North East Coast Institution of Engineers & Shipbuilders

TRANSACTIONS Vol. 82 Part 4

CONTENTS

February, 1966

Price: 8s. 0d.

NEWCASTLE UPON TYNE PUBLISHED BY THE INSTITUTION

THE HYDROFOIL: POSSIBILITIES AND LIMITATIONS

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10th January, 1966

SYNOPSIS.—*Step ladder or Vee foils have a reefing effect but they are wave followers and as such cannot "platform" waves. Incidence controlled foils on the other hand do not reef but, if provided with a suitable auto-pilot, can give level flight over very rough seas.*

Forward pointing feelers and mechanical connections were the obvious ways to begin despite the strange appearance, mainly because the arms can also serve as sea crash preventers. Sonic beam substitutes are very costly and cannot do this and a tidier mechanical system has now been worked out.

The mathematics of wave encounters and vertical accelerations in rough seas are certainly more complex than the simple inclined plane for example, but an easy method of calculation is given, applicable to all vehicles that claim high speeds over water.

Orbital motions control the effectiveness of the various hydrofoil rigs so that the failure of some early rigs is now easier to understand. The matter of maximum possible size is more a commercial than a technical consideration.

Various control methods are possible but simplicity is always important, while the Z drive or power strut is much more difficult than one would expect.

Comparisons on a simple efficiency basis are not always meaningful because of other essential factors such as seaworthiness. Many branches of technology are involved and the process of the survival of the fittest is already at work.

Introduction

THE diversity of hydrofoil boat designs, which tends to create some confusion, has two main contributing causes: firstly the very aims and objects of hydrofoils have shifted from the early preoccupation with pure speed, towards the more rational exploitation of the idea of "wave platforming" or partial elimination of wave effects; and secondly, there are two basic ideas on control in altitude which separate the designs almost as sharply as two different principles separate fixed wing from revolving wing types of aircraft.

The advantage of stacking foils one above the other like a venetian blind seems so obvious (when one understands that this method takes advantage of the proximity of the two media, air and water, to remove the foil area from the heavier to the lighter) that any alternative method of control, say by control of the incidence, appears to be illogical until one looks much more closely at the penalties paid for the first idea. Whereas stacked foils are thus "reefed" by the mere lifting of the hull and whereas this tends to produce a vehicle of almost constant drag throughout the speed range, the same advantage exists in theory for a vee-bottom, but we know that in practice it does not work out so ideally because of the difficulty of controlling hull trim, spray and other factors. In fact the proper exploitation of the reefing quality of the vee-bottom demands a glassy flat calm so that the principle has never really been put to use in transportation.

Although a vee-shaped foil, removed a little distance lower down, does succeed in placing an air gap under the hull, the response of the variations of immersed and emergent portions of the vee to the passage of successive waves must of necessity be passive in nature and must lag (in phase) in relation to the wave system. Furthermore the "hoverheight" (to borrow a new word) is quite small, so that the gain in this respect, as compared to the vee-bottom on the one hand and the fully-submerged foil on the other, is disappointing. Since this matter is basic to the whole discussion about hydrofoils I must now explain this in detail.

Traverse stability with vee-foils depends on hydrofoil geometry and C.G. location as shown in Fig. 1.

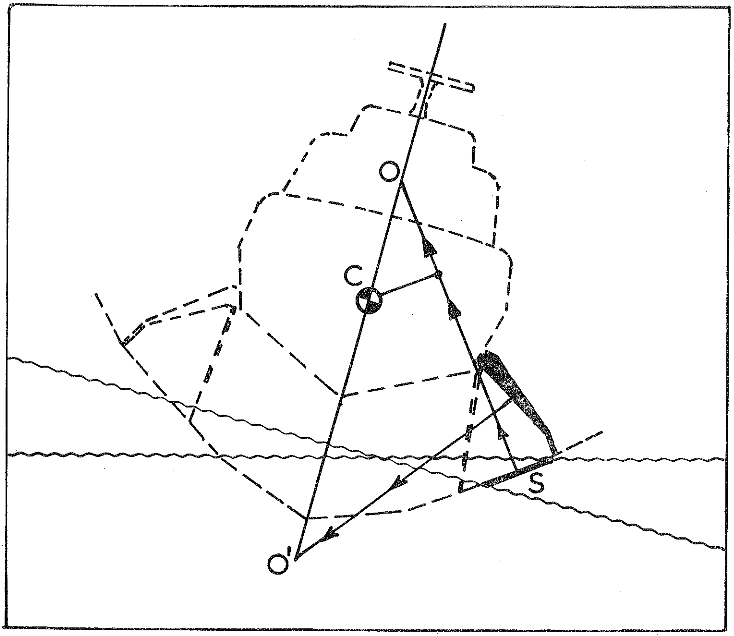


Fig. 1

Assuming the foil assembly to be part of a circle of centre O so that, on heeling, the new immersed area S produces a lifting force SO; then, for stability to be positive, C (the C.G. location) must be below O. This fact of course limits height for a given span. Elements of strut or foil with anhedral have a very good effect on stability since for them it is only necessary that C shall be above O^1, which is of course very easy.[1] Apart from this, dihedral on hydrofoils has no merit *per se* but only insofar as advantage is taken of the two media to allow portions of it to emerge. This is because the rather complex effect of the stability given by dihedral requires that there shall be some sideslip and, with the large vertical areas involved tending to resist it, sideslip is hardly possible.

In Fig. 2 we have a totally different stability method of an activated class. It will be seen that when the craft heels, say to starboard, the lift increase on this side, coupled with the lift decrease on the port side, produces two very powerful moments about the X–X axis, namely $+L\times a$ and $-L\times a'$. These correspond to a quite fantastic equivalent metacentric height and this would in fact be far too "stiff" were it not for the fact that all incidence increment rates are powerfully damped, a free system as drawn, not being practical except for models.

Therefore this method is suitable for very long legs and narrow span between foils, an essential feature if large waves are to be "platformed" or ignored. Furthermore, the response to a wave shape requires an auto-pilot of some sort,

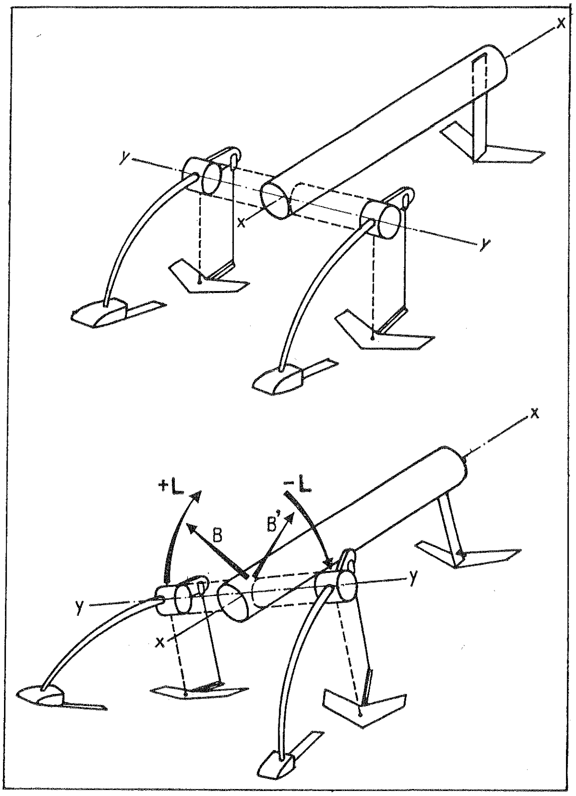


Fig. 2

the three foils by themselves having no stability: in fact the general arrangement is an inverted pendulum and inherently unstable by itself. So whereas the vee-foil is a slave to surface changes, this system is not; and in theory the boat can be "flown" by hand, by gyroscope (or better still by gyro combined with a vertical

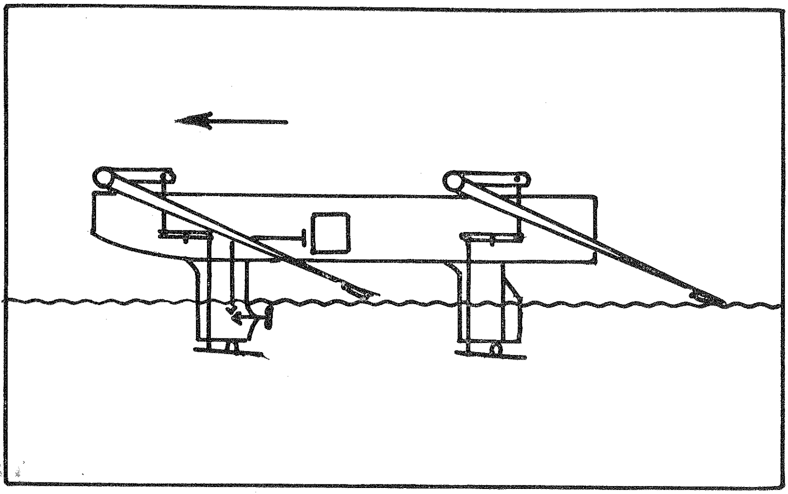


Fig. 3

height sensor), or by mechanical feeler or feelers (or again, these may be replaced by a sonic echo sensor able to measure heights). In general, the sensing device will require to be placed as far forward as possible, in order to gain some prediction effect. This is much more necessary here than in, say, a missile, because whereas the latter may have to avoid an object several miles ahead, in this case we are dealing with waves only a matter of a few feet ahead; and even half a boat length can be quite important.

