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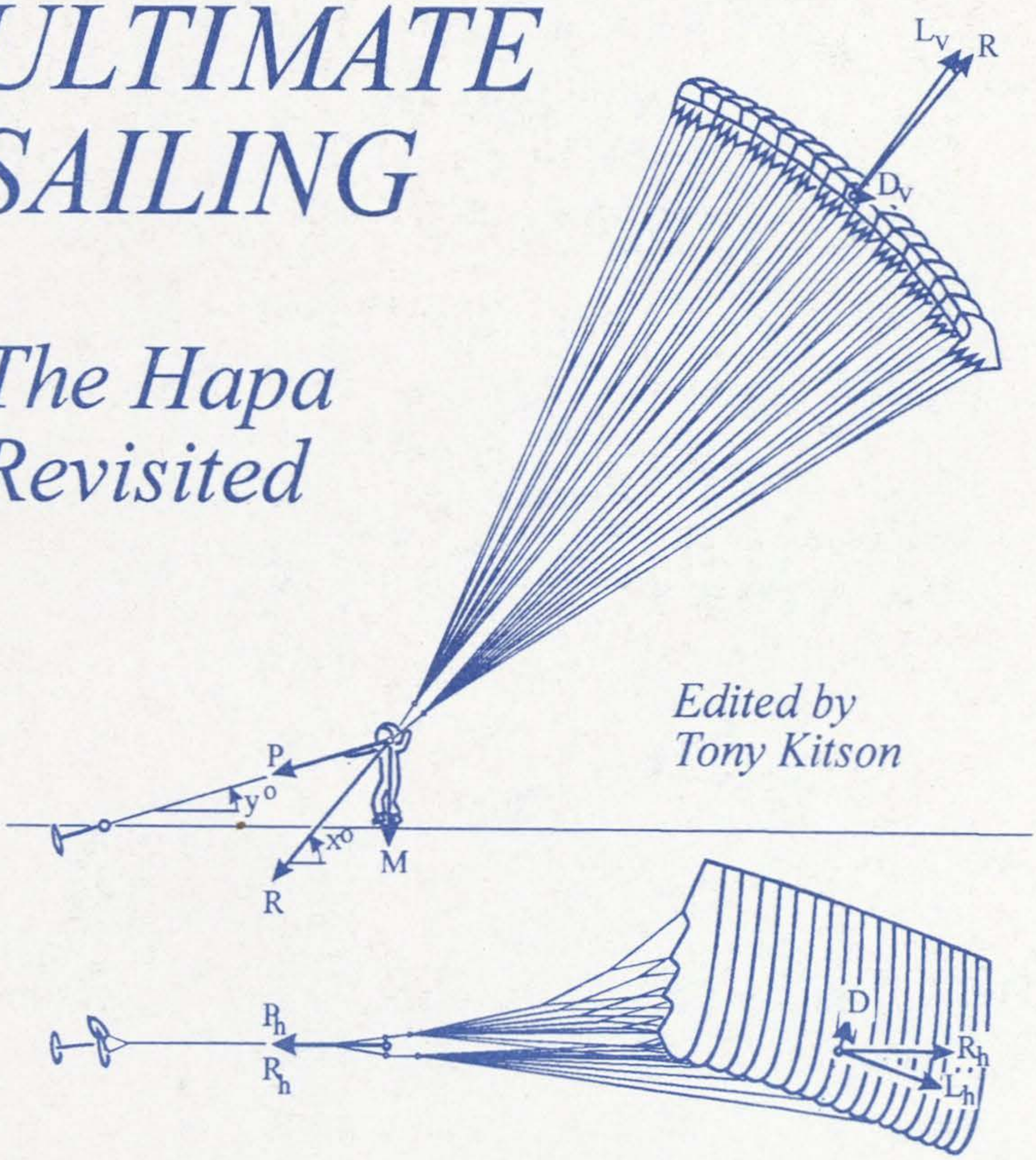
ULTIMATE SAILING

