1919, that the H.D. 4 became the fastest boat in the world.

Towing Tank Tests

Altogether about 20,000 test runs on models of the *Bras d'Or* have been made in the three test tanks, most of them being in the towing tanks.

Resistance, spray behaviour, stability, and response in regular head and following seas have been investigated on a number of models. Impact accelerations have been measured. The upper pictures of Fig. 21 show a one-fourteenth scale model under test in the No. 1 towing tank. At the top the craft is trimming up for take-off and the front foils are lifting the bow almost clear, thus giving a very clean spray pattern. The next picture shows a high-speed run with one foil fully immersed and the next one up just touching the water. The absence of immersed strut foil junctions, at high speed, gives a good lift-to-drag ratio. The level trim and low spray and wake will be observed. In these tests the craft is free to rise and trim and is of correct scaled weight and inertia. Thrust moment is represented.

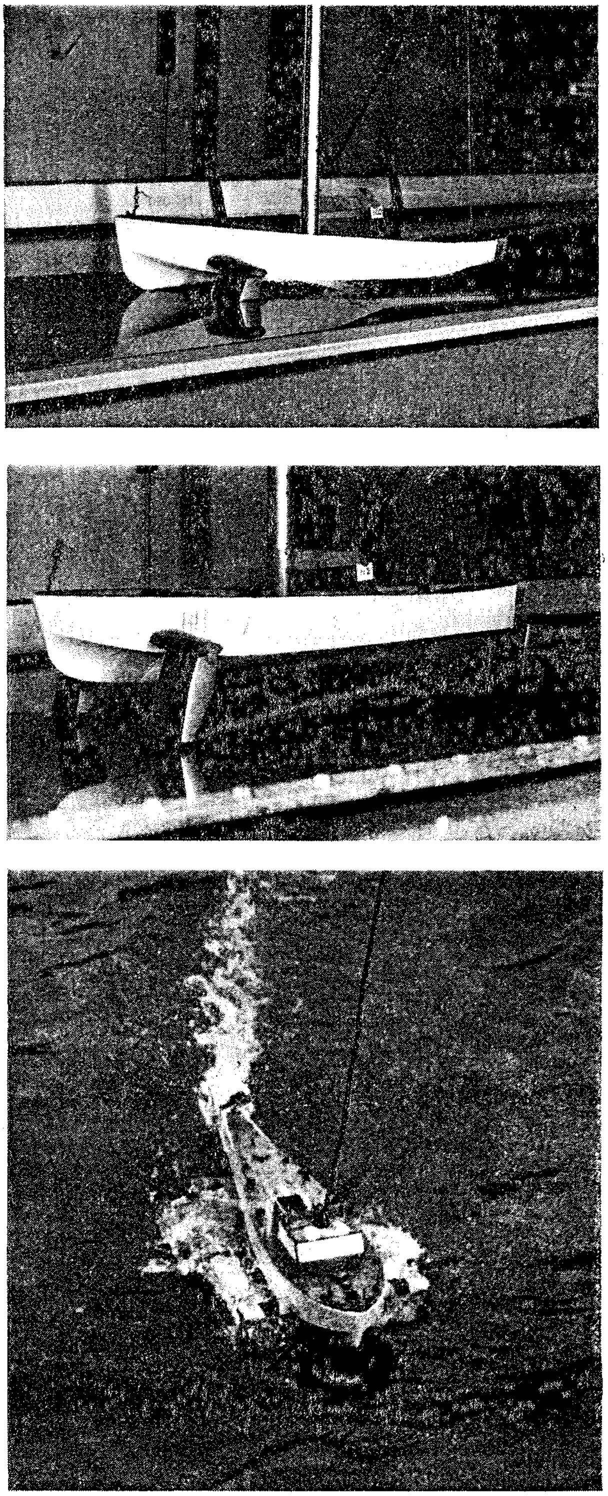


FIG. 21.—1/14TH SCALE MODEL OF "BRAS D'OR" UNDER TEST AT COWES

The towing tests have proved particularly useful in studying response in a wide variety of wave conditions. The transom width and wide sponsons employed on the full-scale craft were developed, in conjunction with the detailed design of the foil units, to give good following sea behaviour.

The fences on the hydrofoils shown in Fig. 21, which restrict aeration, were developed with regard to position, shape, and alignment by model investigations.

Tests have also been made, on a series of models of varying scale, of components such as isolated hydrofoils, hydrofoil units, and propulsion nacelles and supporting struts. Such results are important for checking design estimates of lift and drag and for providing the variations of lift with draught and attitude necessary for making stability calculations.

Turning Tests in the Free Manœuvring Tank

The lowest picture of Fig. 21 shows low-speed turning tests on a self-propelled model in the free manœuvring tank. The deck and superstructure are correctly represented in this model. The craft was driven by a small electric motor via a representative bevel gear transmission system. Various rudder angles and rates of application of rudder were investigated. A detailed analysis of turning behaviour was obtained from films. The cameras were so positioned above the level of the tank that a picture sequence of a turn could be superimposed on a standard perspective grid of the manœuvring area.

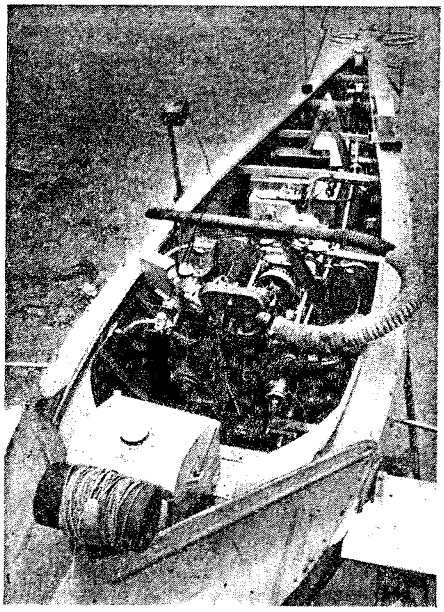
Tests on a Radio-controlled Model at Sea

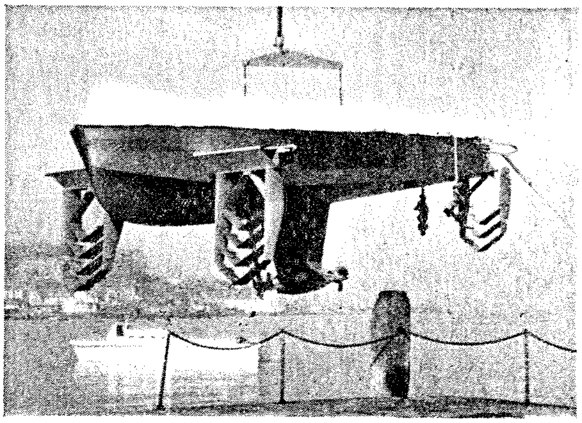
The tank tests were supplemented by investigations into the behaviour of a larger radio-controlled model, which was operated at sea up to speeds of more than 20 knots. The craft has been used to obtain additional evidence on known scale effects and to examine behaviour in more complex seas than those generated in the tanks.

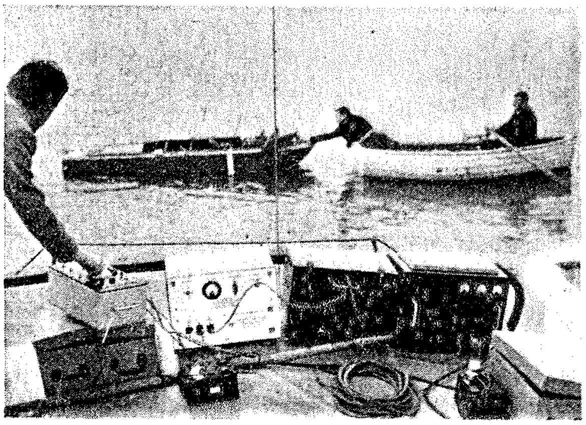
The model is actually to scale 1/4·4, but for simplicity is generally referred to as of "1/4 scale." Several views of it are shown in Fig. 22. Very careful attention to structural and instrumentation design was necessary in order to achieve a correctly scaled weight. The power plant was the heaviest single item, and very few engines having a suitable power-to-weight ratio were available. The single-cylinder J.A.P. 250 c.c. racing unit, manufactured by J. A. Prestwick Industries Ltd., was finally chosen. The Amal T.T. racing carburettor, which provides an unobstructed choke tube, was modified for the tests to allow for changes in craft attitude and flooding associated with vibration. The petrol-to-air ratio was kept within acceptable limits by replacing the standard single float chamber by two identical units located fore and aft on opposite sides of, and equidistant from, the main jet centreline. They were mounted on the hull structure to isolate them from the engine and this completely eliminated float bounce and the attendant flooding and over enrichment.

Radio control of the throttle slide was effected by means of a servo motor. Manual controls were fitted also for level running and turning whilst afloat, prior to switching over to radio control. The ignition control was arranged to "fail safe," so that the engine would automatically cease running if radio contact was lost. In addition, a time switch was included so that if the relay did not disengage after de-energizing, the uncontrolled length of run would be comparatively short.

The transmission system was simple, but required careful engineering in order to combine lightness with the ability to transmit relatively high power. The engine crankshaft was linked







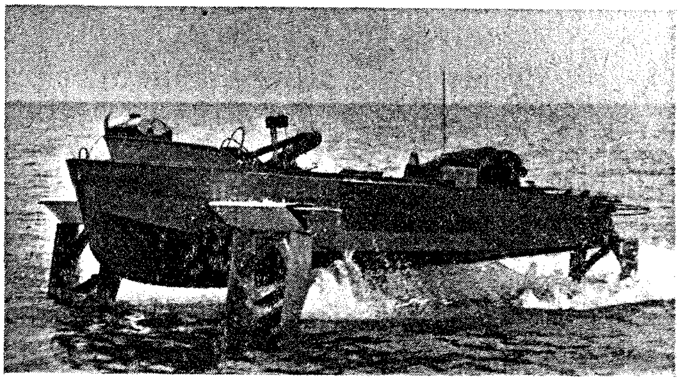


FIG. 22.—1/4·4 SCALE SELF-PROPELLED RADIO-CONTROLLED MODELS OF "BRAS D'OR"

o the main transmission assembly by a chain drive and a simple spring-loaded cone clutch was used to isolate the engine during starting. The clutch output shaft drove bevel gears incorporated in a torque dynamometer and thence two sets of main transmission bevel gears, which turned the shafting through right-angles at the top and bottom of the propulsive strut-nacelle unit.

The propellers were made in manganese bronze by the Ship Division, National Physical Laboratory. The aft unit, which was of an extreme high-speed sub-cavitation design recommended by Professor Burrill, was built in the form of three separate blades. These could be locked in different positions on the hub, to simulate the various settings of the full-scale controllable pitch propeller.

A separate shaft linked by chain drive to the engine drove a mechanical clutch unit which engaged with the rudder hydrofoil at the command of electrical relay circuits and provided steering action.

The instrumentation system was designed around a type A. 22 miniature recorder manufactured by the Société de Fabrication d'Instruments de Mesure (S.F.I.M.). This instrument uses potentiometer pick-offs and ratiometric indicators, which make it independent of fluctuations in supply voltage. The same principles were therefore retained in additional special dynamometers that were manufactured by Saunders-Roe (S-R).

The following table lists the variables recorded and the method of measurement adopted in each case.

Variable	*Measuring method*
Vertical acceleration	S.F.I.M. Accelerometer transducer and S.F.I.M. ratiometer recorder.
Angle of heel ..	S.-R. pendulum fitted in S.F.I.M. recorder.
Draught	S.-R. probe, and galvanometer in S.F.I.M. recorder.
Rate of turn ..	S.F.I.M. rate gyro and S.F.I.M. ratiometer recorder.
Water speed ..	S.-R. log driving a contactor, and event marker in S.F.I.M. recorder.
Thrust	S.-R. dynamometers and S.F.I.M. ratiometer recorders.
Torque	S.-R. dynamometer and S.F.I.M. ratiometer recorder.
Engine revolutions	Contactor on engine and event marker in S.F.I.M. recorder.
Rudder angle ..	Potentiometer and S.F.I.M. ratiometer recorder.