An historical note is in order at this point. The Meacham brothers proposed an arrangement in 1906 based on trailing feeler arms (Fig. 3) but apparently no full sized craft was built and for a fairly obvious reason. Let us assume that the point of contact with the water is $\frac{\textit{hull length}}{4}$ behind the foil and that the time needed for the incidence change to make itself felt represents another period during which both boat and wave are advancing a combined distance equal to another $\frac{\textit{hull length}}{4}$ it follows that in waves of length equal to hull length the boat will react exactly 360° out of phase. That is to say that it will rise when it should fall and vice versa. Nevertheless we shall be returning to the trailing feeler, (but with a major modification) later on.

Manual control by joystick can have all the prediction effect of the pilot's vision and most Hydrofin owners have removed the feelers at one time or another to try this out, only to find that waves are too irregular and the strain too great for piloting to be maintained for long. One must remember that in head seas the waves may be encountered at a rate of about 4 per second and in following seas one would want eyes back and front! With aircraft the conditions are very different, since in normal flight, exact altitude is not required, as there is no surface to hit, and on landing the surface is perfectly level and up-gusts of air are impossible, because the ground forms a screen. Some experience of manual control of flight is essential in order that the "sea crash" may be experienced and its causes properly understood.

The Sea Crash

If the atmosphere came to a sudden stop, for example at an altitude of 100 ft, aircraft would have to carry a sensing device to avoid hitting it because the sudden loss of top surface lift would cause them to crash to the ground. Lift, it must be remembered, originates for the major part in upper side pressure drops and only for the minor part in under side pressure increases. Now, since the hydrofoil flies with its low pressure side next to the infinitely lower density medium of air, it is essential not to hit the ceiling of the high density fluid.

This is no place to explain the circulation theory but it may suffice to point out that with an inrush of air from the surface, seeking to fill the vacuum on the upper side of the foil, the circulation stops and the flow separates from the top camber. Should this occur on the rear set of a tandem hydrofoil arrangement the boat will sit down sharply by the tail, but no great harm is done. Should it happen on the front set, however, the results are disastrous, since, with the sudden loss of altitude forward, the whole hull trim changes and the lift from all foils suddenly changes sign, slamming the craft on to the water with great violence. Allan Hazard of California built several small, manually-flown hydrofoils, which he used to pull right out into the air, foils and all. On falling, the air taken down by the foils prevents an immediate re-establishment of the circulation and the hull will hit the water before lifting off again. It has never been suggested that this kind of acrobatic stunt was anything more than a sport for very small craft (which could not be scaled up).

The fixed incidence vee-foil rig is less dangerous in this respect than the fully submerged incidence-controlled, and although the crash occurs in rough seas the designer is able to give greater incidence to the higher portions of foil. Screens placed from point to point on the upper side are effective in stopping the air from penetrating to the central apex of the vee. In the fully-submerged foil we use no screens, but instead place the foil at the bottom and in front of the strut, so that air which might get down the strut's trailing edge, cannot proceed forward from there against the flow. It is now obvious that a crash-preventing method is essential for all fully submerged systems, otherwise such craft are restricted to protected water operation only or the foils must be run very deep and the controls must be faultless.

How High: How Fast?

We have shown that increases of speed on the sea are not possible without a good "hoverheight": how high should this be? There are so many variables, such as wave size, wave proportions, boat size and weight, boat speeds and boat-heading relative to wave crests, that our discussion will remain vague in the extreme if we do not start off by explaining these in detail. We begin with the waves. To take the maximum roughness is unwise because nobody goes to town in a tank under the pretext that there might be a war. Naval architects such as K. C. Barnaby[2] have defined the proportions of the "average rough sea" and that is a reasonable type to select for the discussion, as it will be understood that rougher seas will merely require some speed reduction, while hurricanes, if encountered at all, will be taken in the displacement condition or as partly planing on the hull, and partly foil-borne. (In our day and age, weather information, high speeds and short ranges make any encounter with a real storm practically impossible). Under the effects of gravity, large waves are much easier than small ones and the L/H ratio varies roughly from 10 to 50 so that this is best shown as a single curve on a log/log graph.

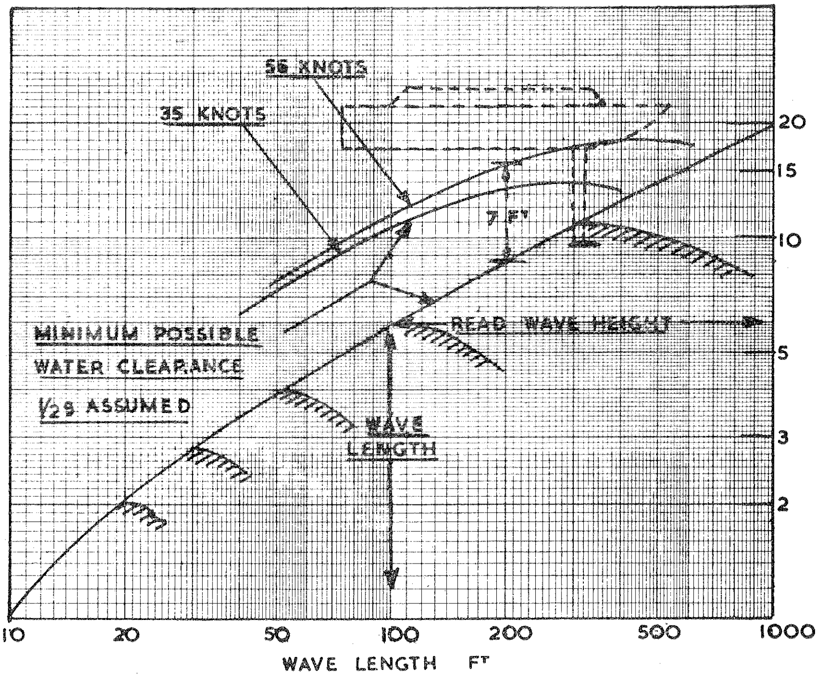


Fig. 4

We next have to make some simplifying assumptions. Waves are taken as sine curves and the line of flight is also a sine curve although this would not be true for any interface vehicle not sustained by wings (air or water) able to select such a path by controls modifying the lift from correct information. This is because the comparison of two sine curves of different amplitudes and/or phase is excellent "computer fodder" but it is not difficult to draw up such tables.

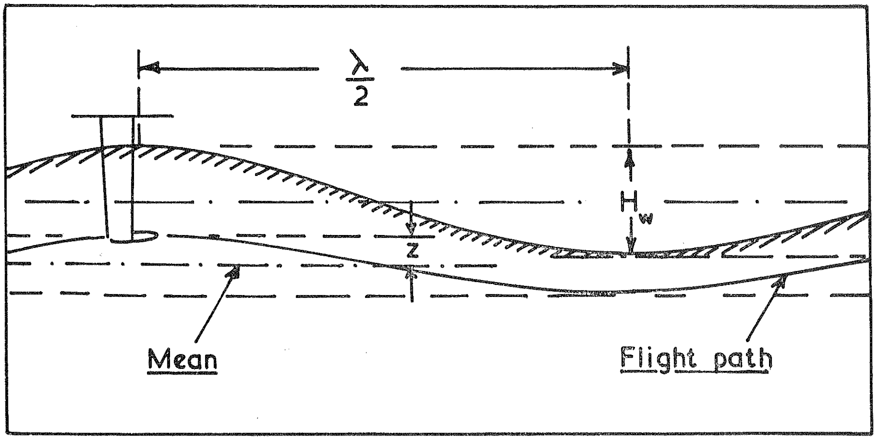


Fig. 5

We wish to draw a curve of water clearances showing, for each wave height, the minimum possible clearance for comfort, but clearly we must start off by defining what we mean by this word. It is generally agreed that $\frac{1}{2}g$ is a maximum for passenger comfort at high speeds although 6–8g has been registered in speed boats when they bury their bows in a steep wave. We now have the simple relationship: the permissible amplitude of boat path is directly proportional to the selected "g," and inversely proportional to the circular frequency of encounter squared, or:

$$Z=\frac{\frac{1}{2}g}{\omega^2} \quad \text{or} \quad Z=\frac{32.2}{2\,\omega^2}$$

where Z is the amplitude of the sine curve described by the foil measured from the mean foil path (so that the total heave is equal to 2Z) and ω is the circular frequency of encounter in radians per second so that:

$$\omega=2\pi\left[\frac{V+2.26\sqrt{\lambda}}{\lambda}\right]$$

for head seas, where V is boat speed in ft/sec and λ is wave length. For following seas the plus sign becomes a minus; or by introducing a cos X term, where X is the angle made by boat heading towards wave crests, it is easy to obtain ω values for any other direction. However, for greater simplicity, we will confine ourselves to the head sea case since it is the most difficult. It is now easy to tabulate values for maximum boat heave (2Z), and by subtracting these from wave heights to draw curves for minimum water clearance for the different wave sizes (Fig. 4). We find, for example, that a wave 200 ft long and 8.6 ft high will require a strut length such that the hull will ride 7 feet clear of the water for a design speed of 55 knots.