The Hapa Revisited



Edited by
Tony Kitson

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Ultimate Sailing

Introducing the Hapa

by J G Hagedoorn

A study in the application of underwater kites

Seadogs for monohulls

by Paul Ashford

A study of the performance

and practical problems of underwater kites

Edited and computer drawings by Tony Kitson

Amateur Yacht Research Society

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CONTENTS

Preface

This publication centres around the paper by Professor Johan Hagedoorn. 'Ultimate Sailing: Introducing the Hapa' it was published in 1971 and a number of copies were sent to AYRS. Over the years these have been distributed to members who had a particular interest in the subject and eventually our stock was used up. It is thanks to the tenacity of Roger Glencross, both in pursuing his own experiments and in pestering me to produce this, that it is now republished as an AYRS publication.

I managed to buy myself a little time by suggesting that we should only republish when we had some new material on developments since 1971. The final spur that was required to dispel my lethargy came with the submission of the paper by Paul Ashford (particularly as Paul had followed all of the exhortations of Ian Hannay and submitted his paper on disk).

Both Roger and myself have attempted to trace Professor Hagedoorn, but the trail was cold. Roger wrote to the University of Utrecht where he once was employed and they provided some minimal information;

Full name:	Johan Gregorius Hagedoorn	
Born:	10th August 1912	
Employed:	1st January 1939	Assistant Physics Department
	1st October 1945	Chief Assistant
	1st May 1945	retired

The Penguin Book of Kites mentions Professor Hagedoorn as Professor of Geophysics at Leiden University. My letter to the university has yielded no response. If anyone has any further information on the professor I would be delighted to receive it.

My thanks are due to the two main contributors. Professor Hagedoorn (Dutch) for having the foresight to provide an English version of his paper and Paul Ashford for his contribution. An additional thanks to Roger Glencross for providing the enthusiasm and perseverance to encourage this publication.

Tony Kitson *Twickenham* *December 1993*

Introduction

Here it is 'Ultimate Sailing'!

Hanggliding has had its day. Boardsailors eat your hearts out. The new sport will combine the excitement of both and it is only 22 years old!

The 1971 paper by Professor Hagedoorn was remarkable for a number of reasons, not the least the date at which it was published. In the 1960s Edmond Bruce had been working with canted foils for countering both leeway and heel, Didier Costes had been experimenting with paravanes, but only Hagedoorn pushed the concept to its extreme, or 'ultimate', in eliminating the hull.

He begins with an analysis of the conventional sailing configuration and proceeds by removing the keel from the hull and replacing it in the much more effective position, on an outrigger to windward. Here it can not only perform its traditional role but also confer stability by countering the heeling moment of the sail. AYRS members will be familiar with this arrangement which we know as a Bruce foil.

But this is only a start, he then pantographs the outrigger to provide rudderless steering and then removes altogether the outrigger and rigid coupling replacing them with a hapa connected to the main hull by cables.

Surprisingly, Professor Hagedoorn does not take the next logical step, a hull mounted kite rig to provide more directly opposing aerodynamic and hydrodynamic forces. This is the concept which has occupied so much of Didier Costes inventive mind over recent years. Instead the professor rejects entirely the hull, that 'superfluous nuisance, contributing unnecessary resistance and instability', and leaps straight to a pair of opposed kites, the underwater kite (hapa) and the para–foil, with pilot (aquaviator) suspended between. This is 'Ultimate Sailing'.

There follows a very detailed analysis of the requirements for such a system of sailing and the performance that may be attained. His analysis is a little hard to follow, since he uses his own system of annotation for diagrams and the accompanying equations.

So far nobody has yet managed to achieve Professor Hagedoorn's concept of 'Ultimate Sailing', despite attempts by Roger Glencross, Theo Schmidt and others. However developments of the two main components, the air kite and the water kite, have been made. In this issue we concentrate on the wet end of the string, the Hapa, Paravane or Chien de Mer. A future issue will address the (hopefully) dry end of the string, covering recent developments in kite traction.