Draught was measured by means of a series of probes located at the leading edge of the transmission strut. When the craft was at rest a common electrode was shorted to all the probes by salt water. As the hull rose, the number of resistors in parallel decreased and a galvanometer showed a definite step in recording for each resulting change in current.

The thrust dynamometer comprised a spring which was compressed by a linkwork system operated by the movement of a thrust collar on the propeller shaft, the travel being proportional to the load. The spring motion was transferred to a potentiometer pick-off. A similar type of dynamometer was used for torque measurement, the movement being transmitted from a special torque box containing the dynamometer bevel gears already mentioned.

A six-channel radio link between the craft and the control base was used, each signal channel consisting of an audio frequency oscillator, the frequencies varying between 2·5 and 6·9 kc/sec. These were impressed on a 27 mc/sec. carrier wave in the normal way. Thus the command signal received at the model was a combination of audio tones which were separated into the appropriate components by means of a filter unit. This operated the relays which energized the control actuators.

The separate oscillators were operated continuously, with their outputs connected to the transmitter but shorted to earth. Operation of the appropriate panel control removed the shorting link and the signal was transmitted.

The six channels were employed as follows:—

Ignition ..	..	On/off switch
Recorder	..	On/off switch
Throttle	..	Two channels
Rudder ..	..	Two channels, port and starboard movement

The power source in the model was a 24-volt secondary battery system comprising a bank of lightweight cells using silver–zinc reaction. The cells employed are manufactured by Venner Ltd. under licence to the André–Yardney system. The above system weighs only about 9 lb. as compared with about 42 lb. for a 24-volt, 15 ampere-hour, aircraft battery of similar capacity.

The Place of Hydrofoil Boats in the Vehicular Field

So far this paper has considered the history and design problems of hydrofoil boats, and some current activities concerning such craft. Their place in the general field of transport and their likely future will now be discussed.

Ideas contained in the lecture "What Price Speed?" by Gabrielli and von Karman,(10) have been taken as a basis for argument on the comparative merits of different forms of transport. These ideas have been extended by Dr. K. S. M. Davidson.

The left-hand diagram of Fig. 23 shows envelope curves of maximum speed in knots against installed horsepower per ton for various types of marine craft and aircraft. There will be many less efficient craft of any given type, lying to the left, but not to the right, of the corresponding envelope. Thus the envelopes represent the minimum specific powers required to reach any given speed and themselves define a boundary curve of rather complicated shape shown as a dashed line, and also an overall "speed limit line" which is straight and gives conditions that only the best of the specific vehicle curves approach, and then only over short ranges. The area between the dashed and chain-dot lines, roughly triangular in shape, is a challenging one for marine craft and aircraft. Some land vehicles come within it, for example autorails at 65 knots for about 6·5 hp per ton, and motor cars at 70 knots for 30 hp per ton. Railways are extremely efficient and come to the right even of the speed limit line, for example diesel-electric trains can achieve 95 knots for 4 hp per ton, and large American freight trains 50 knots for 1 hp per ton.

The only marine craft or aircraft within the triangle is the airship (not shown) at, say, 60 knots for 20 hp per ton!

The curve for hydrofoil craft shows to better advantage than that for planing craft, as would be expected from previous discussion, but at the low speed end they both flatten badly and above 50 knots the power requirements favour aircraft. The low speed flattening is not surprising, since neither planing craft nor hydrofoil boats are very suitable for continuous operation at such speeds.

The indication that 50 knots is an upper limiting speed for hydrofoil boats is interesting but by no means conclusive. The right-hand diagram of Fig. 23 shows that above about 35 knots installed horsepower per ton increases almost as the cube of maximum speed. This of course corresponds to variation of resistance as speed squared. If the resistance remained constant, as ideally it might, especially if air propulsion were used to eliminate appendage drag, then the development marked V in the figure might be possible. This indicates a maximum speed at which hydrofoil craft could have a better power requirement than aircraft of about 100 knots. If resistance increased linearly

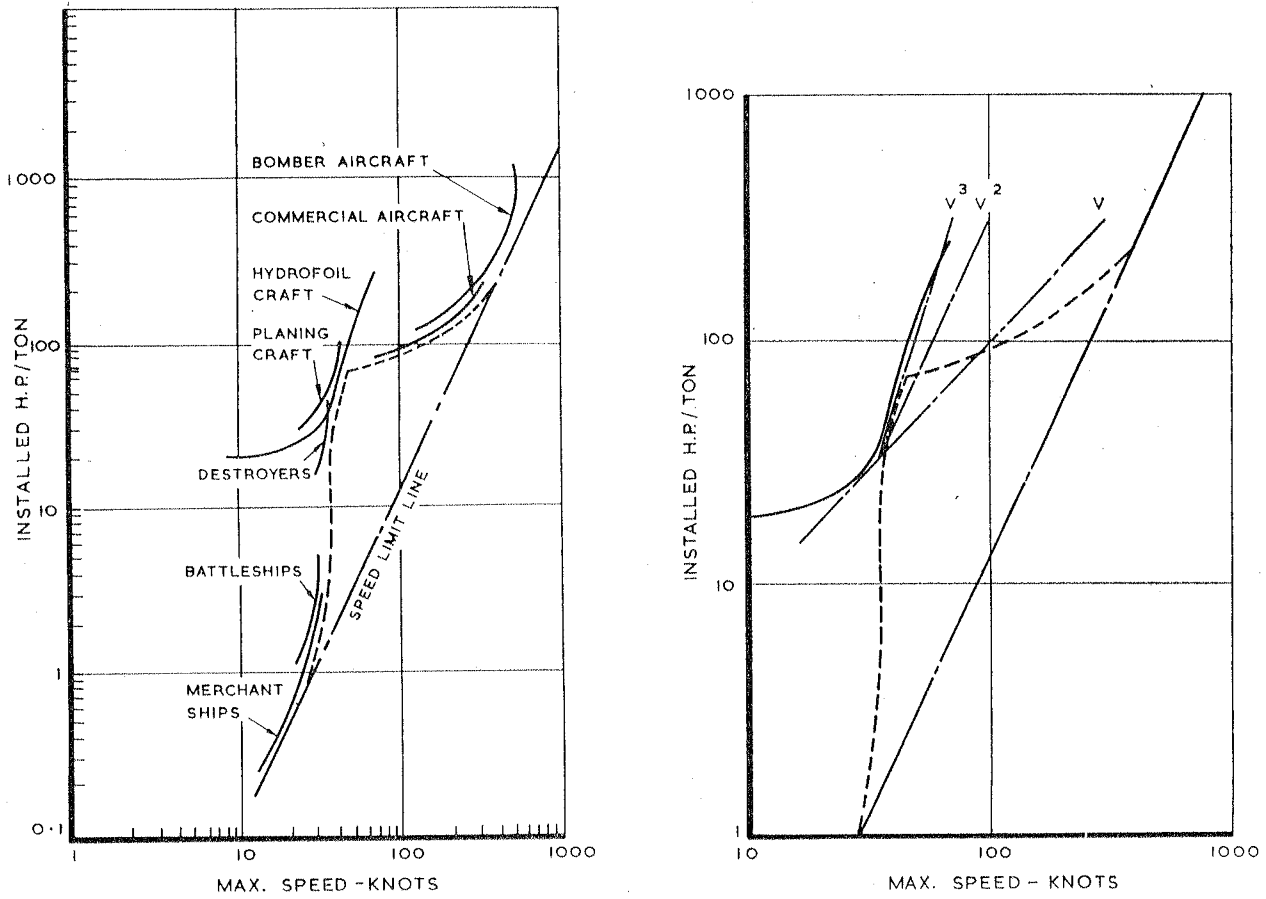


FIG. 23.—THE POWER-SPEED-WEIGHT RELATION FOR SHIPS AND AIRCRAFT

with speed, the V^2 curve would apply and the gain compared with current practice would not be substantial. The 50- to 100-knot speed range could only be achieved by the successful development of super-cavitated hydrofoil units, and perhaps air ventilation devices.

Fig. 24 shows the boundary curves of Fig. 23 in a rather different form. By plotting W V^2/H P (W in tons, V in knots) the speed limit line becomes horizontal at a value of about 750, shown here as the top of the graph. The merchant ship curve approaches this value at about 18 knots, whereas for aircraft the tangency point is around 500 knots. In between these two speeds the optimum power requirements can reach up to 30 times the values given by W V^2/H P = 750, and the worst condition occurs in the region of 50 knots. This speed is thus a fundamentally critical one for travel in air or water. The diagram also shows conditions at constant η L/D, where η is an efficiency factor given by, e.g., ehp/(installed hp):—

$$\eta\ \mathrm{L/D\ equals}\ 6{\cdot}9\,\frac{\mathrm{W\,V^2}}{\mathrm{H\,P}}\Big/\mathrm{V}$$

Thus for the merchant ship and aeroplane conditions just mentioned it is 288 and 10·4, respectively.

An "ideal" value for η L/D at 50 knots, giving a vehicle on the speed limit line, would be 104, which at an η of, say, $\frac{1}{2}$ would require an L/D of about 200. This shows how far any presently envisaged marine craft or aircraft are from such a target. It is, however, interesting to consider what performance might in due course have been obtainable with hydrofoil boats. A civil airliner can have an L/D of about 15, and a similar value should thus be obtainable on a hydrofoil. In fact, such L/D's have already been achieved on small research craft. Marine propulsion systems can have efficiencies as high as 70 per cent at a speed of 30 knots (e.g. the Supramar boat), and considerably larger values are possible at high speed, using air propellers.

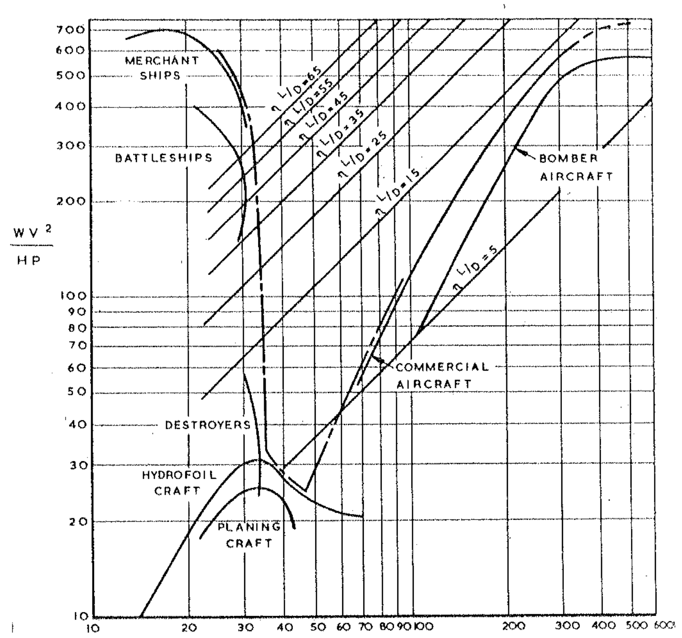


FIG. 24.—L/D REQUIREMENTS IN "CRITICAL TRIANGLE"
(W and V in tons and knots respectively.)