In order more easily to visualise the circular frequencies of encounter Fig. 6 presents these in graphic form. If the boat starts from the left, running against waves of 1,000 ft, 800 ft or 600 ft the point of encounter with the next crest is shown by the circles and can be measured in distance on the x axis and in time on the y axis. The slope of the wave-advance is of course fixed by its speed, which is a standard $2.26\sqrt{\lambda}$, and to get the points of encounter for following seas we would only have to set off the boat speed slope on the other side of the ordinate where the wave length $=0$. It is seen at once that for 35 knots, only the longer waves would overtake, so that, except for the orbital motions, all the smaller waves would become head seas of very long wave lengths. (The orbital motion question will be dealt with later.)

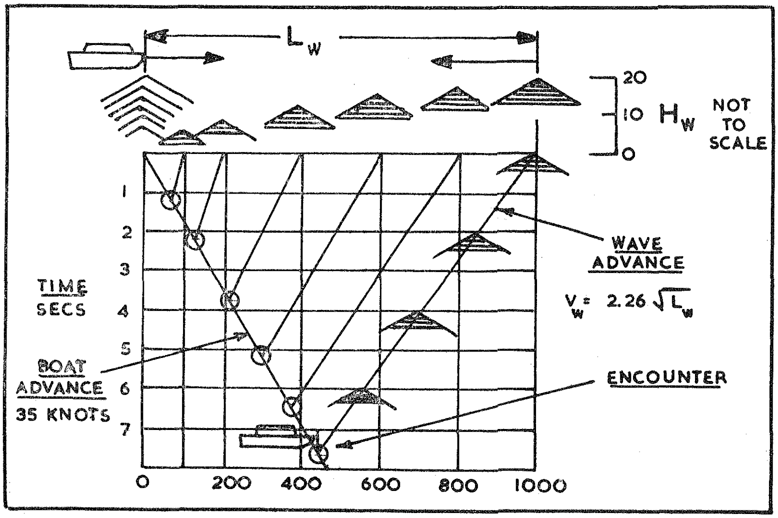
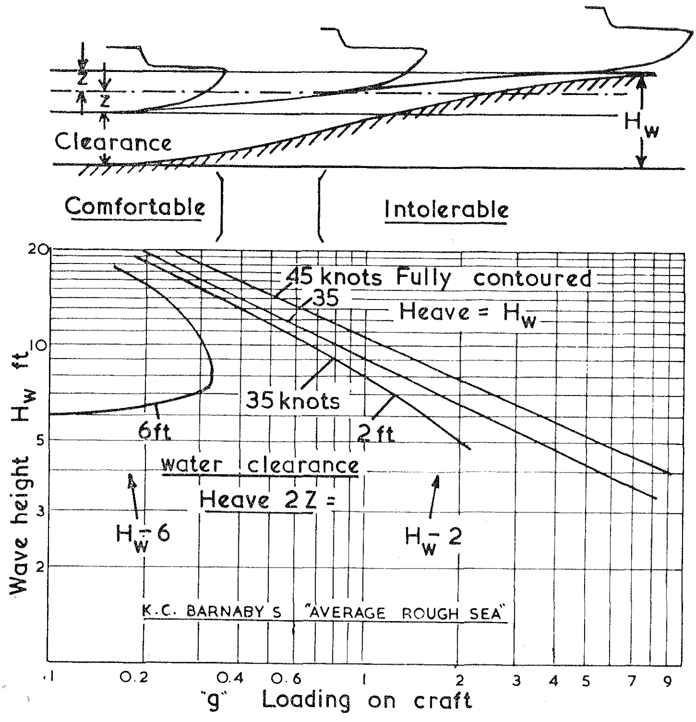


Fig. 6

It is interesting to note that, because of the easier wave geometry in the larger sizes, the required water clearance tends to zero from waves of 17 ft and over (and for 55 knots), so that, were it not for the practical considerations of the superimposed waves on the larger wave contours it would theoretically be possible to take very large waves without water clearance. At the other end of the scale the values for ω increase so fast that water clearance has to be practically equal to wave height, a condition that is now known as "fully-platforming".



EFFECT OF WATER CLEARANCE ON COMFORT

Fig. 7

The next logical step is to generalise further from this information so as to show the effects on comfort (tolerable or intolerable) of fully-contouring waves or of platforming part and contouring the rest. (Fig. 7.) What sort of *g* would this produce?

Assuming head seas and sine curves for boat travel and wave shape, then the curve on the right shows how "*g*" loading increases from a comfortable 0.3 for large waves to an intolerable 5 or 6 for small waves. This assumes no water clearance, i.e. flight path conforms to wave shape. (For a planing boat it is much worse because changing trim results in violent contact with wave fronts.) The next curve is the same for 35 knots. The third assumes a 2 ft-clearance such as for air cushion vehicles and the fourth a 6 ft-clearance for a hydrofoil boat with "active" lateral stability, i.e. by incidence control. Obviously below 6 ft there is level flight and therefore zero "*g*". The seas are the same but shown only in height while *g* loadings are plotted along the *x* axis from 0.1 to 10. The two straight lines are for fully-contoured waves where flight sine curve equals wave sine curve: and we see at once that the smaller the waves the further we shoot off into intolerable *g*. A 2 ft. water clearance brings some improvement but is still impractical for waves under 10 feet high (even for only 35 knots). If, however, we introduce a water clearance of 6 ft so that boat heave equals wave height minus 6, then we have a craft that can take all waves and with a very easy *g* indeed.

Until these "facts of life" were beginning to be understood from practical experience on the sea there was a regular crop of inventors who each year repeated the same disappointing experiments and were as regularly defeated by air bleed and/or by wave encounters at speed. Even with the best Admiralty brains of the time concentrated on the Samuel White boat of 1938, this craft appeared to produce so many formidable problems as to cause the Navy regularly to discourage any private initiative in such a seemingly complex field. A study of the strut arrangement revealed the fact that no steps had been taken to protect the foils or propellers from air entry, so that the disastrous effects of this were confused with cavitation. The net result was that no new proposals that did not first of all find a cure for cavitation were even considered. I was able to unmask air bleed by tests on my own small tank at Cowes 10 years before the first paper on the subject by Wadlin.[3] It must be remembered that observations of what is actually happening on hydrofoils on the sea is almost impossible in our climate and in 1938 there had been almost no tank work done at all.

It is equally certain that in 1906 pointing a feeler forwards was unthinkable, in view of the absence of any flying boat design experience. Naval architects would have expected a negative dive and even in my time this made some observers apprehensive. In reality, the problem was only slightly more difficult than that of mounting a wing-tip float on a flying boat. It may therefore be stated that it was the combined effect of the following five novel points which aroused much interest when I arrived in the United States in 1950:

1. Air bleed cure. (This existed for vee-foils.)
2. Advance wave-prediction.
3. Very powerful lateral stability (differential correction).
4. High line of flight (result of 3).
5. Crash elimination (by way of the damping force).

There will always be controversy about the amount of unorthodoxy that can be accepted in payment for novel advantages. Are we not reluctant to remove ships' funnels even though we no longer have any smoke to push through them? How much more difficult then must be the arguments around a system of marine travel which even goes so far as to ignore Archimedes.

Possibly the step of adding forward-pointing feelers to a boat was an outrageous one, but then so was that taken by the Montgolfiers in actually leaving the ground. The feeler enabled a boat, for the first time, to be stabilised by signals taken from the changing water situation rather than from the direct action on foil geometry based on the density-differential. It has the advantage that the signals may be taken from an advanced location on the boat, integrated, combined, damped, even reversed, or modified by the pilot for banking, and height adjustment, The simple inverted T of the strut/foil assembly lends itself admirably to retraction needed not so much for shallow water as for maintenance and to avoid corrosion.

But if the "outrageous" method of feeler arms was only a means to an end (or an episode, in the same way as the Montgolfier was an episode on the long road to the "Concord"). I still believe that it was an American mistake to apply space rocket-class techniques to the rather simple cam-follower type of requirement of a water level situation signal. For whereas it is understandable that an aircraft lost in fog and needing to make high speed contact with the ground under zero visibility cannot push down a pole to feel for chimney pots (and must perforce use a sonic or radar depth-sounder to establish altitude), one must question whether such sophistication is necessary in the much simpler case that now concerns us. (Fig. 8.) The distance is far too short for radar; nor can sonar be directed forward, ahead of the bow, because of the effect of scatter due to the uneven surface of reflection.

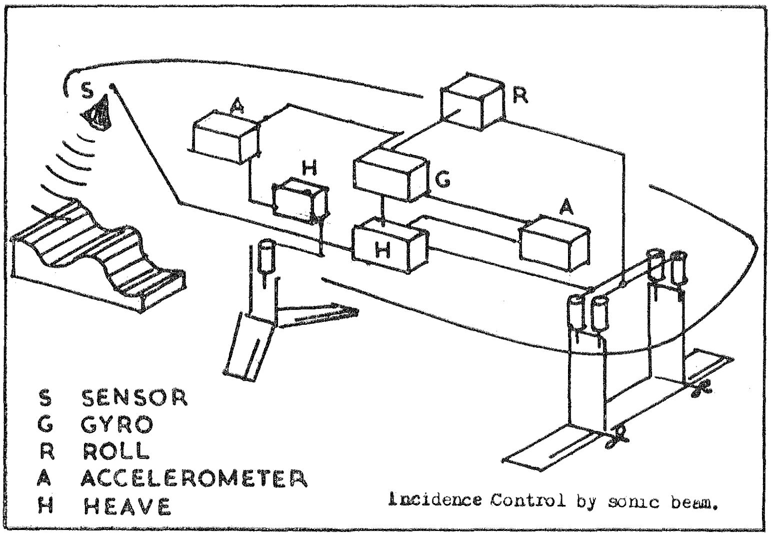


Fig. 8

Since no repellant has yet been created that will rid such projects of swarms of costly "boffins", these projects tend to get out of hand, finishing by producing an unrealistically-priced product of very poor reliability. It is thus that Van Bibber[4] of Lockheed has the right to complain that one large hydrofoil costing several million dollars and $2\frac{1}{2}$ years old has only 40 hours of experimental flight time. Also, despite an estimated total of some $50.000.000 of expenditure (or some 50.000 times the sales price of the small "Hydrofin" demonstrator taken to New York) the Americans still have no real product to sell.