Paul Ashford has taken the hapa concept and applied it to improving the performance of a cruising boat. His experiments are pushing forward the frontiers of knowledge both for cruising and also for higher speed sailing. His concept of dynamic incidence control will be crucial for the development of high speed hapas.

Didier Costes independently invented the hapa, or Chien de Mer, and is well known as a developer of the hapa and of complementary kite rigs for heelfree sailing. His progress along with the experiments conducted by Theo Schmidt will be reported in one of the next AYRS publications. This will also include the paper by Burgess (1939) on hapas and airship sailing.

In the mean time read on and find out...

Ultimate Sailing

(Introducing the Hapa)

by J.G.Hagedoorn

Even though a vast literature on the theory and practice of sailing already exists, a special approach to the subject is indicated in order to clarify the concept of the Hapa.

A sailboat can be considered to exist of three basic units: a sail, a float and a keel. In this abstraction of a normal sailboat, the float or boat proper can be regarded as the connecting link between sail and keel, between the forces exerted by air and by water.

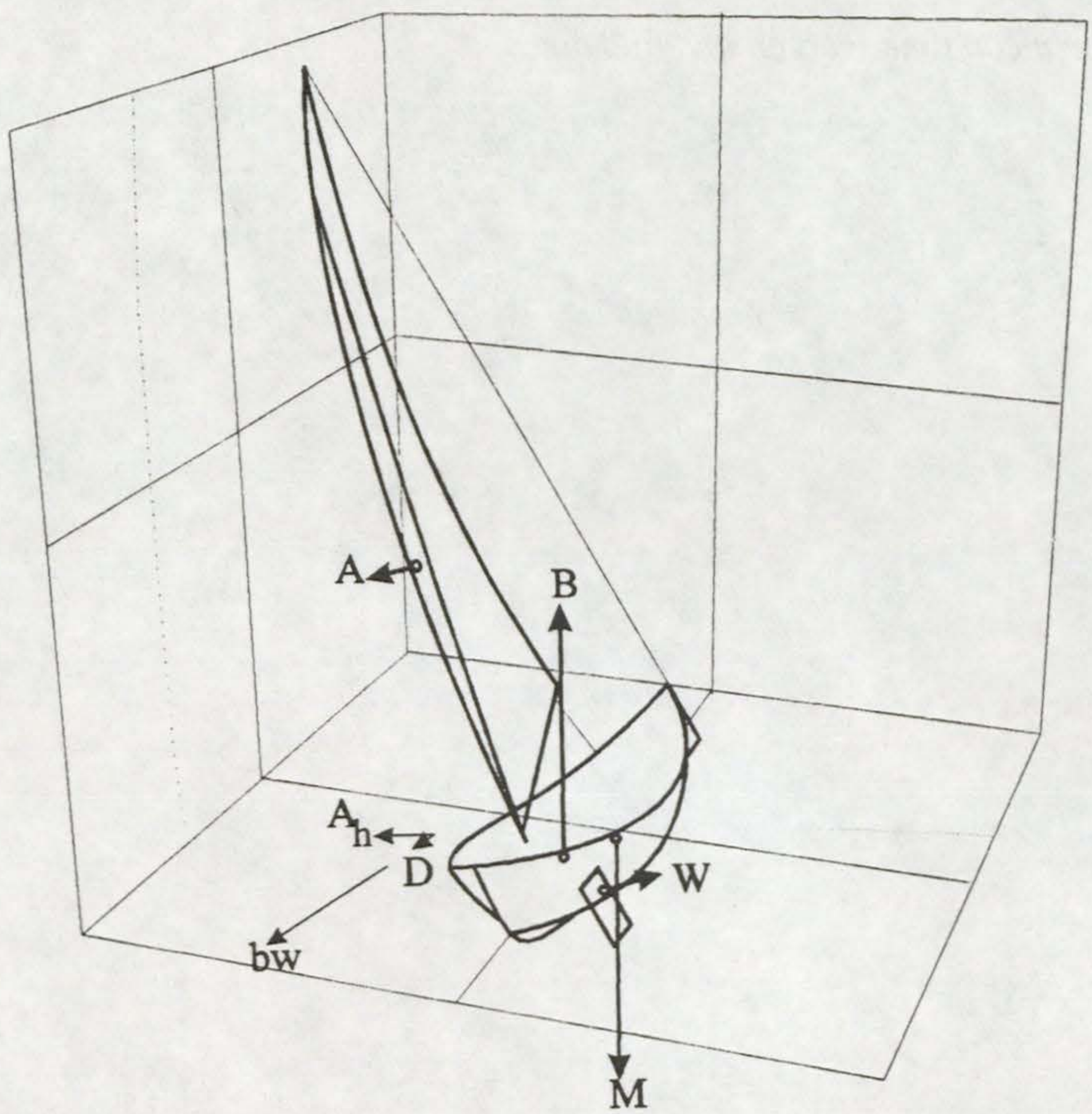


Figure 1 –

The four basic forces exerted on a sailboat are contained in one vertical plane

This is illustrated in figure 1 with a simple model of a close–hauled sailboat. The sense of perspective has been strengthened by including the three mutually perpendicular squares, each divided into a further four equal squares. The model boat is apparently inside a cubic box from which the three near sides have been removed. The lower horizontal square represents the surface of the water into which the boat is sunk so that it floats. The two vertical squares are respectively parallel to and perpendicular to the long axis of the boat.