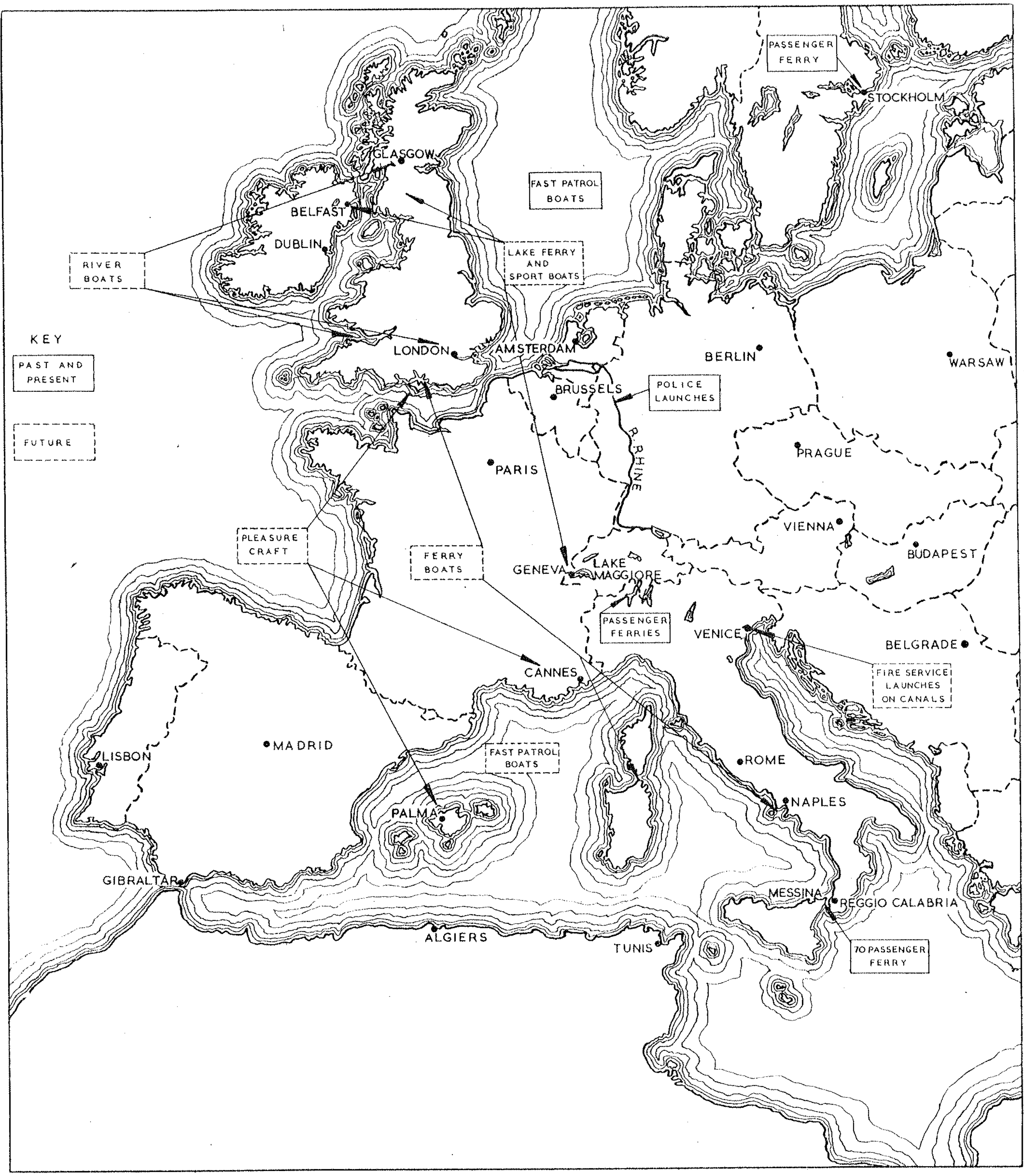


Fig. 25.—Past, present, and possible future roles for hydrofoil craft

These two values in combination give an η L/D of 10·5, which crosses the aircraft boundary at 130 knots. If an even more extreme but perhaps not impossible L/D of 21·4 is taken, then η L/D is 15, and at this value the hydrofoil boat has a lower specific power requirement than aircraft, at all speeds.

A recent paper by Dr. Davidson[11] predicts that deeply submerged submarines may ultimately have performances indicated by:—

$$W V/H P = 12{\cdot}5 \text{ at } V/\Delta^{1/6} = 11$$

Thus taking	Δ tons =	10,000	20,000	40,000
then	V knots =	51	57	64
	$W V^2/H P$ =	640	710	800

These results approach the limit line in the 50-knot range! However, this is another story.

The Future of Hydrofoil Craft

The somewhat visionary observations made in the final paragraph of the previous section are here followed with a more sober appraisal of the practical possibilities and applications of the hydrofoil boat in the immediate future.

Operational duties for which hydrofoil craft have already reached a stage of developed design are illustrated by Fig. 25 and are listed below.

1. Fast passenger ferries on lakes, rivers, canals, and coastal waters.
2. Coastguard and Customs launches, police boats, fire launches, air-sea rescue craft, and work boats.
3. Sporting and pleasure craft such as fast runabouts and boats for use in water ski-ing.

There are also obvious service uses. Such craft could be utilized for transportation purposes and fast patrol and assault duties. For the latter, existing hydrofoil systems may be suitable. It is claimed that pressure mines are insensitive to the passage of foilborne craft.

As more hydrofoil craft come into service and experience of handling them in rough seas and narrow waters becomes widespread, the doubt and distrust with which they are sometimes regarded will disappear. The Baker, Hook and Carl systems are already marketed in the United States, for use on small pleasure craft, and such an application of simplified versions of the Supramar and Aquavion systems is equally feasible.

A most important factor in increasing the utilization of hydrofoil boats for more serious purposes would undoubtedly be the provision of a disposable load greater than the value of about 25 per cent all-up weight at present obtainable. As aeronautical experience has so amply shown, improvement in structure and power plant weights comes only from building and yet again building actual operational craft.

Concluding Remarks

It has been the aim of this paper to demonstrate that hydrofoil craft have a bright future provided that sufficient technical care is taken in designing them. It cannot be too strongly emphasized, however, that the problems arising are as difficult as those encountered with transonic aircraft, and similar technical facilities and experience are necessary to ensure success.

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The author would also like to acknowledge the invaluable assistance he has received from those people, too numerous to mention individually, who have supplied information and discussed design problems with him.

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DISCUSSION

Mr. H. M. Barkla, M.A., B.Sc. (*Associate*): I am very pleased to be the first to congratulate Mr. Crewe on this first-class paper. Though I have not been personally concerned in research on hydrofoils, I can speak as one of those interested in the subject, who have so far felt starved of quantitative information. This paper will be hailed with delight by a great number of people, who will be grateful to Mr. Crewe for giving them so much to think about, as well as data on which to base their back-of-the-envelope sums.

Among the systems discussed is that of the Hook Hydrofin. Mr. Hook is a British inventor, and, if he had not been out of the country, I am sure he would have been here. Having for some years taken an interest in his system—not, may I say, a financial interest—I feel that members may care to see a short film showing the behaviour-pattern of this highly individual marine creature. This demonstrates the capacity of the system to ignore small waves, but to give the vessel a rise and fall with waves of a height greater than the already quite good clearance height. The feelers, with spring-loaded heel to the jockey float, are kept in reasonably close register with the water surface ahead of the vessel by a combination of gravity, spring loading, feedback from the foil and friction damping, which give the characteristics found necessary in practice. (*A film was then shown.*)

Mr. H. P. Rader: Mr. Crewe has collected a great deal of information which should prove very useful to those interested hydrofoil boats. It is perhaps inevitable that in covering so uch ground the author has made some statements which are ther controversial.

Comparing the merits of various hydrofoil configurations, comes to the conclusion that cavitation and structure requireents may favour ladder systems for high-speed designs. In g. 5 he has drawn a boundary between craft with monoplane ils and those with ladder foils. Apart from three small craft ere is only one sizeable craft with ladder foils on the high-speed de of this line. I presume this is the *Bras d'Or*. Two sizeable onoplane craft with speeds above 50 knots, however, are left it, the 17-ton Tietjens VS–7 and the 46-ton Schertel–chsenberg VS–10. If the Tietjens boat did achieve 55 knots ere is no reason why she should be ignored, though she may ave been unsatisfactory for other reasons. The speed of 60 knots uoted for the Schertel–Sachsenberg VS–10 was the design speed. he craft was destroyed during an air-raid on Hamburg on the e of her launching day. It appears, however, from the results model tests that, fitted with suitable propellers, the boat would ave been capable of the speed quoted.

It is true that structural requirements may favour ladder stems for high speeds, but in my opinion this does not apply far as cavitation requirements are concerned. The increase in sistance due to partial or full cavitation is bound to be higher r ladder foils than for monoplane foils because of the greater umber of joints between foils and struts in the ladder rangement.

It is perhaps fair to say that had there been more monoplane ydrofoil boats with horsepower-weight ratios of the same order for the ladder type boats like the HD–4 and the *Bras d'Or*, ey would have achieved speeds of the same order.

Mr. Crewe says rightly that the hydrofoil resistance per ton displacement is in general a function of absolute speed and ot of speed coefficient. The same applies to the power-weight tio of hydrofoil craft, because

$$\frac{\text{bhp}}{\Delta} = \frac{2{,}240\,R}{550\,\Delta} \times \frac{1\cdot689\,V}{\eta}$$

$$= 6\cdot88\,\frac{R}{\Delta}\,\frac{V}{\eta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

ith V in knots and η = propulsive efficiency as used by Crewe here both R/Δ and V/η are functions of absolute speed.

Hence the merits of different hydrofoil configurations can asily be assessed from a graphical representation of powereight ratios as function of speed. Numerical values of craft r which data are available are shown in Fig. 26. Also shown a power-weight ratio curve which follows from Mr. Crewe's pproximation

$$\eta\,\frac{L}{D} = \eta\,\frac{\Delta}{R} = 12\cdot9 - \frac{V}{6} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

hich, when substituted in (1), gives

$$\frac{\text{bhp}}{\Delta} = \frac{6\cdot88\,V}{12\cdot9 - V/6} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

his approximation is obviously limited to a certain speed range ecause it gives values approaching infinity as $V/6 \rightarrow 12\cdot9$, i.e. as e speed approaches 77·4 knots.

Fairly reliable estimates of power-weight ratios for the higher peed range should be possible by separate assessment of R/Δ nd V/η. A tentative curve for tandem arrangements of monolane hydrofoils carrying approximately equal loads fore and aft as been added in Fig. 26. The resistance-displacement ratios n which this curve is based are shown in Fig. 27. The values r the single hydrofoil are deduced from results of cavitation nnel tests on a narrow-bladed propeller. The corresponding ft coefficients and foil loadings in tons per sq. ft. are shown