Solution to "The Outrage"

An alternative solution to the need for a tidier type of auto pilot far less sophisticated than sonar beams has now been worked out, known as the "New Hydrofin". It must be well understood that while the concept of the fully submerged foil was accepted with enthusiasm because of the advantages already explained, the feeler arm method of control has remained difficult to sell. Not that this was necessarily because of the existence of something strange up in the bow, since sailing ships have always carried bowsprits. The crime of the mechanical feeler arm has been its appearance, the difficulty of greatly increasing its size and the fact that it has been both forward and off centre, i.e. at a location where it might be expected to get wiped off on coming alongside. It is also true that the addition of so many extra gadgets needed to turn the arm into a veritable by-pass wave filter has tended to become somewhat absurd, as will be understood from Fig. 9. In this drawing the servo plane G normally flies well above the surface so that small waves merely lift the heel K against the spring L. The work done on the arm by the passage of a wave is small compared to the strength of the shock absorber F which can also be freed from the arm for retraction of the latter. Alternatively, both arm and leg may be retracted together by turning about the tube spar. The height of travel in respect to the water surface depends on the position of the rod B for any position of the arm but this can be changed at any time by pilot intervention. The change may be the same each side (producing a gain or loss in height) or it may be opposite for each side (producing bank).

For example, pushing the steering column forward rotates the tube in the spar. Since this is connected to a stud that fits a slot in the middle of the floating arm, it is seen that the rod B must rise setting the foil more negative for the same position of the feeler arm.

Pushing the column to port produces the same action on the port side but the opposite on the starboard side. Therefore the craft banks to port and will fly banked until the column is brought back to a central position.

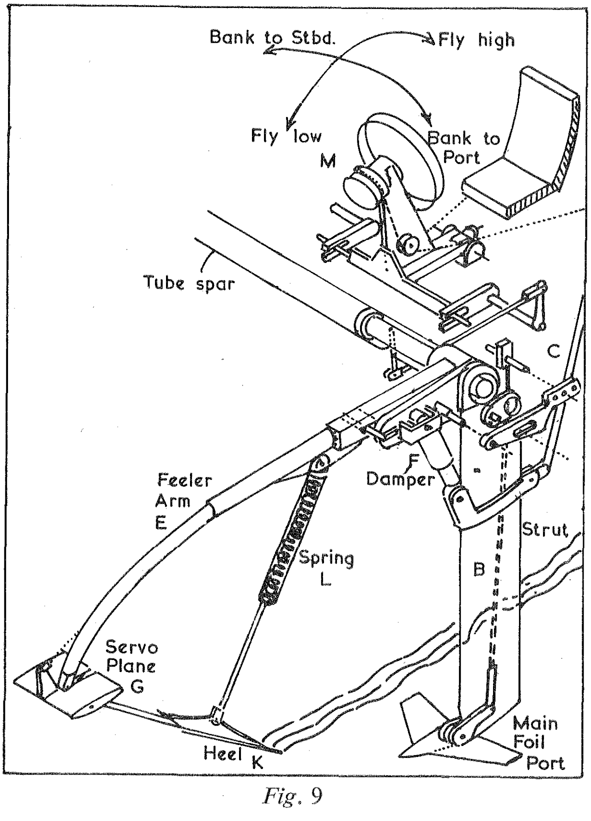


Fig. 9

But the need to separate pitch from roll signals, bringing us back to a modified Meacham conception is the key to the new "Hydrofin" system.

We have seen that a trailing feeler can give a reversed signal for certain wave lengths and is therefore unsuitable, but we have thought only in terms of head seas where encounter speeds are boat plus wave speed. We have thought only in terms of pitch signals. But a forward and off-centre feeler has very little prediction advantage in respect to beam seas, and in fact none is required because they arrive only at wave-speed and the response of the system is always adequate to deal with the situation. Only for the head sea is this not true, because here encounter speed is wave plus boat speed and this is critically high, so that prediction is a sine qua non. Furthermore, pitch-control by the parallel motion of two forwardly pointing arms and roll-control by their differential has a serious fault. Any damping that is correct for the pitch or critical rates is incorrect for the roll so that if one damps enough to get acceptable head sea reactions there will be too little differential and the boat will sway drunkenly sideways to the alarm of the passengers. However this cannot be properly understood without explaining the general effects of orbital motions.

Orbital Motion Effects

This is another situation that the aeroplane does not have to deal with in quite the same form. This has all been too complex for any general treatment

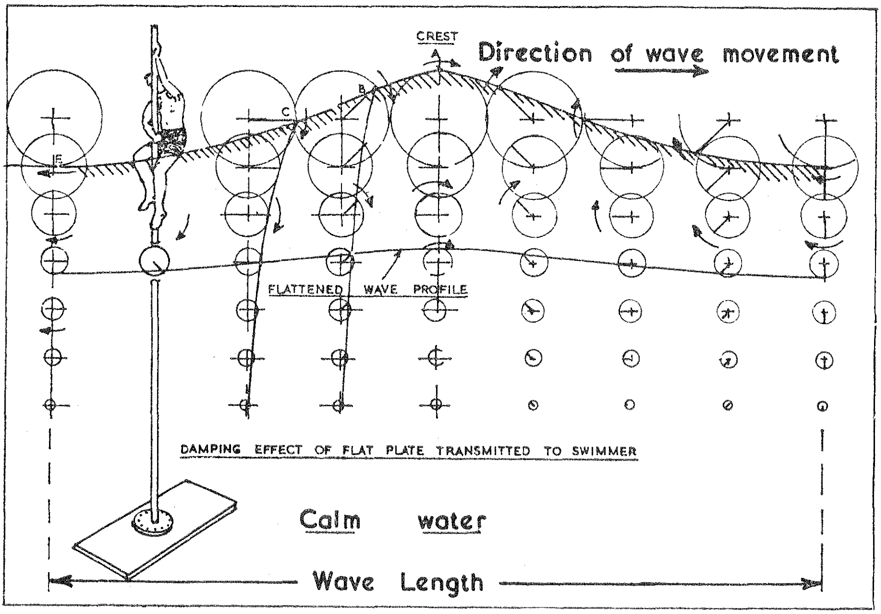


Fig. 10

based on theory alone. Quite apart from a backlog of many past failures there could well have existed some quite impassable "sonic barrier" and in fact the super-cavitating hydrofoil may never be solved although super-cavitation works for propellers. (This seeming anomaly is due to the fact that whereas the latter can accept a non-linear relationship between C_L and α, the foil cannot since it introduces an instability that cannot be controlled.)

A wave, as is well known, is composed of circular motions of the water particles in a sequence giving an illusion of translation, an effect that decreases with depth (Fig. 10).

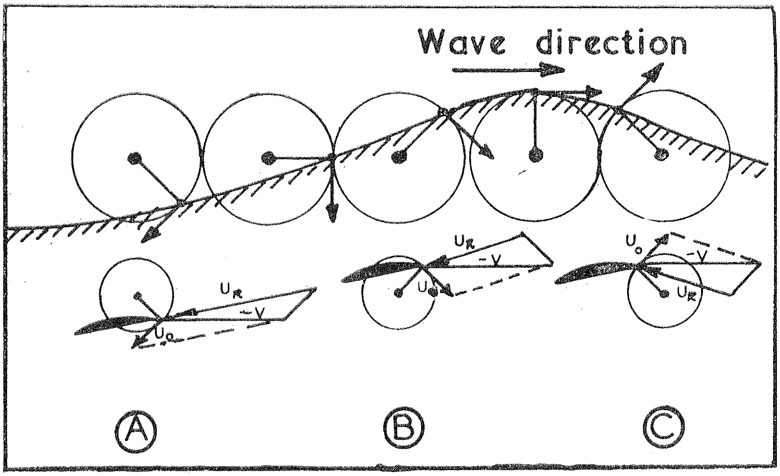


Fig. 11

Now a hydrofoil (Fig. 11) will encounter orbital motions *Uo* which must be vectorially added to the hydrofoil velocity *V*. Combining the *Uo* velocities for the different wave positions A, B, C, with the incident horizontal velocity relative to the foil —*V* produces the resultants *Ur*.[5] At *A*, *Ur* is larger than —*V* and it is seen that the foil is producing negative lift, a situation that improves somewhat at *B* and becomes positive at *C*. All this time —*V* has remained constant.

This shows that fixed hydrofoil craft tend to sit down in following seas due to negative lift at A and B. (Incidence control is the only possible choice for a landing craft). However this will not happen to the I.C. system since even before *A* the feeler system will be feeding in some extra positive angle of attack (due to the detected wave shape) and lift will tend to remain constant, a condition which will minimise cavitation inception.