A is the total resultant force due to the relative movement of the air and *W* is the total resultant force due to the relative movement of the water. By the combined effect of air and water the boat is moving along, "sailing" in a more or less orderly and desired manner. This movement is assumed to be constant, every point of the whole system "sailboat" having the same velocity. This will be, in practice and on an average, a workable approximation of reality, even when taking into consideration pitching, rolling and other incidental movements involving accelerations. According to Galilei and Newton this constancy of movement implies that the total resultant force on the whole system must be zero.

The only other forces exerted on this sailboat, besides *A* and *W*, are the total weight *M* due to the mass and the total buoyancy B due to the volume immersed in the water. *M* and *B* are both forces due to the gravity attraction of the earth, so that they are essentially vertical. They must counteract the combination of the forces *A* and *W*, so that no more can this combination of *A* and *W* have a horizontal component. This means that A and *W* must, moreover, lie in that particular vertical plane that also contains both *M* and *B*.

This vertical plane, containing all four resultant forces, is shown in figure 1 by its intersections, the dashed lines, with the water, with the boat and with the vertical plane parallel to the axis of the boat. This plane is the obvious choice for presenting a scale drawing of the actual forces.

In the upper part of figure 2 the projection of the whole system onto this plane is shown, seen from the back. The lower part of this figure shows the corresponding projection onto the surface of the water.

For simplicity's sake the two forces *A* and *W* have been assumed to be parallel, so that they must also be equal, thus forming a simple couple. The two forces *M* and *B* are then also equal and parallel to also form a couple. These two couples must have equal, opposite moments in order to balance.

In the particular example of figures 1 and 2 the perpendicular distance between A and W has been assumed to be five times the perpendicular distance between M and B. This means that A and W are only one fifth of M and B. The force on the sail can only be one fifth of the weight of the boat, otherwise it will heel over even further and presumably sail less efficiently.