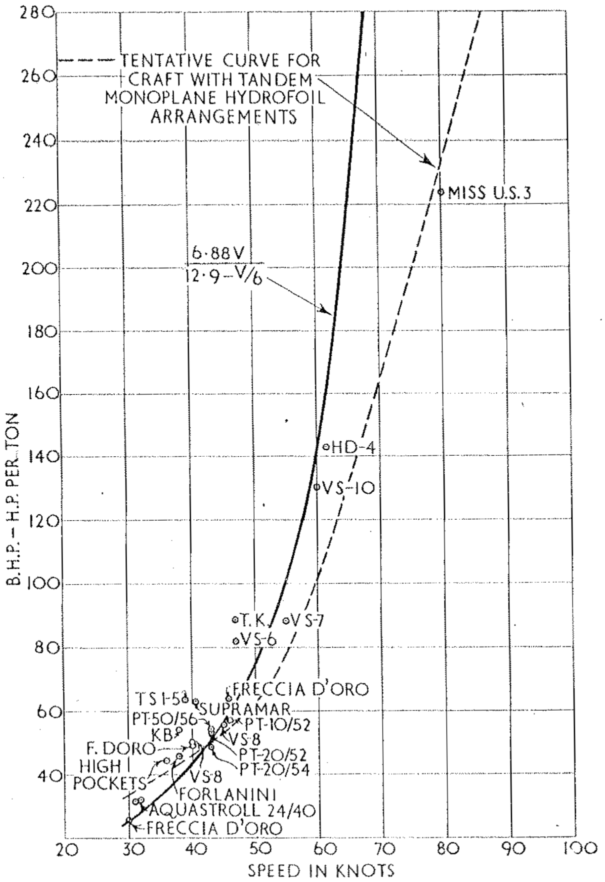

FIG. 26.—POWER-WEIGHT RATIOS OF HYDROFOIL CRAFT

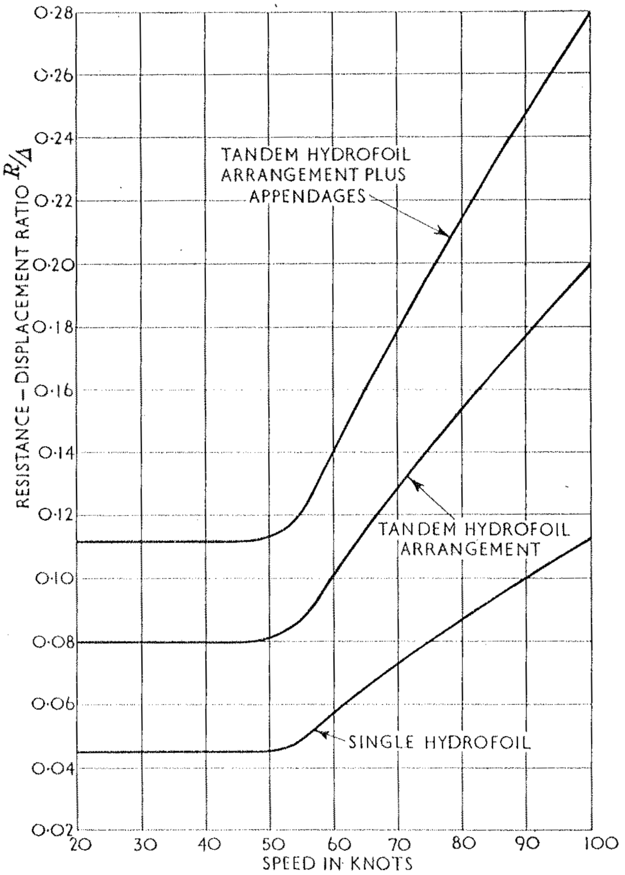

FIG. 27.—RESISTANCE-DISPLACEMENT RATIOS OF HYDROFOIL CRAFT

in Fig. 28. The drag-lift ratios for a single hydrofoil shown in Fig. 27 are not the best results obtainable but were chosen with regard to reasonable foil loadings. The resistance-displacement ratio curves shown for the tandem hydrofoil arrangement with and without appendages are based on conservative estimates and should be realizable without great difficulties. It is assumed, however, that super-cavitating conditions can be maintained on surface-piercing hydrofoils at speeds in excess of about 60 knots. This should be possible by means of fences on the suction side.

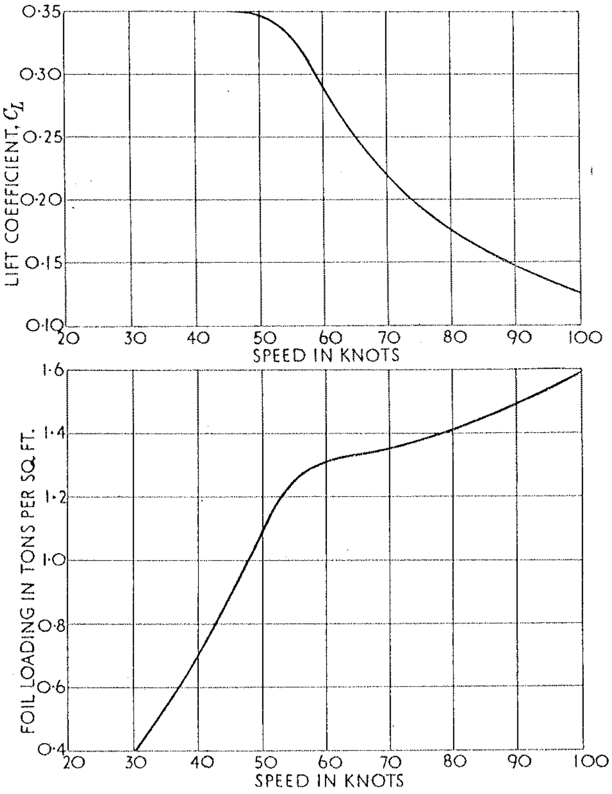

FIG. 28.—LIFT COEFFICIENTS AND FOIL LOADINGS OF HYDROFOILS

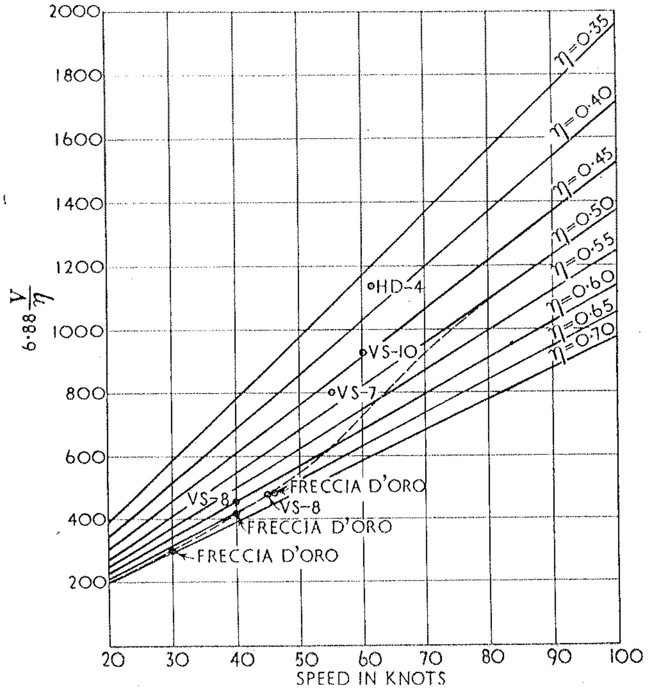

FIG. 29.—SPEED-EFFICIENCY RATIOS OF HYDROFOIL CRAFT

Values of the speed efficiency ratio $6{\cdot}88\,V/\eta$ are given in Fig. 29. Lines for constant efficiency values are shown in addition to numerical values for boats. The solid line curve represents the values used for the power-weight ratio curve in Fig. 26. The values for high-speeds may seem optimistic, but it appears from cavitation tunnel tests that at cavitation numbers below 0·3 the efficiencies for super-cavitating conditions remain almost constant at the same rate of advance. The efficiency as used should not differ much from the propeller efficiency because appendage resistance is included in the resistance displacement ratio of the whole arrangement as shown in Fig. 27. Propeller efficiencies of the order of 55 to 60 per cent appear to be possible at speeds up to 100 knots and more. The amount by which the efficiencies, as used in the speed efficiency ratio, differ from the propeller efficiencies will depend mainly on the angle of the propeller shaft relative to the direction of flow and on the degree of disturbance in the velocity field in which the propeller has to work. In a tandem arrangement of contra-rotating propellers as used on the *Bras d'Or*, for instance, the after propeller will be working under adverse conditions. The good efficiency of the front propeller is also not fully utilized because the shroud parts in the slipstream will have an appreciable increase in resistance. Moreover, shroud and after propeller are exposed to the danger of cavitation erosion.

Investigation of propulsion systems for high-speed craft in towing tanks can give misleading results. A far better assessment of the physical relations can be obtained from tests of the propulsion system in a cavitation tunnel. It appears even feasible to test the whole underwater system of hydrofoil boat models in a cavitation tunnel with free water surface in the working section.

The problems which have to be solved before boats with super-cavitating hydrofoils capable of speeds between 60 and 100 knots become a reality are not easy, but should be within the scope of modern technology. The most difficult problem I can foresee is that of finding a customer who will pay the bill.

Mr. A. Silverleaf, B.Sc. (*Member*): Mr. Crewe's paper excellently fills a very important gap in our TRANSACTIONS. It is the most thorough discussion of the general problems of hydrofoil boats that has yet appeared, and for those of us who have a personal interest in these rather unusual and exciting craft it provides a great deal to think about and to digest.

My own interest in hydrofoil boats started in 1942, when I joined the team under Dr. Allan at Dumbarton, who were then developing what we came to know as M.T.B. 109, whose genesis Mr. Crewe mentions. I hope that one of the few people now alive who can give anything like a complete story of that boat will take the opportunity provided by this paper to supplement the very full data the author gives on other hydrofoil craft. Since then I have maintained a general interest in "ships with wings," particularly during the last two or three years, and I have had the opportunity to travel on one or two of them. Last year I travelled on the *Aquastroll* 24/40 some six months after Mr. Crewe did so, and although I was very impressed, I did not come away with quite such glowing impressions of her behaviour as he gives in his quotation from the designer's description of the boat.

There is one almost surprising omission from the paper; I would have expected to see a section devoted exclusively to propulsion problems, which only get occasional mention. There are many problems associated with the propulsion of hydrofoil boats, such as the best methods of mounting orthodox marine propellers. Mr. Crewe showed us in his film the unusual mounting of the two screws of the *Bras d'Or*; I would be interested to hear how this rather complicated transmission has behaved. He also draws our attention, in passing, to the air engines fitted to the Carl XCH-4, but this is perhaps a rather double-edged feature. I have heard it suggested that if the stub wings were extended by about 6 ft. on either side, this craft would fly at about 200 mph. This raises a fundamental point, of course; is the air–water interface the best place for really high speeds?

However, I will confine my main comments to the section of the paper on cavitation and aeration. I am a little puzzled by the argument on page 346, which seems to imply that there is an absolute limit on hydrofoil loading imposed solely by insistence on complete freedom from cavitation. I agree with Mr. Crewe that partial cavitation conditions can lead to unsteady behaviour, lower lift/drag ratios and to erosion, but I would not have thought that at this stage in the development of hydrofoil boats we should regard complete freedom from cavitation as an inviolable design characteristic. Can we not go a little further along the speed range and allow some cavitation which does not necessarily introduce unsteady behaviour and does not necessarily increase drag? It may well result in some erosion of the foils, but at present we might regard that as a justifiable risk.

The work at N.P.L. on aerated or ventilated cavities mentioned by the author was not begun specifically to study super-cavitating conditions although, of course, it is hoped that it will provide some useful information on that topic. Recent theoretical and experimental work at the California Institute of Technology has given us for the first time some really good data on the super-cavitation performance of hydrofoils.

In discussing the model test work at Saunders-Roe on the *Bras d'Or*, Mr. Crewe writes: "Hydrofoil sections are tested in cavitation tunnels. . . ." Does this mean that some work has already been done in tunnels on the foil section and on the combinations of foil units used on the *Bras d'Or*? If so, can he say something about it? He also states that the effective aspect ratio of ladder foils of the type used on the *Bras d'Or* is low. I would expect the two end shields to increase the effective aspect ratio of the foils, but if this is not so, is it because they do not extend fore and aft sufficiently? Would increasing the fore and aft extent of the shields raise the foil effective aspect ratio and so improve performance? Is the fall-off of the thrust curve in Fig. 3B at high speeds a cavitation effect?

Finally, a word about the prospects for hydrofoil craft. I have to weigh natural enthusiasm for them against a necessary professional caution, and Dr. Allan and I had many discussions as to whether or not we should devote some of our limited effort at N.P.L. to studies of hydrofoil craft. I find that the paper does not answer this difficult question. Mr. Crewe is by no means so enthusiastic or optimistic as were the Americans four years ago, when they talked gaily about hydrofoil-supported ocean-going ships.

The list of possible hydrofoil craft is fairly long, but it is unlikely that it justifies any serious devotion of national resources to the development of this type of craft. In fact, as his final verdict, the author states: "It cannot be too strongly emphasized, however, that the problems arising are as difficult as those encountered with transonic aircraft, and similar technical facilities and experience are necessary to ensure success." If this is indeed so, I find it difficult to believe that we in this country would be justified in devoting anything like the tremendous effort required to the future development of hydrofoil craft. Mr. Crewe, discussing the economic aspects of hydrofoil boats, gives figures of earnings for the Messina ferry. I should be interested to know whether the normal fares were charged, or whether an extra charge was imposed for the privilege and pleasure of travelling on the hydrofoil craft. If so, it might affect the economic aspects even of such minor types of craft as short-run ferries.