If we now reverse the wave direction we will get a totally different set of conditions. The *rising* water *Uo* will increase a fixed foil's lift so that it will tend to rise to head seas without any help (albeit with some phase lag due to inertia and "late" information). The I. C. foil will experience this too, together with another increase due to wave shape detection as before: total two increases or double heave, hence the need to reduce this for head seas by a change of link factor or damping or both. The difficulty of doing this with respect to pitch without making the roll signal unacceptably sloppy shows the need to divorce the two and deal with them separately. We see at once that the roll signal, not being interested in critical head seas, may come from a Meacham arm picked off at any phase angle of any wave. It will merely inform a single and centrally placed pitch signal what to do about roll, either in terms of horizon or in terms of local water surface: preferably a bit of each. Perfectly level flight without roll in rough seas is not good because of the constantly varying drag forces on the struts tending to induce yaw. Need we prove that a fixed tail foil will lift the stern to an overtaking wave? A glance at *C* proves this at once. To overtake, *Uo* will be relatively larger with relation to —*V* and in consequence *Ur* will show an even steeper positive lift angle.

Wagner Effect

Aircraft engineers tend to be more aware of the problems explained above than are naval architects and they tend to conclude that the net result of all these varying forces will be violent vibrations of a type similar to those of a craft subjected to surface waves at high speed, or only slightly attenuated by the effect of depth. They have difficulty in visualising signals so carefully calibrated as to balance the other variables at all times, particularly in view of the irregularities of waves.

Fortunately there is another, but little known phenomenon, the Wagner effect and, without going into details this may be briefly summarised as a hysteresis tending to level out or nullify all quick changes of incidence. Broadly speaking, it takes a travel of about 10 chords for a change to become fully effective and it is this which explains the total absence of any vibration or brutal changes in lift from hydrofoils: a very important advantage not shared with surface planing elements.

Necessary Qualities for a True Platforming Hydrofoil

We can now list the essential features of a practical sea-going craft able to do for maritime travel what the iron rail did for terrestrial. We cannot lay rails over the sea, nor can we build viaducts or cuttings through waves, but we can obtain the same effect from the fully platforming hydrofoil.

Size. It is probably on the matter of size that there are the most misconceptions regarding hydrofoil craft and this is clearly because we are trained from childhood to think of ships as colossi, the image of the "Queens" coming immediately to mind. But the navigational problems that had led man to this by degrees are all based on waves and their domination by mere mass and mere length. Based on purely passive acceptance of wave forces a 1,000 ft wave can only be matched by a 1,000 ft hull. But here we are discussing a totally different product and one which deals with waves in an active manner, hoisting itself up to override them, so that we now have to put the questions how high and how big? If height of travel is basic to the calculation of "*g*" loadings at various speeds, it is just as basic to the question of size, since, if we think back to our man on the pole in waves (Fig. 10) we see that the extreme in this direction would be an infinitely small boat on infinitely long legs. In this concept all mass tends to zero, which is possibly a *reductio ad absurdum* but it makes my point. It remains to find a practical ruling in this matter.

The parameters change vastly if we consider fixed or extendible legs on the oil platform idea; and although these have been built, taking into consideration the cost and weight factors involved I am of the opinion that the designer will have to accept fixed legs even if he has to use extra boost for take-off (which is a fairly regular power plant feature these days anyway). Variable pitch propellers would also help greatly, but the difficulties of transmission of the controls through a Z drive are much greater than through a straight (angled) shaft. Longer legs also call for thicker strut sections high up and these may have to be so thick (if there is a long unsupported length) that cavitation can be a problem at this part even before take-off. Hence the radical design change in the "New Hydrofin", introducing a long supporting diagonal (Fig. 12) and generally making the strut as short as possible in relation to the water clearance. It is clear that in the measure where size increase is necessary to stand up over waves it is the craft that can increase height almost without increase in size which wins the race towards smallness. Why should the usual shipping idea of large size be now put in reverse? Because we are dealing with passengers, and only with short range, an area wherein more and smaller units with more frequent departures is the rule for sound commercial exploitation. Admittedly it will take much work to get small craft accepted for passenger work by the Classification Societies. The Navy also tends to think in very large sizes.

It is still difficult to establish a rule for specific power related to strut length because of the many variables and lack of experience so that the water clearances given in Fig. 18 B & E of L/30 and L/8 are still only approximate. The A.C.V.

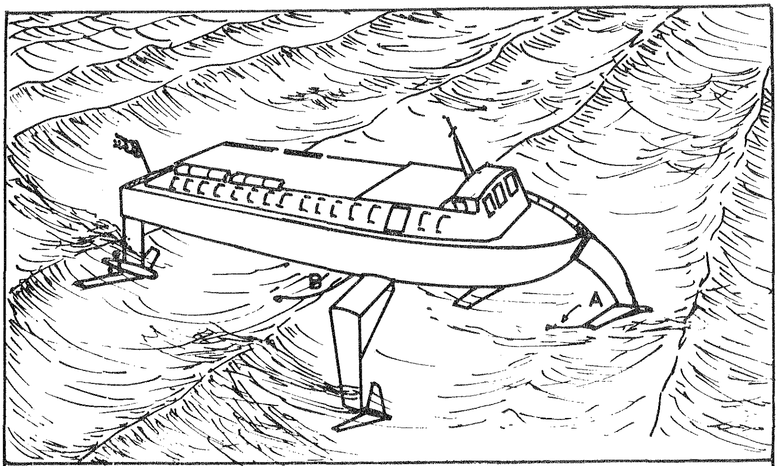
figure of 1/50 seems to be generally accepted. Taking two craft where the second has a three fold height advantage this could clearly be built with 1/3rd of its length and $1/3^3=1/27$th of the weight of the first, a tremendous advantage. Now, since a 100 ft hydrofoil weighs about 100 tons, and since this size with I.C. can clear a 100/8 or a 12½ ft wave in level flight (and even a 20 ft wave with only 7½ ft of heave) it follows that on the basis of wave negotiation we need go no bigger. This advantage will be better appreciated when it is remembered that all the "expensive craft" (i.e. aeroplane, ACV, hydrofoil, helicopter) must work on a basis of high passenger density and this means 2–3 passengers per ton in hydrofoils: say 250 passengers for our 100-tonner. (Contrast with the normal ship's 15 tons per passenger, more or less.) So our first craft looks like having to build to 2,700 tons as against 100 tons for the same wave sizes. (This is of course a gross over-simplification in the interests of clarity.) How would one go about handling 7,000 passengers? Where are the A to B locations where such potential passenger flow is to be found? Seasonal demands alone make for very costly exploitation.

Seeing that high density seating is only tolerable for 5 to 6 hours this fixes at once hydrofoil or ACV range at 200 to 300 miles maximum. Cargoes will of course continue to go in ship's bottoms since world economy could not support any massive increase in the transport costs of basic commodities and most cargo time is lost in warehouses anyway. The point to retain in all this (i.e. the world revolution that makes it all possible) is that man is no longer content to travel at cargo ship speeds and in more or less cargo ship discomfort—in the motion sense. We may say that the common man is today an avid buyer of the reciprocals of time and "g" and he further wants this for short as well as long range. We may also see that, had the helicopter turned out to be cheaper safer and more amenable to scaling up (rendered impossible because of the rotor and the cube square law) there would be no room for hydrofoils or A.C.V.s and the great versatility of the helicopter would meet all needs. Many men now wonder why the flying boat was killed so soon and purely on the basis of its handicap on long range without due regard for its better versatility.

It is therefore in view of these manifold considerations that one may be permitted to doubt whether the American "megabuck" hydrofoil programme will ever reach a profitable market, North American geography not being particularly favourable to hydrofoils; and this fact forces the industry to export, generally to the under-developed countries, unable to pay United States' development costs. Much nearer home, Pringiers[6,6a] has shown in a detailed and carefully documented study for his company, the Cie Maritime Belge, that a London to Rotterdam (town centre to town centre) service by hydrofoil would be faster and much more attractive than the rail-air-coach alternative. He has also written an exhaustive mathematical study of Hydrofin controls[7].

The Design

The general appearance of such a craft is seen in perspective in Fig. 12, and it will be noted that when floating it reveals nothing "outrageous" to the most conservative. The crash plane is carried on a bow extension to the keel and advantage is taken of this position to mount the pitch sensor under this. Since no hull-sustaining effort is expected of the sensor it may be in the form of a "whisker" or hollow steel rod and its information passes up inside the keel extension. The crash plane also assists take off and may retract. The objects of the cantilever spar protruding from the hull are to increase the span, allow clearance for retraction and for the connecting plane which steadies the strut, at the same time providing a fixed hydrofoil for take-off with pronounced anhedral which, as we have seen, is particularly good for stability. (Fig. 1.) The B or roll whiskers may also be mounted at the rear of the main struts instead of at the chine as shown. All hydrofoil craft in regular service operate



IN THE NEW HYDROFIN THE ANTI CRASH FUNCTION IS ENTRUSTED TO THE FORWARD PLANE 'A' NORMALLY ABOVE WATER. PITCH CONTROL, REQUIRING ADVANCED WAVE PREDICTION, IS AHEAD, WHILE ROLL CONTROL IS TAKEN FROM BEAM AT 'B'

Fig. 12

from quays where some fending-off platform has been built to take care of the main hydrofoils. For oil rigs or pilot vessels and lifeboats the fender may be a fixture to the rig, to the boat or inflatable buffer units may be used. Since the diagonal fixed hydrofoils replace the need for a deep vee to the hull the struts are very short for the water clearance and the bottom very flat. This means that for an amphibious landing craft inflatable rollers or tracks could emerge from the bottom after full retraction of the 3 legs as shown in Fig. 13.