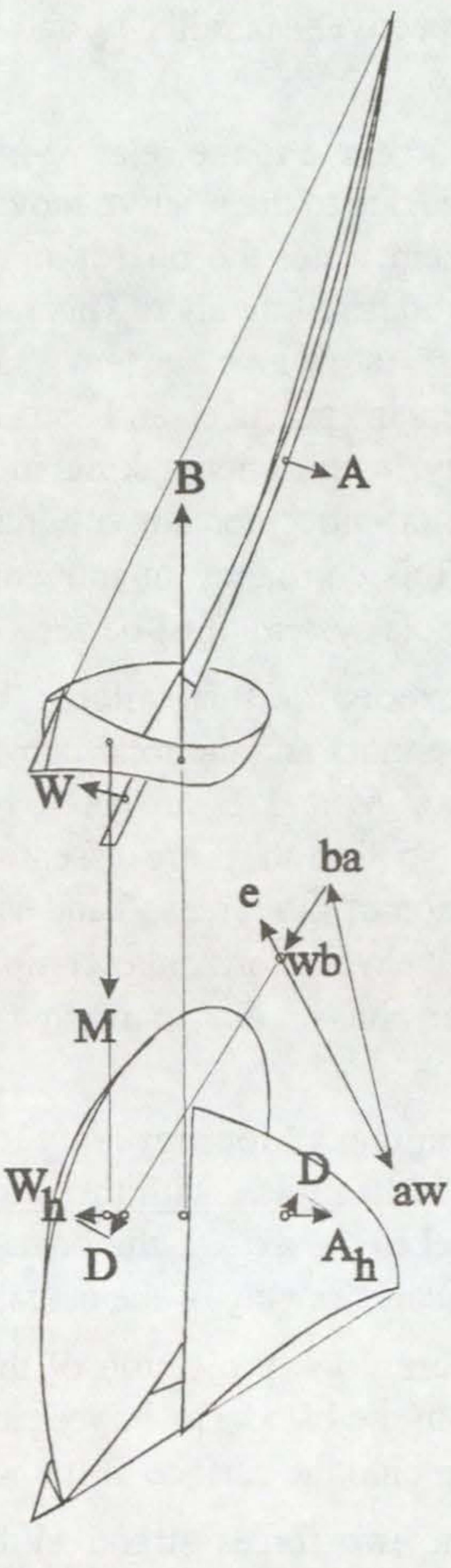


Figure 2 – The sailboat of fig 1 projected onto the vertical plane containing the four forces and onto the surface of the water.

The driving force D is the component of force A in that direction in which the boat moves relative to the water. It results in a drag of equal size which is the component of force W in the opposite direction. In figures 1 and 2 the direction of movement is assumed to be such that the forces D are half the forces A and W. The net driving force on the sailboat is one tenth of its weight.

The triangle composed of arrows with triangular heads, in the horizontal projection in figure 2, shows the relative velocities: aw is the velocity of the air in regard to the water, *wb* is the velocity of the water in regard to the boat and consequently ba is the velocity of the boat in regard to the air, or the "apparent wind". *e* is the effective tacking velocity, the component of *bw* in the direction of the true wind *aw*.

It must be borne in mind that the example presented in figures 1 and 2 is purely for illustrative purpose. No actual dimensions or scales are given. It could, for instance, be a boat of 4m length sailing in a 18.5 Km/h (10 knots) wind, with the crew hanging to windward.

M would be some 300 Kg so that the driving force of 30 Kg would be delivering a velocity of 7 Km/h through the water and an effective velocity to windward of 3.5 Km/h. These numerical values are not essential but may serve to bring alive the picture. Actually the example could just as well refer to a much larger boat with a big hunk of ballast in its keel.

The most important criterion for the quality of a sailboat is its performance when tacking closehauled into the wind. There will always be a vertical plane containing the four main resultant forces and its angle with the course of the boat will become smaller for a reaching course and become zero when running straight before the wind. It is clear that progressively more sail can be piled on, because the distance between M and B can be markedly increased and, moreover, the apparent wind decreases.

The simple picture with two opposing couples has been chosen in order to bring out clearly and to stress the very essential difference between these two couples. On the one hand M and B are both constant forces. As the boat heels B moves to leeward due to the width or beam of the boat. When M is partly due to ballast on the keel, it will move outwards in the opposite direction as the boat heels, while in small boats M can be shifted by the weight of the crew. However, the perpendicular distance between M and B, the "arm" of the couple, is severely limited.

On the other hand,the couple due to A and W depends on the strength of the wind and the resultant movement through the water. For every sailboat of this type there is an optimal wind where use can be made of an optimal couple *MB* to obtain a maximal performance. An increase in wind cannot be turned to account and is only a nuisance.