Nevertheless, with all these reservations, I end as I began by saying how delighted I am to find the story put down in such a consistent and coherent way.

Mr. E. C. B. Corlett, M.A., Ph.D. (*Member of Council*): I had the pleasure of accompanying the author on one of his fact-finding trips and travelled with him in the boat on Lake Maggiore; as he has said, on this particular trip she was running in calm water. Later we went out on a 16-ft. runabout on Lake Geneva in far from calm conditions and I was impressed, not only by the performance of the particular boat, but also by the possibility afforded by hydrofoils in general of high-speed passenger transport on inland waterways and lakes and not only this, but in areas such as the Straits of Messina, and, indeed, the Baltic, the West Indies, and many others.

Turning to the paper itself, I have one or two questions to ask and one or two points to make.

Firstly, is Table I correct? I feel that the beam of the *Freccia d'Oro* is not 4·58 ft. but 4·58 m.* This would bring the length/breadth ratio into accord with that for the other vessels.

Basically, the hydrofoil boat is attractive by virtue of the high lift/drag ratio obtainable from the foils relative to that obtained with a planing boat which is, in effect, a hydrofoil boat utilizing only the pressure sides of the foils. This advantage relative to the high-speed planing boat tends to disappear with speed, although, of course, the other main advantage, namely, better seakeeping qualities, does not. In a planing boat, the lift obtained from the planing surface is proportional to the square of the speed as is the area of plane in contact with water, the weight of the boat being constant. As a result the frictional drag also remains constant and therefore the horsepower required is very nearly linear with speed. If a hydrofoil boat running at high speeds depends upon reducing the angle of incidence as in the case of an aircraft to limit the required lift, it seems to me there may come a time with a fully submerged foil when the drag advantages relative to the planing surface will disappear and I would question whether, under these conditions, it would not be better to use a submerged planing surface, depending upon pressure lift only. For such a foil which would be fully cavitating, one would propose a wedge-shaped section or some derivative thereof. If the speed becomes very high, say of the order of 100 knots plus, it is difficult to maintain water in contact with the back of any curved foil surfaces and it may be better to design a foil so that the top surface has zero incidence to the water flow and all lift is obtained by positive bottom incidence. Experience of rudders with a double wedge section with angles of entry of approximately 5 deg. at speeds of up to 200 knots shows that the flow has been stable and entirely satisfactory.

If such a foil is used, the great advantage of the hydrofoil boat, namely, its ability to maintain speed at sea under adverse conditions, will remain even at very high speeds, but I would welcome the author's views as to whether such speeds would be safe, in view of the possibility that the ship might encounter a wave sufficiently large to reach the main buoyancy hull. One can envisage a nasty accident under a combination of adverse circumstances.

Turning to the Supramar system, where a convex hoop foil is used, would it not be better at very high speeds if this hoop were of a different shape, namely, with the curve of the foil convex upwards rather than downwards? It would seem to me that at very high speeds, where large lifts per unit area are generated, there will be a tendency with the convex downward hoop for the craft to run on a small area near the centreline, and under these conditions the lateral stability might well be poor. With the inverse type of foil, as the craft lifted further and further out of the water, it would tend to run on the outboard sides of the hoop with unimpaired stability.

A final point I should like to make arises out of previous contributions to the discussion. It is apparent that in many of these hydrofoil boats, but not, incidentally, in the type for which

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* Since corrected in Table I (ED.).

Mr. Crewe is responsible, the propeller shaft is fitted at very large angles of inclination to the horizontal. This being so, there is clearly a vertical component of thrust, but even more important, if one draws a velocity diagram for the blades when they are in the horizontal position, one will find that the effective angle of incidence is different in the case of the blade going down to the blade coming up by, perhaps, a factor of 2 or more. This means that the torque is variable circumferentially and there is, in fact, a lift force generated by the screw which can be quite considerable, and in the well-known "surface propeller hydroplane" is used to support the stern of the vessel with the propeller boss clear of the surface, only the lower part of the blades touching the water. Longitudinal stability of the vessel is maintained in this condition by careful and specialized propeller design, the details of which are not relevant, but the lift forces involved can reach a ton or more in quite a small boat. It seems to me that in the type of hydrofoil boat mentioned, a longitudinal trimming moment could be present, dependent upon whether power was on or off. I would welcome Mr. Crewe's opinions on this feature.

In conclusion, I should like to ask him if he would give a few more details of the factors governing very large hydrofoil boats. We have seen reference to American feasibility projects for large passenger carrying hydrofoils for Atlantic operation and it would seem that the square cube law will operate against such projects. Their feasibility will depend upon a large number of hydrofoils needed in order to supply the required lifting area and the resulting parasitic and interference drag might be prohibitive.

Mr. E. C. Tupper, B.Sc., R.C.N.C. (*Associate-Member*): The author has covered a wide field in his paper and by no means the least interesting section is that on the history of hydrofoil craft. His mention of the work of Dr. Graham Bell recalls some work carried out by the Admiralty Experiment Works, Haslar, in 1921.

The investigation was concerned with battle practice targets and in particular with a design proposed by Dr. Bell based on the hydrofoil principle. The target cannot strictly be regarded as a hydrofoil "craft" since it was not self-propelled and its towing characteristics were of greater importance than usual. However, the following details may be of interest to this meeting.

A 1/6th scale model which was tested consisted of three floats, each 34½ in. × 10 in. × 5 in., rectangular in plan and section. In profile the floats had the forward end of the bottom rounded up and the after end of the top rounded down. These floats carried the ladder type foil units and were connected to a wood framework in the form of a "T," a pair of floats being arranged forward on the arms of the "T" and one aft at the foot of the "T."

An early modification to the design was to arrange for the after foil unit to swivel so that it might serve as a rudder. Also since initial runs showed the target's transverse stability to be small the spacing of the forward floats and foils was increased from 24 to 34 in., centre to centre, leading to greatly improved stability.

Trial runs among waves of varying lengths and heights showed that in general the craft moved through the waves cleanly and with little pitching motion, but that at speeds corresponding to about 10 knots and below the forward floats had a tendency to nose dive. Tapering the floats forward in plan view and increasing the spacing of the forward floats to 38 in. gave no improvement, but inclining the forward floats at about 10 deg. to the horizontal completely eliminated the trouble. With this last configuration she was found to be quite dry and clean at all speeds and to lift the floats clear of the water at corresponding speeds of 10 to 12 knots.

The model was run with three different settings of angle of incidence on the foils, viz. 10 deg. forward, 3 deg. aft; 7½ deg. forward, 2½ deg. aft; 5 deg. forward, 0 deg. aft; and behaved well at corresponding speeds of up to 30 knots. During resistance tests the last foil settings proved least resistful.

Towing trials of the model in Portsmouth Harbour showed the model to behave very steadily even among comparatively large waves. When turning, however, the slackening pull of the tow rope caused the model to "sink" somewhat, but this was soon corrected. Rough spring balance readings taken during these trials indicated that the resistance of the model in the crest of a wave was considerably less than in the hollow, indicating the effect of the orbital velocity of the wave particles both as regards effective velocity and effective incidence of the foils.

So much for history. I should now like to ask the author to comment on the relative merits of the hydrofoil craft and the helicopter.

In his comparison of the hydrofoil craft and a planing form he has shown that the former suffers in respect of payload and that its use will depend upon the importance of its other attributes. In many cases, however, it would appear that if the lower payload is acceptable then the helicopter has even greater advantages than the hydrofoil craft, e.g. in ferry work the latter is restricted to plying between coastal towns, whereas the former can proceed direct between inland towns. Also the speed of the helicopter is greater and it can often take a more direct route than a surface vehicle.

Mr. W. A. Crago, B.Sc. (*Associate-Member*): You will probably appreciate that I find myself in a somewhat difficult position in relation to the paper because quite a lot of the material in it stems from the test facilities for which I am responsible, and any criticism of the paper must inevitably, somewhere, reflect on and be a criticism of the tank work which has been carried out on various hydrofoil craft for various customers.

Nevertheless, there are some comments I would like to make, based partly on some years of experience of model experiment and also on full-scale experience.

In his introduction Mr. Crewe claims for the hydrofoil concept certain potential advantages. They are: (1) reduced resistance; (2) greater maximum speed for a given power; (3) a more comfortable ride; and (4) the ability to maintain speed in severe sea conditions.

Of course there are only two real advantages here, namely the reduced resistance, which results in a greater maximum speed for a given power or, conversely, the same speed for reduced power, and the more comfortable ride, resulting in the ability to maintain speed in a severe sea.

This last corollary implies that the limitation on performance in waves is set, not so much by the structure, but by the human element, which can stand only so much repeated high acceleration.

To the potential advantages already mentioned there should be added a considerable manœuvrability potential and the absence of the wash normally set up by high-speed craft due to wavemaking. But there are also a number of serious disadvantages. Mr. Crewe has laid emphasis on the foil weights—rightly so, in my judgment—and on the way they eat into the payload as the craft size is increased.

What has perhaps not been brought out quite so much is that it is a relatively difficult technical design problem to produce a hydrofoil craft that is stable and which in actual practice has anywhere near the optimum performance in waves that elementary theory indicates. In other words, it is a considerable technical problem to realize the potential that such craft undoubtedly possess. Furthermore, the analogy between hydrofoil craft and aircraft can be extended still further, and we can say that when anything does go wrong with a hydrofoil craft the consequences are likely to be serious, and possibly disastrous. I have seen uite a number of model hydrofoil craft suddenly crack up nder heavy sea conditions; and I have a particularly vivid emory of being aboard a full-size hydrofoil craft and recording ith reliable instrumentation a roll from the vertical of 23 deg. nd a roll rate of 45 deg. per second, and at the same time an cceleration near the *LCG* of 3½ g. I hasten to add that this as not the *Bras d'Or*; and in any case the driver said he had ever before experienced anything quite so bad.

Once the possible or potential vices of the hydrofoil craft are ppreciated, the engineer, knowing something of the possibility f fatigue failure, is inclined to reject the hydrofoil system which quires elaborate moving parts in the way of flaps or attitude ontrollers. Here I appear to find myself in slight disagreement ith Mr. Crewe. It is true that aircraft have flaps, elevators, nd so on, but they do not have to contend with flotsam, marine rowths, and the relatively rough handling to which the foils f an operational hydrofoil craft must inevitably be subjected. implicity and robustness have much to commend them.

I am also rather surprised by the statement that it takes so ong to get a critical phasing of the craft response and the forcing nction—so long that the tank may not be able to pick up the henomenon in one run. If we assume a 1/14th scale model unning in a 600-ft. tank at a speed representing 40 knots—llowing for acceleration and braking—a time equivalent to 00 seconds full scale is represented. If the head waves in the ank are twice the hull length, say 100 ft., then about 90 waves ill be traversed. If the phenomenon does not occur in 90 waves, ne must question what statistical significance must be attached o it if and when it is isolated.

On the other hand, tests in following seas at or near wave ropagation speed at constant thrust conditions, do run into he difficulty that Mr. Crewe has mentioned; but here the hull is enerally in the water, and I am given to understand that such onditions are impossible to deal with, at least reasonably simply, vith a computer.

The term "take off" is used in the paper and, since it is not lefined, I feel that it may be a little misleading to anyone who as never seen a hydrofoil craft running. No satisfactory hydro-oil craft in my experience, model or full scale, has ever suddenly eaved itself out of the water on to the foils at any given speed. Rather the process is gradual, and if *CG* rise from rest is plotted gainst speed, the curve is surprisingly smooth. Thus, to speak f a "rise speed" as many people do is misleading. The hull nd foils gradually exchange their functions in providing lift s the speed is increased, and the actual speed at which the ull is, say, 1 in. clear of the water is not very significant. On he other hand, as the late Dr. Gawn once pointed out, the peed region where the hull is just in the water presents onsiderable potentialities for porpoising instability with a poor lesign.