Controls

Fig. 14 illustrates the controls system in its mechanical form with hydraulic boost servo at the last stage actually to move the foil. The same method can also be worked by an electrical amplidyne system (Fig. 15). The servo power could also be pneumatic or, for very simple systems, mechanical action may be used throughout. In reality the levers are of course much smaller than drawn. The pitch signal after possible intervention by a floating mass (damped) to reduce pitch signals and again by the pilot (not shown) divides into two, after which there is intervention by the differential of the (two) roll signals before each half operates the spool valve of the final servo controlling the foil. Only the spool is shown on the starboard side. A hydraulic piston to rotate the tube spar for full retraction is also shown. Marked arrows show the directions of the various signals.

Z-Drives

The propulsion problems connected with hydrofoil craft are more complex than might at first appear. While relatively low-flying vee-foil craft can use long shafts angled at about 15°, this solution is not popular and the irregular flow to the propeller induces cavitation. (Supramar type.) High-flying incidence-controlled craft must use air drive, water jet or Z-drive, i.e. a vertical drive shaft included inside the tail strut with bevels above and below, the latter set being inclosed in an under-water torpedo. Fig. 16 shows in some detail a power strut that steers and retracts through 180°, and is also fitted with a fail-safe device that allows it to trail out behind should a very heavy object be struck. (Similar systems are also fitted to the main struts.) Tail incidence may be manually set in flight. This design, developed in Germany and Norway is extremely simple in that only two main castings are required, joined in the middle, and only two through machinings (at 90° to each other) in each casting. The steering yoke is another casting, the hydrofoil a fourth. The upper vertical shaft is machined with an Archimedes screw that lifts oil to lubricate the upper spiral bevels and reverse gear.

Some American craft have used a canard configuration, and twin rigid power struts so as to reduce the power to be transmitted down each. Drive on the front struts is another idea of the same class. Much experience has been gained in small sizes by using air drive or outboard conversions with extra long extensions but in general the demand is still too small for mass production of a really satisfactory and properly engineered small unit. The public is looking for free rides rather than hydrofoil yachts at this stage in the development and this is likely to continue until cross channel services are well installed.

The Future of Hydrofoils

Seeing that the basic principles involved can offer really well-supported high flight without any wasteful air losses or need for rubber air containers as with the A.C.V., it is obvious that incidence controlled hydrofoil craft will be employed mainly for rough sea passages of short range where the demand is great enough and not too seasonal. From the experience gained by these ferries, larger naval craft, oil rig boats and lifeboats will follow, based mainly on the use of the marinised gas turbine which will find here another outlet for sales and export.

Comparisons On An Efficiency Basis

The totally different principles involved with hydrofoils and A.C.V. make direct comparisons rather complex. Whereas the former is really a flying machine so that efficiency can be measured as with an aircraft (i.e. the over-all L/D ratio at cruising speeds multiplied by the propulsive efficiency η) the case of the A.C.V. must be thought of first in terms of the gain obtained by the ground effect or "lift-amplification factor" but this vanishes with altitude and thus requires the hovering height/diameter ratio to be small (e.g. 1/50). This imposes a severe limitation on altitude ("Aerodynamics", Houghton & Brock). Thus power for the air cushion to maintain hoverheight must be considered separately from power for forward propulsion, the latter increasing less with speed for higher hoverheights, but the latter are of course more costly in air losses. Fig. 17 shows relative efficiencies in HP/Ton plotted against speed for ships, vee-bottom boats, helicopters, A.C.V. aeroplanes and hydrofoils. To the last is added a purely theoretical extension into the supercavitating range. From this it is seen at once that on the efficiency basis hydrofoils should be used at between 35 and 60 knots, the extra complications (compared to normal ships) being hardly worthwhile below this speed. The excellent efficiency of the aeroplane at high speeds is obvious, pointing clearly to the absurdity of trying to use anything else commercially for long range. The helicopter is expensive both to run and to build but extremely versatile, not being restricted even by mountains. The A.C.V. tends to be expensive but has mixed terrain-versatility where this can be used. Efficiency will improve with size but this can become expensive again if the vehicle is forced to become too big to be filled to the correct passenger density. Hydrofoils are no more versatile than ships but they sell tickets three times as fast (as do A.C.V.), so that their extra cost is not important provided they are kept in good employment. Their speciality is very rough seas, short range and the virtual elimination of sea-sickness.

V. H. Van Bibber[4] of Lockheed's sums up this last point neatly in his paper to the S.N.A.M.E. Hydrofoil symposium of May 1965 in Seattle as "g" loadings vertically, laterally and in heave and pitch equal to ships four times their tonnage going half their speed. There is an urgent need for more engineers and scientists bold enough to make such statements so that we, as a nation, can get on with the job and stop procrastinating.

Short Hydrofoil History and The Survival Of The Fittest

The advantage of putting the historical part at the end is that it enables space to be saved that might have otherwise been spent on unprofitable descriptions of ideas or systems that have not survived the test of practical application. The variant of the "Hydrofin" as designed in Miami for the U.S. Navy and incorporating hydrofoil and strut retraction in full flight was of this class and it would clearly be a waste to give any more time to it here.[8] Similarly with the possible exception of Canada with its associations with Bell, the stacked foil idea is out of date and no longer considered to be practical.[9a] Emerging area however survives with "Supramar". Early Italian hydrofoil work around 1906 by Forlanini, Crocco, Caprini, Pegna and others was mainly concentrated on assisted take-off for seaplanes, an application that could outrage nobody. This requirement vanished when aircraft engine powers were vastly increased and take off was no longer problematical.[10] I was however just able to obtain some assistance in the form of R.A.E. tank tests motivated by a slight anxiety concerning the S.R. Princesses in 1947.[11] Bell bought the Fornanini patents but his "Hydrodromes" were rather too spidery in design to be considered practical by the U.S. Navy despite their 71 m.p.h. More simplification and cleaning up was going to be required and this was the main contribution of Baron H. von Schertel[12] and G. Sachsenberg, a partnership later to become Supramar A.G. of Switzerland, designers and licensees of the very successful Vee-foil Supramar passenger ferries.[13] Supported as minor "V-weapons" (nuisance raiders in selected weather or possible North Africa troop carriers) the Schertel-Sachsenberg team gained a head start during the war and wisely took advantage of the abundant finance in Switzerland. Their work also gave rise to the Russian river hydrofoil system (Fig. 18A) claimed to be almost as cheap and efficient as rail. The Grunberg[14] principle first tested in France in 1937 was later taken up by Sweden and later in Holland but this hybrid system illustrated in Fig. 18C does not platform, nor does it take advantage of I.C. powerful transverse stability to lift high, since all incidences are fixed in relation to the hull.

Incidence control, developed by my team at Cowes, was taken to the U.S.A. in 1951 and was the only possible choice for the Navy's landing craft project since such a craft, by definition, is a following sea negotiator. At that time no builder would have even contemplated sonic beam control of a marine craft. The mechanical system enabled such a step to be taken since it provided experience of 38 knot speed in a 13-ton craft riding 6 ft waves with approximately 0.25 g.

Thereafter American development again split into two branches, Grumman's with Maritime Administration[15a] assistance returning to Vee foils for a time with the Denison despite the fact that the fully submerged foil was already known to be far superior for waves. Boeing's and Gibbs & Cox developed the sonic beam information technique applied to I.C. either in canard or conventional planform. (Fig. 8.) Since the Denison developed cavitation in all waves above 2 ft for reasons which have been briefly explained on page 176 under "Wagner Effect", the Vee-foil too has been definitely abandoned in the U.S.A., leaving in practice the following surviving methods:

1. Vee-foil ferry craft System Schertel (Supramar) Fig. 18B
2. Surface effect river boats. U.S.S.R. ,, 18A
3. I.C. "super sophisticated" (sonic beam) ,, 8
4. I.C. mechanical New Hydrofin[16] ,, 18E

In cost these craft are sharply divided into two groups, and although little is known of Russian costs we may assume them to be comparable to that of Supramar. Very roughly speaking numbers 1, 2 and 4 are in the £3,500 per ton class while 3 would appear to cost about five times this or even more. This, considering North American geography which is not very favourable as regards islands and climate, must give rise to doubts as to whether such a costly vehicle can find a market in view of helicopter competition.[18]

Conclusion

The reader will already have noticed how many different branches of technology are involved in the exploitation of the hydrofoil for smooth sea travel: Naval architecture, aircraft engineering, control engineering, aircraft style propulsion engineering etc. In the present age of extreme specialisation (knowing more and more about less and less) this constitutes a very real problem of assessment of the relative merits of the different ideas so that the value of studies such as that of Professor Yangos[19] cannot be over emphasised.

REFERENCES

1. CREWE, P. R. M.A., "The Hydrofoil Boat: its History and Future Prospects." *R.I.N.A.* October, 1958. **100** p. 329.
2. BARNABY, K. C., "Basic Naval Architecture."
3. WADLIN, K. L., "Mechanics of Ventilation Inception." 2nd Symposium Naval Hydrodynamics O.N.R.
4. van BIBBER, V. H., "The Major Problems of Hydrofoil Craft." *S.N.A.M.E.*, Hydrofoil Symposium—Seattle May 1956.
5. SAUNDERS, Capt. H. E., "Hydrodynamics of Ship Design," Volume 2.
6. PRINGIERS, C., "Les Bateaux à ailes Porteuses," Sociéte Royale Belge des Ingenieurs et des Industriels. March 5th, 1964.