In his description of the 1/4·4th scale model Mr. Crewe does ot mention that the helm control was of the proportional type. Thus, if the helm were turned 10 deg. at the radio control tation, the rudder on the boat also turned 10 deg. On the other and, in order to obey the laws of dynamical similarity, the elmsman had to have a reaction twice as fast as a normal elmsman (the factor 2 being approximately the root of 4·4), nd when he *had* reacted he was restricted to an irritatingly low elm movement.

There is one last point I would like to make. Mr. Crewe has quoted me as saying that 20,000 tank test runs were made in connection with the *Bras d'Or*. I did not realize that this would look so bad in print before this Institution. Lest that high number and the associated cost should utterly dismay any prospective customer or hydrofoil craft designer, I hasten to say that the larger part of these test runs would never have to be repeated, since they were associated with the gaining of fundamental data.

Written Contributions to the Discussion

Commander Peter Du Cane, O.B.E. (*Member*): Mr. Crewe has done well to provide so much information on a subject which for many years past has inevitably led to much debate and conjecture where high-speed craft are under discussion.

In considering the relative merits of hydrofoil craft before this Institution it is, above all, necessary to publish only performance data which the author sincerely believes to be reliable. This is always a difficult matter, but on the whole Mr. Crewe has succeeded, and though without detailed first-hand knowledge, I would be inclined to agree that the performance figures given in Table II for craft with speeds above, say, 45 knots should be regarded with considerable reserve from the point of view of results actually achieved, though they have interest as "pointers" as to what might be aimed for.

In discussing performance it is always difficult to know exactly what power is being absorbed by the propeller unless a torsionmeter is installed, so that round figures such as are given in the hp column must be assumed approximate—at least it would be an extraordinary coincidence if they were not. Similarly in discussing behaviour in a seaway so very much depends upon a reasonably exact description of the wave dimensions in which the performance is obtained. It means but little to say that the wave height was 6 ft., because if, for instance, the length between waves was 1 mile the effect upon the boat of this disturbance would be negligible. For this reason to form any real judgment of the nature of the disturbing wave it is necessary to know the distance between crests. In practice the sea consists in an irregular system of waves and frequencies extraordinarily difficult to define precisely.

In Ref. (7) the writer pleads guilty to a lack of precision in describing the waves experienced in trial run No. 35. They were described somewhat loosely as 2–3 ft., so that when this is associated with a maximum forepeak acceleration of 8·36 g. it creates a wrong impression of the riding qualities of the hard chine craft in question. This particular acceleration was in fact the maximum recorded throughout a fairly exhaustive series of trials, including the very severe test resulting from driving the boat into the artificially severe conditions set up by the bow wave train of the *Nieuw Amsterdam* running in calm water at 20 knots. An acceleration of 9·36 g. was experienced in the course of a deliberate effort to find adverse conditions by running at full speed into tide rips or overfalls off Dunnose Head and should not, of course, be considered as arising from running in 2–3 ft. waves.

However, such experience as I have been able to gain at sea in hydrofoil boats leads me to agree that in head seas there is a definite amelioration of the accelerations usually associated with such conditions. How far this is applicable is one of the unknowns in the situation, because one must expect that after a certain height of wave is reached the situation will be perhaps comparable or worse than for the case of the normal planing craft. Certainly in following sea conditions the hydrofoil craft is rather frightening compared with the hard chine type provided this is properly designed and trimmed.

As regards turning qualities the author suggests on page 353 that the information on radius of turn supplied by me for the 68-ft. hard chine type of craft represents about as good performance as is possible for this type. I have verified the trial reports, of which there are many for this particular type, and can confirm that several craft have equalled or even exceeded this performance. At the same time I have personally experienced extraordinarily good performance in turning in the case of small hydrofoils of both the Carl and Supramar types.

At the foot of page 355 the author, when referring to the effects of cavitation and aeration on controlling surfaces, infers, *inter alia*, that analogue computers may provide the best medium for prediction of performance. It is just where the effect of cavitation is remarkably difficult to predict, as in the case where the phenomena of cavitation or aeration are unstable in their formation and extent that I would have thought it would be difficult, if not impossible, to feed in the necessary coefficients to the analogue computer. Analogy here is found for the transonic aircraft case where the full-scale performance provides the only guide approaching to satisfaction. The wind tunnel will be a good second best while equally for the hydrofoil case I would suggest more could be obtained from the cavitation tunnel provided the experiment was properly organized than from a computer for this particular case. In fact the paragraph at the top of page 357 on the subject of the *Bras d'Or* test work rather tends to confirm this view. It could, perhaps, be suggested that where full back cavitation is encouraged the flow regime might be more amenable to a usable law.

In considering Fig. 23 it is of interest to observe that the prismatic planing surface of reasonable loading beyond a relatively low "hump" speed will follow the law R/Δ = const. = 0·15 approx. It is interesting to consider how resistance will vary with speed for a naked hydrofoil when the speed is such that the whole of the top or suction surface is running in a cavity (super-cavitating). There is, at least superficially, close analogy here with simple planing conditions disregarding appendage drag and air resistance. However, it is probable that in the generation of cavity conditions some extraneous energy is involved which will have the effect of resulting in an increase in resistance for the cavitating foil as compared to the simple planing surface as speed increases.

From Mr. Rader's Fig. 27 it appears there may be a cross-over point for the single hydrofoil somewhere about 120 knots. In practice, of course, the influence of appendage drag will greatly affect the R/Δ curve for both planing craft and hydrofoil. It is probable that in the really high speed range it will affect the hydrofoil to a greater extent.

Certainly a planing boat has achieved nearly 250 mph under very favourable conditions. It might be expected that the hydrofoil would prove a superior shock absorber.

Mr. M. C. Eames, B.Sc., M.E. (*Associate-Member*): Until very recently, hydrofoil craft have been the prerogative of the individual inventor, and many widely different types have been produced, in the absence of a proper understanding of the mechanics underlying the problem. The inevitable result has been a series of marginal performances, and a few outright failures, while the experts have tended to be outspoken protagonists of their own particular patented system. General acceptance of the hydrofoil craft as a serious vehicle has naturally been hindered by this approach. Only recently has the problem been given serious attention by organizations equipped with the facilities necessary for the scientific development of such craft. Now, at last, the fundamental problems are beginning to be appreciated.

It is very fitting that at this "coming of age" of hydrofoil development, The Institution should be introduced to the subject in so comprehensive a manner, and the author is to be congratulated on the scope of his paper. A student approaching the subject for the first time will find here all he needs to know about many of the earlier developments, and will be able to commence his thinking with an unbiased mind.

As a direct consequence of the manner of evolution of hydrofoil craft, the subject tends to be a most disjointed one, and the author has made a valuable contribution in integrating the whole picture. Only in one respect does the present writer feel a different approach would be desirable, and this is essentially a matter of emphasis, rather than one of fact.

It is believed that any classification of hydrofoil systems must begin on a basis of the maximum design speed of the craft. The entire design philosophy, hydrodynamic and structural, depends on which of the three regimes of speed the craft is required to operate. These may be termed the "Subcavitation," "Transcavitation," and "Supercavitation" regimes, and several useful analogies can be drawn between these and the corresponding subsonic, transonic, and supersonic regimes applicable to aircraft. As an example, the critical cavitation number of a hydrofoil section and the critical Mach number of the geometrically similar aerofoil are uniquely related by a simple formula.

Broadly speaking, a design requiring a maximum speed not exceeding 40 knots can be carried out without particular regard to cavitation problems. It is, of course, possible for cavitation to occur at lower speeds, but usually some other requirement will in any event contra-indicate the use of conditions in which this is likely. In this subcavitation regime, therefore, the designer has a free choice of the various configuration types, but the significant point is that it is *only* in this regime that his selection is so free, and even within it, the most elementary considerations lead to the elimination of certain systems, as the author himself has indicated.

Within the range of design speeds from 40 to 60 knots or thereabouts, over which cavitation would be developing on hydrofoils of "normal aerofoil" shape, cavitation can be delayed by the use of the special sections described by the author. However, the characteristics of these "transcavitation" hydrofoils preclude the use of several types of hydrofoil systems, notably those involving incidence control.

Very little is known of the practical behaviour of supercavitating hydrofoils, although extensive work is being done on the characteristics of such sections. The obvious practical difficulty arises from the extremely low pressure in the cavity. Should the hydrofoil break surface or otherwise become ventilated, the cavity pressure will rise suddenly to that of the atmosphere, causing an increased effective load of approximately a ton for each square foot of hydrofoil surface so affected. At a first glance, therefore, it would appear that all supercavitating hydrofoils must be run fully submerged.

It might be practicable to operate surface piercing "superventilating" hydrofoils, in which the cavity would be maintained at atmospheric pressure under all conditions so as to keep the hydrodynamic forces reasonably steady. Under these conditions, of course, the hydrofoil would be behaving as a planing surface only, no lift being derived from its upper surface. However, it could be designed as a much more efficient planing surface than can be provided in the hull of a boat, and it would not be subject to the latter's seakeeping limitations caused by the necessity of following the surface. To the writer's knowledge no craft has yet been built with hydrofoils of this type, but it remains an intriguing possibility for removing the present speed barrier of hydrofoil craft.

It is not possible to say, at present, what hydrofoil configurations will be suitable for craft operating in the super-cavitating regime, but again it seems clear that the choice open to the designer will not be unrestricted.

A discussion of the reasons why certain hydrofoil systems are appropriate only to certain speed regimes would involve a second paper. The writer merely wishes to emphasize the importance of the design speed in this regard.

Taking the author's comparison of various configurations, and extending his ideas a little, one arrives at the conclusion that for craft in the transcavitation speed range the most logical configuration is one which has not yet been tested. The interesting point to the present writer is that the configuration suggested by these thoughts is the same as that which has resulted from a study of his own, made along somewhat different lines. In other words, there is a hint that development is leading towards one ideal system for each speed regime, although in practice compromises demanded by operational requirements her than pure effectiveness of hydrofoil action will lead to iriants, probably based on craft size.

The extension of the author's ideas which is required to arrive the particular configuration mentioned, stems from his sugstion that a hydrofoil ladder is not a surface following unit. is true that ladder units fitted to past craft have not been of is type, but it is believed that a ladder can be designed to llow the surface as closely as would be desired. One of the ain arguments, and a valid one, put forward by ladder progonists is the extreme flexibility of design which this concept lows. This is, of course, offset by reduced hydrodynamic ficiency and increased structural weight, but if one accepts the asibility of designing a surface following ladder unit, one can evise a system which minimizes these disadvantages.

The envisaged system would combine the advantages of the irrent ladder and Grunberg types by carrying about 90 per cent the load on a monoplane foil aft, and 10 per cent on a single irface-following ladder unit forward. It is believed that this rangement would give the designer far more control over the sponse of the craft in seas than is possible in any existing stem, although design techniques would require further development before the full potential of this could be realized. Good teral stability could be provided by making the main hydrofoil surface-piercing type, as in the Aquavion or Tietjens system, hile propulsion appendages could well serve a double function supporting this large span unit. (It is felt that the damping iaracteristics of the forward ladder unit would enable the rear il of the Aquavion system to be dispensed with.)

Many other attractive characteristics of this combined runberg-ladder system could be explained, but they will obably be apparent to any reader sufficiently interested to be oncerned with such details, and the writer would run the risk extending this discussion into a second paper.

Mr. M. F. Gunning (*Member*): I studied this paper with great terest as far as my limited knowledge of hydrodynamics lowed me to understand it. My own approach to the matter of a more practical kind, more like that of a yachtsman. nd however much I admire the work of the hydrodynamist, id realize that we cannot get anywhere without him, I still el that the infinite variety of actual conditions at sea will onfront him with problems that are beyond mathematical ialysis, even when aided by an electronic computer.

I thought I did a very clever thing when, on my first trip on ie *Pilen*, I collected all my fellow guests right aft, and then arched them forward at a rush without prior notice to the perator of the craft. The *Pilen* apparently could not care less, id later I realized that in actual service much harsher conitions are met with, e.g. when we ran a 20-ft. Aquavion through ie bow wave of a coaster driven beyond its economical speed colleague of Mr. Crewe may remember the occasion), or hen we drove the *Aquastroll* through the tide-rip at Hook Holland where the 4–5 knot ebb of the New-Waterway meets e North Sea waves. Under these conditions one requires mething simple, solid, stupid, if I may use the word, something at will keep the bow up regardless of hydrodynamic refineents, and the admittedly inefficient waterskis of the Aquavion st seem to fill the bill.

I therefore beg to disagree with the author's statement on ige 336, that because an aircraft has elevators, incidence ontrol can be accepted on hydrofoil craft. We want an ordinary ipper to be able to run our boats, not a qualified air-line pilot.

Some other points require comment. On page 339 the author ates that for the Supramar and Aquavion the change in imersed foil area between take-off and cruising conditions is out 2 : 1. This is probably right for Supramar; for Aquavion e ratio is about 1·2 : 1, because the latter type obtains the cessary lift at low speeds by pivoting about the front skis, thus increasing the angle of incidence. From this one might deduce, either that the weight of the foils is some 80 per cent larger on the Supramar, or, inversely, that the loading per square foot of foil area is that much greater.

We might carry this line of argument a step further and point out that if we bring the two foils of the Supramar closer and closer together, until finally they merge into the single wing of the Aquavion, we can make the thickness of the latter twice that of the former, while retaining the same t/c ratio, thus making the foil twice as strong for the same weight, or else twice as light for the same strength.

Combining now the arguments of the two preceding paragraphs we find that the Aquavion system of foils is 1·8 × 2 = 3·6 times as good as that of the Supramar, and not even the most ardent partisan of the Aquavion will support that statement. But it shows how careful one must be with mathematical deduction from necessarily incomplete premises, and I rather fear that this applies to the general remarks on hydrofoil weights given on page 348 of the paper.

In arriving at the factor 3·6 we have conveniently forgotten the weight of the waterskis of the Aquavion. Also the relatively wider foil of this type will have a lower aspect-ratio with reduced efficiency. But could Mr. Crewe give us an estimate of the procentual value of this loss, and of the extent to which it is compensated by the lesser number of wing struts on the Aquavion, and the absence of interference between the front and rear foils that must to some extent be present on the Supramar?

Turning now to cavitation, Mr. Crewe seems to imply that it will be difficult to avoid cavitation at speeds beyond 40–50 knots. But we seem to be able to do this without much trouble on propellers with tip speeds (and speeds at 2/3 radius) of twice and three times that value. Perhaps Mr. Crewe could tell us the cause of this apparent difference. Again the author shows that cavitation speeds drop rapidly as the loading per square foot of foil-area rises. It would also appear from the paper that the ladder-type of boat is best suited for high speeds, the Supramar for medium speeds, while the Aquavion comes last. Yet the ladder-type boat loses three-quarters of its foil area as it reaches operating speed, the Supramar one-half, and the Aquavion next to nothing, so that the latter type would appear to have the lowest loading, and so be least susceptible to cavitation. Another riddle that Mr. Crewe may be able to solve.

I trust that the author will not deduce from all this that I am criticizing his interesting and thought-provoking paper. On the contrary, he has whetted my appetite, and I am asking for more. I heartily agree with the author when he states that hydrofoil craft have a bright future, and also when he adds the rider that the problems confronting their designers are difficult. And I am confidently looking forward to further contributions by Mr. Crewe towards their solution.

Mr. Christopher Hook: The paper contains a great deal of information and represents a major contribution to hydrofoil research, but it is perhaps unfortunate that it is restricted to the fixed foil types which must, by their nature, follow fairly closely all wave forms.

The author's statement that a merit of incidence control is that the craft can follow the wave contour more closely without having to have large water clearance, is an exact inversion of the aims that we have been following for 14 years.

In fact very simple calculations of rates of encounter with waves of small size at hydrofoiling speeds will show at once that it is essential to be able to ignore these, and it is the main virtue of the incidence control method that it allows the hull to be lifted so high as to render this possible.

The reason why such high travel is made possible is one of lateral stability and recovery. A Vee or surface-piercing foil has static stability as shown in Fig. 14, and this explains why water clearance must remain small. With two independently controlled hydrofoils, one on each beam, on heeling we will have two active recovery forces produced by the feeler mechanism. On the lower side an increased angle of attack will combine with a more negative angle called for on the higher. It is *the sum of these two* which constitutes the recovery moment and the same can also be called for by the pilot or modified by him according to circumstances. This has been described as "active" recovery forces. As a result it becomes possible to fly very high and to ignore a series of wave sizes. This same height of wave can also be subtracted from the effective height of the next wave size up so that a boat with a clear space of 1 metre can deal with a 2-metre wave as if it were only 1 metre high. The sensitivity of the feeler arm is restrained naturally.

It is now clear that we have no desire to develop a *wave following* device of any kind.

When a feeler element is no longer a part of the hull, skipping a wave is no longer a fault but a virtue.

We have found it totally impossible to sell hydrofoil boats to the public that are not provided with full retraction, and this feature is also essential for patrol boats that have to cruise economically and be able to run into bays and shallows. In the U.S. Navy's Hook hydrofin landing craft (not listed in the paper) this is accomplished at full speed since a stop just beyond the breakers to retract would be fatal. Furthermore, the vertical surfaces provided by the legs and stern power strut on running through the breakers are of the greatest value in preventing any tendency to broach to, and this means that retraction must be carefully timed to depth to take full advantage of this.

The operation of retraction is hardly more than that of hauling in the boom on a sailing vessel and is operated by similar means.

Author's Reply

I would like to thank the various speakers very much for their many kind remarks. Their valuable technical contributions have helped to fill gaps and correct obscurities of which I was very conscious.

In order to make some reply to the many points raised, in a reasonably few words, my remarks are grouped by subject, and consider in particular topics to which several speakers contributed.

Ventilated Foils and comparison with Planing.

I very much agree with most of Mr. Eames's technical points and in particular his remarks on the importance, for future developments, of a classification based on design cavitation or ventilation conditions. This was not emphasized in the paper, since at the time it was written only information on craft designed to operate at sub-cavitation conditions was available. The importance of super-cavitating or ventilated hydrofoils, in achieving speeds in the 50 to 100 knot range, stated on page 360 of the paper, and emphasized by Mr. Eames, Mr. Rader, and Mr. Silverleaf, is being investigated in the United States, where a symposium on relevant declassified material is being held in August 1958.

True super-cavitating hydrofoils would no doubt have to be fully submerged, and might be employed, for example, on bodies operating at great depths. It seems likely that surface hydrofoil craft will employ ventilated, and not strictly super-cavitating foils, to avoid the great problem of preventing air bleeding down the supporting struts. Surface piercing ventilated hydrofoils are possible also. In either case the flow past the hydrofoil closely resembles a super-cavitating condition, with the exception that the upper surface cavity is filled with air instead of water vapour. Making the foil ventilated at comparatively low speeds, so as to achieve continuity of operating condition throughout the range of foilborne speeds, is a design problem.

Although a "super-cavitating" or "ventilated" hydrofoil section has a gas-filled cavity on its top surface, it can be misleading to consider it as a fully submerged planing surface. The section is a wedge in that the leading edge is sharp and there is a flat base at the rear, but the surface contour between can be complex, being based, for example, on mathematical studies such as those of Tulin.(12) Such sections as these may give better lift to drag ratios than any planing form that is capable of operating on the water surface without an unacceptable tendency to dig its nose in.

Once a foil has achieved the ventilated condition for which it has been designed, its speed can be increased as much as desired with little significant change in its stability and lift to drag ratio, if anything the latter may tend to improve. The high speed variation of R/Δ with speed given in Mr. Rader's Fig. 27 and the tentative dashed line curves of Figs. 26 and 29 depending upon it, may therefore be pessimistic. Similarly the cross-over speed of, say, 120 knots, above which Cdr. du Cane suggested that a planing craft would be best, probably does not exist. In any case the R/Δ of a stepless hydroplane increases as speed increases, due to reduction in attitude.

With reference to Dr. Corlett's remarks comparing planing with hydrofoiling, an uncavitated hydrofoil is in practice a basically more efficient lifting system not only because it utilizes its top surface to generate lift but because of reduction in drag due to suction at the nose. A fully submerged hydrofoil will have to run at an inefficiently high attitude at low speed, if it is to be efficient at high speed, but a surface-piercing hydrofoil can reduce area, as speed increases, more efficiently than a hydroplane.

Mr. Rader's Fig. 26 is very interesting. The simple empirical formula I gave on page 341, which has been used in calculating the full line of Fig. 26, was not intended to be more than descriptive of past practice, and it should be extrapolated with extreme caution. The positioning of, e.g., VS-10 and HD-4 on this line, as compared with the *Miss U.S.* 3, which is near Mr. Rader's dashed line, reinforces my suggestion on page 341 that the latter alone was working in a steady and efficient condition of extensive ventilated cavitation. With reference to Cdr. du Cane's remarks concerning the difficulty of knowing the power absorbed, the powers in Table II are in general bhp's installed, which should be borne in mind in basing performance coefficients on them.

In connection with the above remarks on the comparative merits of hydrofoil and planing surfaces for high-speed operation, it is of interest to note that studies of marine aircraft mounted on hydrofoils are being made in the United States because the hydrofoil appears to offer advantages over the hydroski (i.e. planing surface) at the very high speeds at which aircraft land and take-off. Some work of this type has been described by W. Carl.(13)

This development provides some answers to Mr. Silverleaf's comment that the aero engine-stub wing arrangement of the Carl XCH-4 is perhaps rather double edged. The air–water interface would certainly seem to be the place for high speeds, up to at least 100 knots, if η L/D's coming appreciably above the commercial aircraft line of Fig. 24 can be achieved.

Mr. Tupper mentioned the helicopter. This has a low transport efficiency as measured by WV^2/HP, and helicopters carrying only 48 people (compared, for example, with over 70 for the *Freccia del Sole*) are still in the development stage.

Carl(13) provides some evidence that hydrofoils have a substantial advantage over planing surfaces, for both surface craft and marine aircraft applications, in severe rough water conditions. This applies throughout the speed range, which in the case of aircraft greatly exceeds 50 knots. The writer states that model trials have demonstrated the possibility of reducing the impact loads on a high-speed seaplane to one-fifth of the plain hull value, by fitting hydrofoils. He claims that this will permit the routine operation of marine aircraft in sea states considerably greater than the present limitations. Waves about 10 ft. high would seem possible. Full-scale tests of a JRF aircraft, fitted with a hydrofoil, to obtain pilot evaluation, are planned.

Dr. Corlett challenged this view, asking what happens if a wave so large that it reaches the hull is encountered. With proper design, allowing the hull to kiss the water gently, behaviour in extreme waves should still be better than for a hull alone because of the damping effect of the hydrofoils. It is important that the system should not follow the surface too closely at very high speeds, however, or else for example accelerations exceeding, say, 15 g. will be inevitable at 100 knots.

Again if, in an incidence control system, a servo-mechanism is employed to provide foil incidence changes, the servos will have to operate at a limitingly high rate.

This suggests that a system of surface-piercing type, having good inherent water clearance, and relatively low response in waves, should be the best.

I am grateful to Cdr. Du Cane for his clarification of the conditions under which the 8·36 g., stated in his paper to have occurred on a planing craft in 2 to 3-ft. waves, was actually obtained. However, there are considerable data available showing that accelerations exceeding those shown in Fig. 7 are sustained full scale in rough water by high-speed craft that do not have hydrofoils. Also the critical regular wave system employed in the tank tests of Fig. 7 is in general considerably more severe than the more random conditions that occur full scale.