6a. PRINGIERS, C., "A Belgian Naval Architect looks at Hydrofoils." Hoveringcraft and Hydrofoil, August, 1963.

7. PRINGIERS, C., "A Theoretical Approach to the Problems of Harmonic Motions and Forces on a Hydrofin Boat in Regular Waves."
8. LACEY, E. R., "A Progress Report of Hydrofoil Ships," *R.I.N.A.*, January, 1965.
9. MILMAN, J. W., and FISHER, Cdr., R. E., "The Canadian Hydrofoil Programme." *R.I.N.A.* 24th March, 1965.

9a. BEAUMONT LEWIS, C., "A Hydrofoil Ship for the Canadian Navy." S.N.A.M.E., Hydrofoil Symposium. Seattle, May, 1965.

10. HAYWARD, L., "The History of Hydrofoils." Publication, Hoveringcraft and Hydrofoil.
11. ROYAL AIRCRAFT ESTABLISHMENT., "Tank Tests on a Hydrofoil Boat with Incidence Control (Hydrofin)." Tech. Note No. 1922, November, 1947.
12. VON SCHERTEL, H., "Design and Operating Problems of Commercial Hydrofoils." 3rd Symposium, Naval Hydrodynamics. O.N.R.
13. HARBAUGH, K. H., and FITZGERALD, W. H. G., "Hydrofoil Operations and Development Experience." 3rd Symposium Naval Hydrodynamics, Seattle, May, 1963.
14. GRUNBERG, V.,"La Sustentation Hydrodynamique par Ailettes Immergees." L'Aerotechnique, June, 1937.
15. GRUMMAN AIRCRAFT, "Study of Hydrofoil Seacraft." Maritime Administration.

15a. KRACK, R. C., and GROSS, J. G., "Experience with the Hydrofoil Craft Denison." 3rd Symposium, Seattle, May, 1963.

16. HOOK, C., "The Battle of the Hydrofin." Trans. *Manchester Association of Engineers*, 29th October, 1965.
17. HOOK, C., "Wake up England." Publication—Hoveringcraft and Hydrofoil.
18. STANFORD RESEARCH INSTITUTE, "The Economic Feasability of Passenger Hydrofoil Craft in US Domestic and Foreign Commerce." Maritime Administration.
19. YANGOS, Prof., P. P., "An Appraisal of Hydrofoil Craft for the Benefit of the Aeronautical Engineer," N.A.T.O., Advisory Group for Aeronautical Research and Development. Reprinted in Hoveringcraft and Hydrofoil, January, 1965.

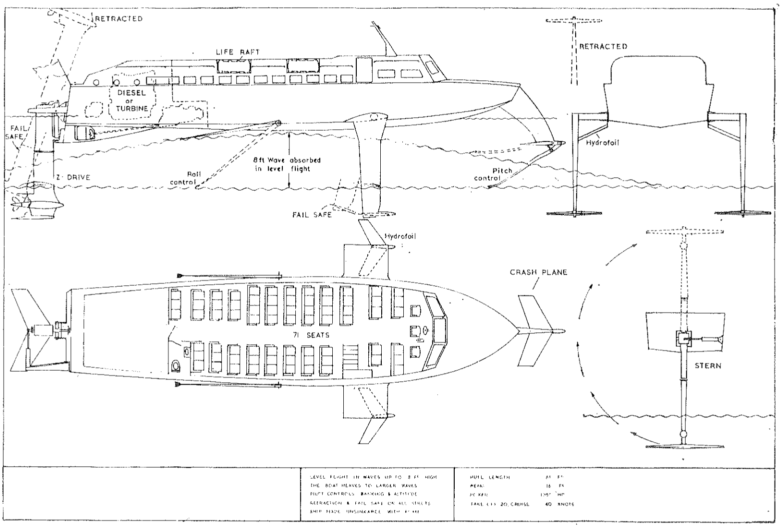

RETRACTED
LIFE RAFT
DIESEL
or
TURBINE
FAIL SAFE
Z-DRIVE
Roll
control
8 ft Wave absorbed
in level flight
FAIL SAFE
Pitch
control
Hydrofoil
RETRACTED
Hydrofoil
71 SEATS
CRASH PLANE
STERN
LEVEL FLIGHT IN WAVES UP TO 8 FT HIGH
THE BOAT HEAVES TO LARGER WAVES

Fig. 13

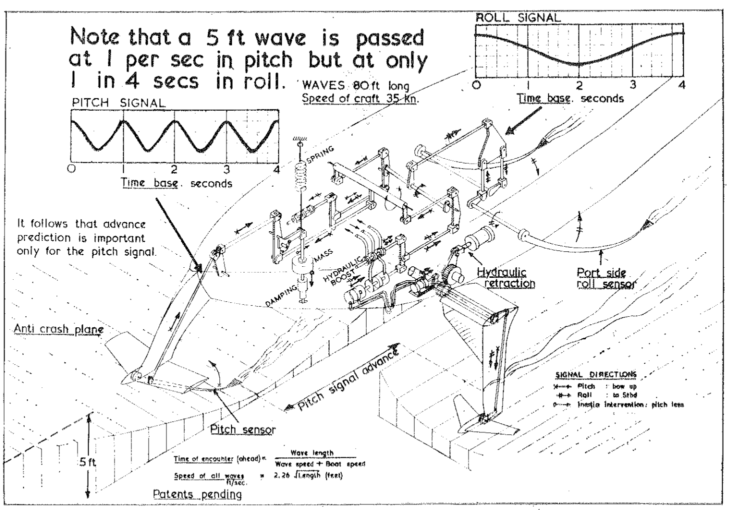

Note that a 5 ft wave is passed at 1 per sec in pitch but at only 1 in 4 secs in roll.
WAVES 80 ft long
Speed of craft 35 Kn.
ROLL SIGNAL
0 1 2 3 4
Time base. seconds
PITCH SIGNAL
0 1 2 3 4
Time base. seconds
It follows that advance prediction is important only for the pitch signal.
SPRING
MASS
DAMPING
HYDRAULIC BOOST
Hydraulic retraction
Port side roll sensor
Anti crash plane
Pitch signal advance
Pitch sensor
SIGNAL DIRECTIONS
Pitch : bow up
Roll : to Stbd
Inertia intervention: pitch less
5 ft
Time of encounter (ahead) = Wave length / Wave speed + Boat speed
Speed of all waves ft/sec. = 2.26 √Length (feet)
Patents pending

Fig. 14

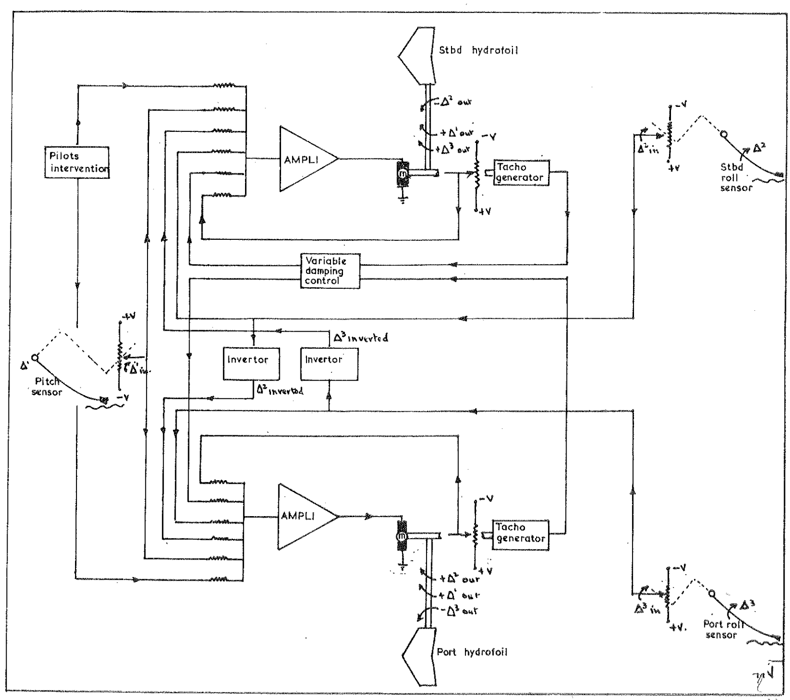

Stbd hydrofoil
Pilots intervention
AMPLI
Tacho generator
Stbd roll sensor
Variable damping control
Invertor
Invertor
Pitch sensor
AMPLI
Tacho generator
Port roll sensor
Port hydrofoil