In connection with rough water behaviour, Mr. Crago remarked that the claims for a hydrofoil boat that it gives a more comfortable ride and that it is able to maintain speed in severe sea conditions are really one and the same. As far as I am aware requirements for comfort have as yet only very partially been correlated with structural loading or structural fatigue measurements. In fact it has been suggested that a systematic study of human reactions to craft motions on the water should be made with a view to isolating the critical effects and designing a craft which is comparatively free of them. He also emphasized the technical difficulties of designing for adequate stability and behaviour in waves. This has been generally admitted, but due to intensive effort during the last few years, especially in the United States, the problem is gradually being overcome. It is here that electronic computers can be particularly valuable. Both Mr. Crago and Cdr. Du Cane expressed doubts about computer solutions, but I consider that they can be extremely useful in indicating design trends and in making some allowance for partial cavitating conditions that cannot be represented on a tank model. Fully cavitating or ventilated conditions should be even easier to represent. Cavitation tunnel results are, of course, of vital importance in providing values of derivatives to use in the computations.

In rough water response tests a critical phasing between craft and waves may take ten to twenty wavelengths to occur, so that, as Mr. Crago says, a 600-ft. tank should provide an adequate test length, but experiments in an appreciably shorter tank could still be suspect.

With regard to the remark that if anything goes wrong with a hydrofoil boat the consequences are likely to be serious and possibly disastrous, I cannot recall any serious injury, let alone a death, having been caused by such malfunctioning.

The term "take-off speed" was introduced on page 339 in a context intended to define it as being the speed at which the hull ceases to provide water lift. I agree that there is in general no sudden change in draught, associated with this condition, although hysteresis effects may exist particularly in poor designs.

Mr. Crago implied that the paper omitted the advantages that a hydrofoil boat has in the way of manœuvrability and absence of wash, but he will find these listed on page 337. In the light of Cdr. Du Cane's figures on the turning of well-designed planing craft, it would seem clear that the former can better the *Aquastroll* and *Freccia d'Oro*. However, I also have experienced extraordinarily good turning behaviour in the Carl runabout, which makes a half g. turn without appreciable heel, having been specially designed to do so.

Structural Considerations

It is possible that sections as thin as anything shown in Fig. 8B may be necessary to achieve good lift to drag ratios under supercavitating or ventilated conditions, and that structural difficulties will therefore be severe.

This is a convenient point to take up Mr. Rader's criticism of the upper part of Fig. 5. The boundary between monoplane and ladder systems was only intended to indicate a tendency followed by craft whose performances have been demonstrated as reasonably satisfactory, full scale. The trend is still there even if the VS–7 having monoplane main foil units is included at 55 knots. Page 344 refers to the VS–7 and states that the VS–10 was not included because it was never operated.

Mr. Rader's remark that had there been more monoplane boats with large power to weight ratios, they would have achieved speeds comparable to those of the ladder craft, ignores the effects of section thickness and high aspect ratio on cavitation and stability.

The structural point that I was trying to make is that the thin sections needed to avoid cavitation (or perhaps to establish a satisfactory resistance level with a ventilated foil) demand more struts and junctions than is necessary with the thicker sections that are appropriate up to design speeds of about 40 knots. Once cavitation or ventilation have been accepted it is necessary to offset the drag of junctions against the increased drag of the thicker section that is required if they are eliminated. I do not know whether monoplane or ladder arrangements will prove best in these circumstances.

An alternative approach to high-speed design, which would be structurally simpler, might be to use relatively thick sections but extremely high sweepback in plan.

Mr. Silverleaf has suggested that my argument on page 346 implies an absolute limit on hydrofoil loading imposed solely by an insistence on complete freedom from cavitation. Experimental evidence suggests that when a three-dimensional subcavitation design becomes partly cavitated an absolute maximum limit on the load in lb. per sq. ft. it will support is found to exist. Increasing attitude or speed makes no further difference. Thus design to such a limitation of loading, and the increase in relative hydrofoil weight with craft size it imposes, is a feature of subcavitation designs. My present, and tentative, viewpoint is that if a speed of not more than say 40 knots is adequate, and operation in severe rough water is unnecessary, then it is best to design completely to avoid significant cavitation. In any other case complete upper surface ventilation should be achieved at as low a foilborne speed as possible.

The above remarks are relevant to Dr. Corlett's query concerning the feasibility of large passenger carrying hydrofoil craft for Atlantic operation. If they are designed for subcavitation conditions a square-cube law will certainly apply, as indicated in Fig. 10. The hydrofoil units if not divided should at least require multiple support, but the American projects mentioned by Dr. Corlett are believed to have relatively simple systems with large unsupported spans. The stressing cases assumed must certainly be less severe than in the studies with which I have been associated, but the justification for such a reduction is not clear. Only extensive service experience with strain gauged foils can determine the significant stress levels actually occurring, and the importance of fatigue.

Mr. Gunning criticizes the remarks on hydrofoil weights given on page 348. Perhaps he would be prepared to quote detailed figures for the Aquavion craft, as it is only in the light of such evidence that really efficient hydrofoil structures can be developed.

His comparison of the Aquavion main foil strength or weight with that of two Supramar foils is striking, but perhaps a little exaggerated. The immersed areas of the two systems should be about the same at the same design speed, for cavitation reasons. It is then true that if the foils are thin-walled structures the Aquavion foil can have about half the wall thickness of the Supramar foils, for the same bending stresses to occur. Thus the Aquavion foil can be half the weight of the two Supramar foils. On the other hand, equality of shear stress requires equality of weight.

Propulsion

Turning to propulsion, I agree with Mr. Silverleaf that this is an important aspect of hydrofoil craft design which should have been given more attention. However, the paper was already too long, and hydrofoil craft propulsion systems raise questions of detail rather than generality, which can best be dealt with in papers on specific hydrofoil craft, rather than in a broad study of the present type. The matter would have been mentioned if it had been a major problem in the past. There have been many engineering "snags" in connection with the propulsion systems, but these were often overcome during trials.

The R.103 propulsion system, having a nacelle on a strut, with a fixed pitch propeller forward and a controllable pitch propeller aft, is certainly unusual. However, it was chosen not for novelty but in order to keep the hydrofoil performance as free as possible from propulsion interference, since this is a research craft. Our studies suggested that the appendage drag would be about the same for the system used and for an inclined shaft arrangement, but the extreme angles that the latter would have needed might have introduced propeller difficulties.

The R.103 propulsion system has behaved satisfactorily in service, to date, apart from some initial trouble with leaking seals.

Mr. Silverleaf also asked whether the fall off of thrust at high speeds, in Fig. 3B, is a cavitation effect. Some fall off is of course normal, even with a fully controllable pitch system. Cavitation tends to aggravate this at the higher speeds unless super-cavitating propellers are used, but in that case efficiency is low at intermediate speeds.

Dr. Corlett suggested that the low thrust line might give some difficulty with trimming moment, but this is not known to have occurred in practice.

I do not follow Mr. Gunning's argument that hydrofoil cavitation should easily be avoidable at speeds beyond 40–50 knots, in view of propeller experience. The mathematics of the situation is well understood in both cases and does not support such a conclusion.

Individual Types of Craft

Now I would like to take up some of the points concerning individual types of craft and first the Bell–Baldwin system. Mr. Tupper's contribution on the investigations of towed targets at Admiralty Experiment Works in 1921 are an interesting addition to the history of the subject. He does not say whether the significance of orbital motion of the water particles in the waves was appreciated at the time, if so it would antedate other work on the same subject, in connection with hydrofoil boat performance, by many years. Also it is not clear whether the resistance fluctuations, stated to be due to orbital motion, occurred in head or in following seas. It is noted that the lowest foil settings tried proved the least resistful.

In answer to Mr. Silverleaf's question, no cavitation tunnel work was undertaken specifically in connection with the *Bras d'Or*, but the section used had previously been the subject of general cavitation tests.

The struts do increase the effective aspect ratio, but it still remains comparatively low. Extending the strut shielding fore and aft would cause additional frictional resistance, and increase the tendency to trap debris. The degree of shielding provided was considered a practical compromise.

Mr. Crago felt himself to be in a somewhat difficult position in criticizing the paper because it contains test results for which he was responsible. I would therefore like to acknowledge indebtedness to him for the work on the *Bras d'Or* described on pages 357 to 359, and say that it made a relatively small contribution to the general arguments put forward.

The proposal made by Mr. Eames for a Grunberg system having a monoplane foil aft and a ladder forward is very interesting. The Gibbs and Cox company are understood to have considered using a combined hydroski and ladder forward to reduce the danger of skipping off, and give inherent incidence control in combination with a relatively softly riding front supporting member. Such a development may offer a means of producing high-speed rough water craft of Grunberg type.

I was very glad to hear of Mr. Silverleaf's association with M.T.B. 109 and agree with him that the full story should if possible be told. Why should we keep quiet about our achievements when others advertise theirs so widely?

I also agree with Mr. Silverleaf that a ride on *Aquastroll* 24/40 does not quite live up to the company's brochure description. None the less, it is a most interesting craft, and we are much indebted to Mr. Gunning for clarifying some of her design features. The small change in submerged main foil area from 1·2 to 1, in the foilborne speed range is a most interesting characteristic which I had not appreciated. However, the implication is surely that if at a given design speed, a ladder, a Supramar, and an Aquavion system have the same foil loading, and the same effective incidence, determined by cavitation limitations, then at a given lower speed the Aquavion craft will have to trim the highest to remain foilborne, which will be resistful. Alternatively, if all the craft have equal loadings and incidences at intermediate speeds, the Aquavion craft will have a more restricted high-speed range than the others.

Turning to incidence control systems, the film of the Hook Hydrofin runabout presented by Mr. Barkla was impressive. This system would appear to have excellent possibilities for use on comparatively small sport boats, but more evidence on its possibilities at greater weights and higher speeds are required. I cannot agree that skipping a wave is a virtue for a feeler, but travelling through one with little response would be. Is it not the latter that Mr. Hook is claiming? Surely the Hook system has the merit of following long waves but ignoring short ones.

Contrary to the remark in Mr. Hook's written contribution, the U.S. Navy landing craft based on his system is mentioned on page 335 of the paper. The retraction system for the hydrofoils and propulsion unit of this project appears to have been particularly well thought out.

Some authorities consider that the future of incidence control lies with non-mechanical draught sensing devices such as the one used on the very successful Gibbs and Cox runabout illustrated in Carl's paper.(13)

Both Mr. Crago and Mr. Gunning argue against the use of moving pitch and roll control surfaces, such as ailerons. Although simplicity is desirable, I cannot agree that it should be carried to extremes. Fatigue is not necessarily more serious in moving than in fixed parts, and the possibility of using moving controls greatly extends the designer's scope to optimize his design in other respects. Mr. Carl at first marketed his runabout hydrofoils with no moving surfaces, but he soon found that trimmer tabs, which can be adjusted at will while riding, avoid undue fussiness in mounting the foils on a craft, and are greatly appreciated by the owner. If the passengers are sitting offset, it is a matter of a moment to bring the craft on to an even keel for example.

Dr. Corlett's query concerning Table I is quite correct. The second and third lines referring to the *Freccia d'Oro* are reversed. The beam should read 10·2 ft. and the L/B is 4·58.* His criticism of the heel stability of most Supramar craft is also valid, they are designed so that adequate stability is available at the greatest attainable speed. Spreading the main supporting foils laterally is a standard method of retaining adequate heel stability at high speed. This method is employed on the *Bras d'Or* and Supramar runabout of Fig. 6, and in the Hook, Baker, and Carl systems for example.

In conclusion, I would like to refer to the comments of various speakers on the future prospects. In my opinion radical developments in transportation in or under the surface of the water are inevitable, both for passenger carrying, especially over short ferry routes, and for moving bulk cargo. I also think that hydrofoils have a significant part to play in this development, and that the technical effort required, although of high quality and relatively expensive, is less than will need to be expended on some of the other types of craft now beginning to be considered. Certainly it would not require a serious devotion of national resources, but could utilize capacity no longer required on defence projects.

It is understood that the Messina ferry charges a fare that the market will stand, and this is surely all that an operator can ask for.

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* Since corrected in Table I (Ed.).

References

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