Fig. 15

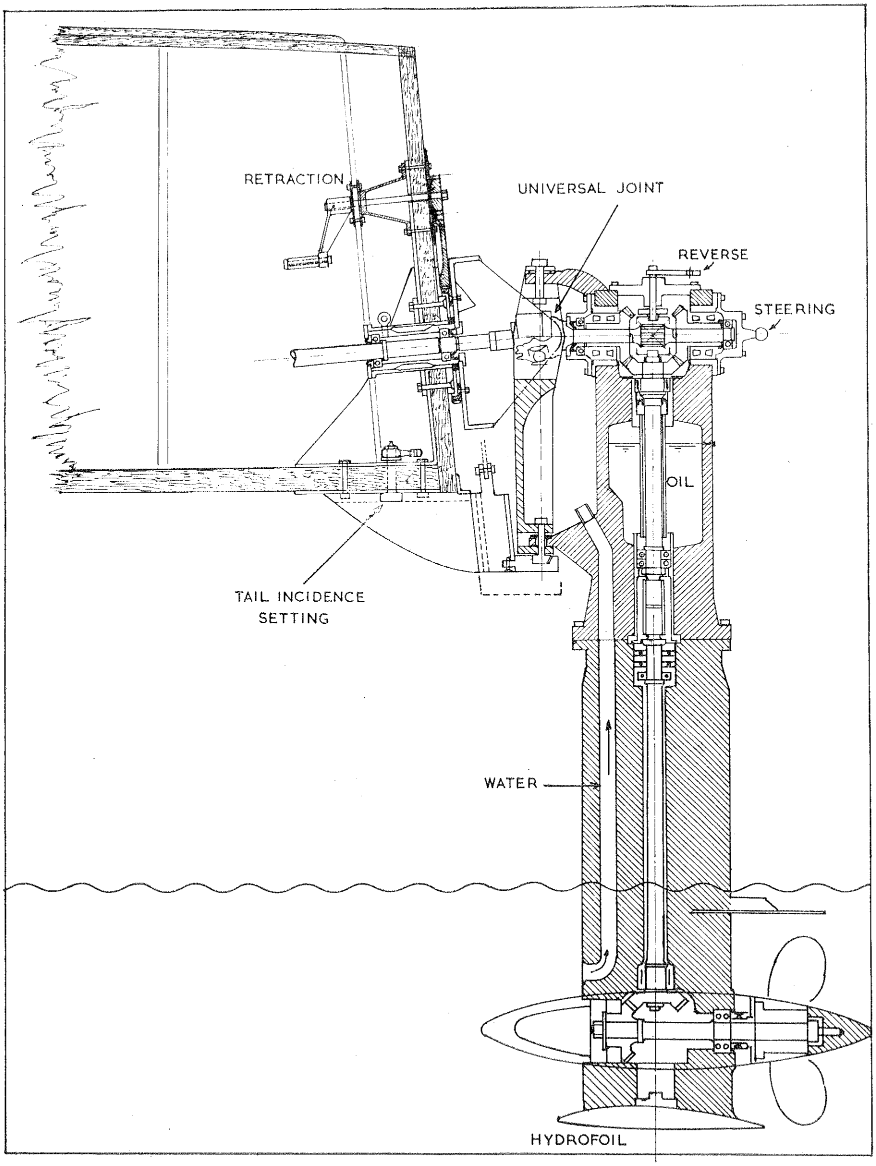

RETRACTION
UNIVERSAL JOINT
REVERSE
STEERING
OIL
TAIL INCIDENCE
SETTING
WATER
HYDROFOIL

Fig. 16

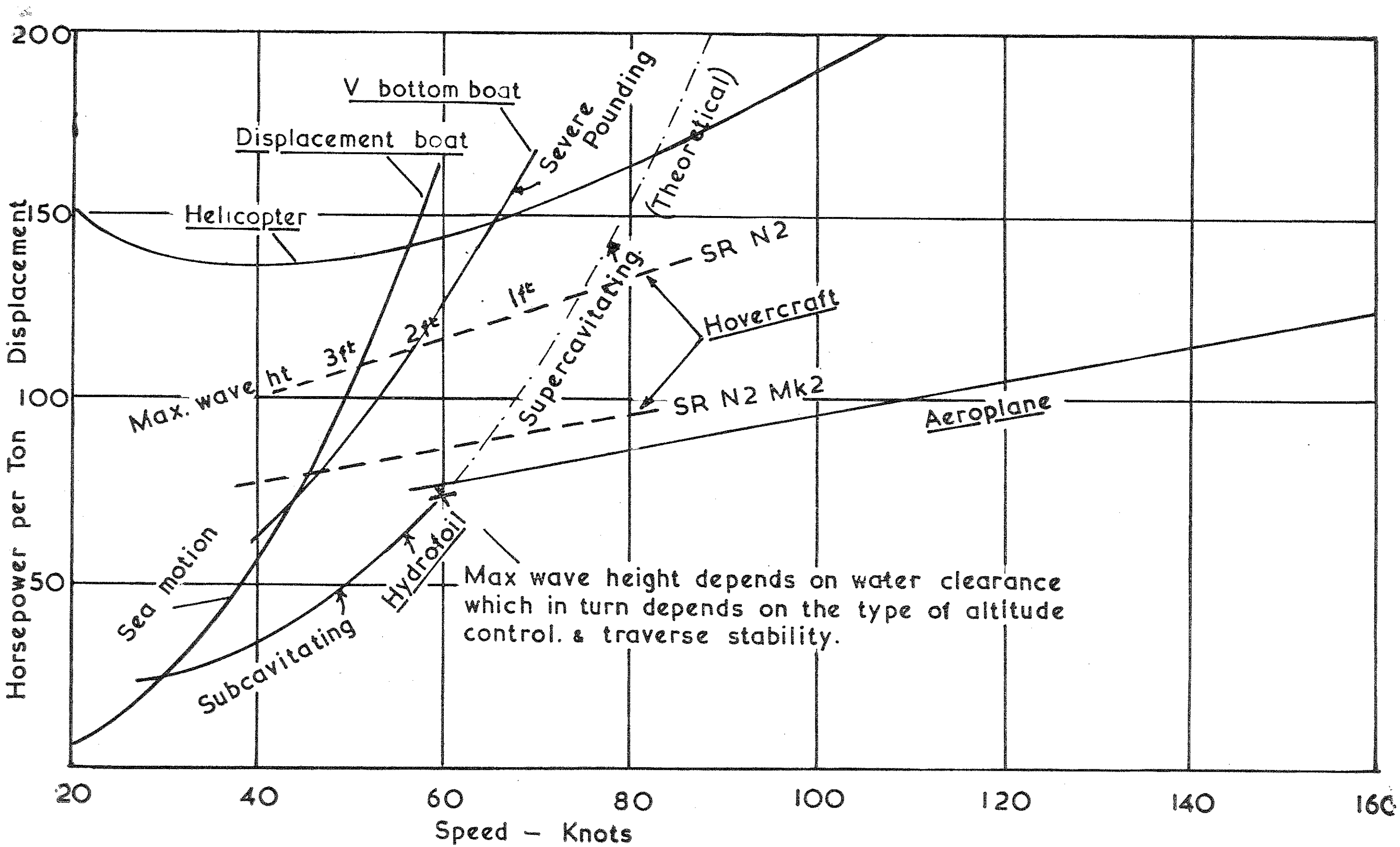

Horsepower per Ton Displacement
Speed – Knots
200
150
100
50
20
40
60
80
100
120
140
160
V bottom boat
Displacement boat
Helicopter
Severe Pounding
(Theoretical)
Supercavitating
SR N2
Hovercraft
SR N2 Mk2
Aeroplane
Max. wave ht 3ft 2ft 1ft
Sea motion
Hydrofoil
Subcavitating
Max wave height depends on water clearance which in turn depends on the type of altitude control. & traverse stability.

Fig. 17

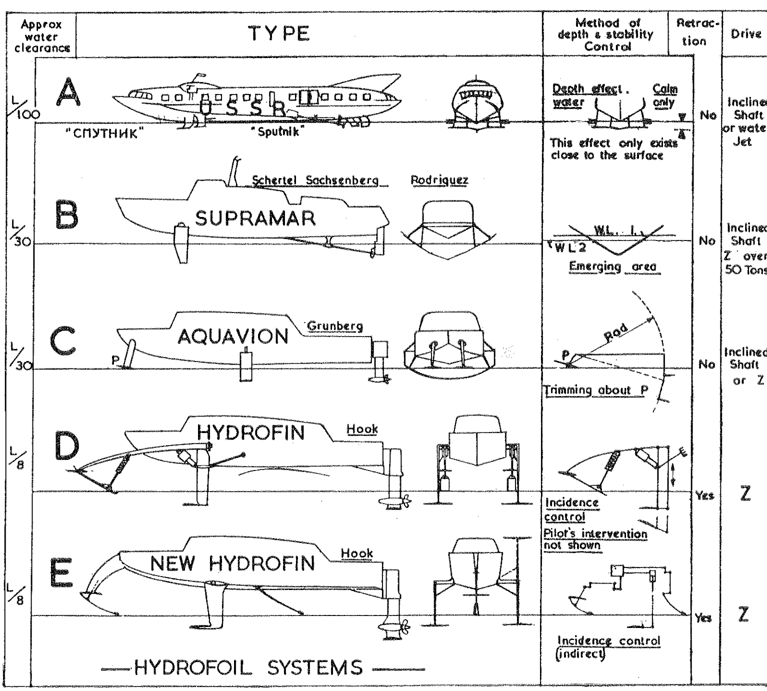

Approx water clearance
TYPE
Method of depth & stability Control
Retraction
Drive
A
L/100
"СПУТНИК"
"Sputnik"
Depth effect. Calm water only
This effect only exists close to the surface
No
Inclined Shaft or water Jet
B
L/30
Schertel Sachsenberg
Rodriquez
SUPRAMAR
W.L. 1
W.L. 2
Emerging area
No
Inclined Shaft Z over 50 Tons
C
L/30
AQUAVION
Grunberg
P
Rod
Trimming about P
No
Inclined Shaft or Z
D
L/8
HYDROFIN
Hook
Incidence control
Pilot's intervention not shown
Yes
Z
E
L/8
NEW HYDROFIN
Hook
Incidence control (indirect)
Yes
Z
HYDROFOIL SYSTEMS

Fig. 18