The essential difference between these two couples is also the reason why large boats are faster than small boats. It is a matter of dimensions in the same way as the reason why the sparrow has such relatively thin legs and the elephant such relatively thick ones. If the sparrow were enlarged a hundred times in all its linear dimensions it would weigh a million times more. This weight would then have to be carried by legs with their cross sectional area only increased ten thousand times. There is a factor of one hundred missing, so that the legs of a monster sparrow the size of an elephant would also have to be relatively ten times thicker in order for it to be able to stand on them.

By increasing all linear dimensions of a sailboat ten times one would obtain a boat that would sail about just as well, because both the area of the sails and the area of boat and keel have been increased a hundred times. At the same time, however, both the weight and the buoyancy have been increased a thousand times. There is thus an extra factor of ten available to increase the areas of sail and keel of the larger boat.

There are of course innumerable other factors that influence the relative performance of sailboats: cross section and aspect ratio of sail and keel, form and smoothness of the hull, etc, etc. The arm of the couple weight–buoyancy is increased markedly and with excellent results in the catamaran. However, this available couple weight–buoyancy will always limit performance and, moreover, always strongly favour the larger boat. It is a frustrating prospect that mass and money must always win. The small, lively sailboat, dashing along in a smother of spray, with the expert sailor balancing on a trapeze, is inexorably overtaken by the comfortably large and sedately moving yacht.

The proa, the catamaran and the trimaran are all quite successful attempts to increase the arm of the couple formed by mass and buoyancy. In principle,the catamaran and trimaran have been respectively fitted out with one and two boats too many, because they are derived from the primeval boat, symmetrical only with regard to its long axis.

The proa presents the ideal solution for increasing the arm of the couple massbuoyancy. The float at the end of the outrigger hardly need touch the water so that no unnecessary amount of wet surface is involved. It is rather tricky sailing however because it all depends on expert balancing by the crew on the outrigger. If a gust lifts the outrigger they must be very fast in shifting their weight before the whole affair turns over. On the other hand the strong drag of a too deeply dipping float tends to turn the boat sharply to windward.

Our ancient nautical ancestors saw these curious contraptions flitting about at incredible speeds and they were duly impressed. However, they preferred their blessed, heavy, slow and unwieldy floating boxes to these tricky heathen contraptions. It is no wonder that they did not see any connection between the two widely different systems of sailing. But it is amazing that nobody, not even a chinaman, ever realised that the solution to really fast, ultimate sailing can be derived from the proa.

The concept of the hapa is arrived at by eliminating the trickiness from the proa. The float or boat of the proa does not need lateral stability and therefore its chosen form is long and slender. What is not generally realised is that such a long slender body needs an exorbitant amount of correction by fin and rudder to keep it going straight and prevent it from turning broadside. One sees the Papuans paddling happily along in a small hollow log, but when one actually tries it the log turns inexorably sideways and no amount of frantic paddling can prevent it from sticking its nose into a mudbank. It is necessary to acquire a fast instinctive flicking rudder action of the paddle to counteract a sideward inclination before it starts. It is one of those unpleasant hydrodynamic facts that a moving body tends to choose, from the possible symmetrical orientations with no turning couple, the particular one with the highest resistance. A body can be made to behave by providing turning couples with the aid of fins. A bomb has fins to keep its nose in front, but it wobbles and screams horribly because there is no corrective force when it is properly aligned. This unpleasant phenomenon is called "hunting". To keep a body aligned an actively operated rudder is needed or some stabilising couple.

In the case of a sailboat such a stabilising couple can be provided by the forces on sail and keel. Some boats can be sailed on a stable desired course with the rudder in a fixed position. In this respect a centre keel will obviously be better than a leeboard and a "luffboard" would be even better.

This leads to the logical conclusion that obviously the best position for the keel is at the outer end of the outrigger of the proa. If it is then realised that this keel can also be made to counteract that part of the force of the wind on the sail that would lift the outrigger with its keel out of the water, then the concept of the hapa is born!

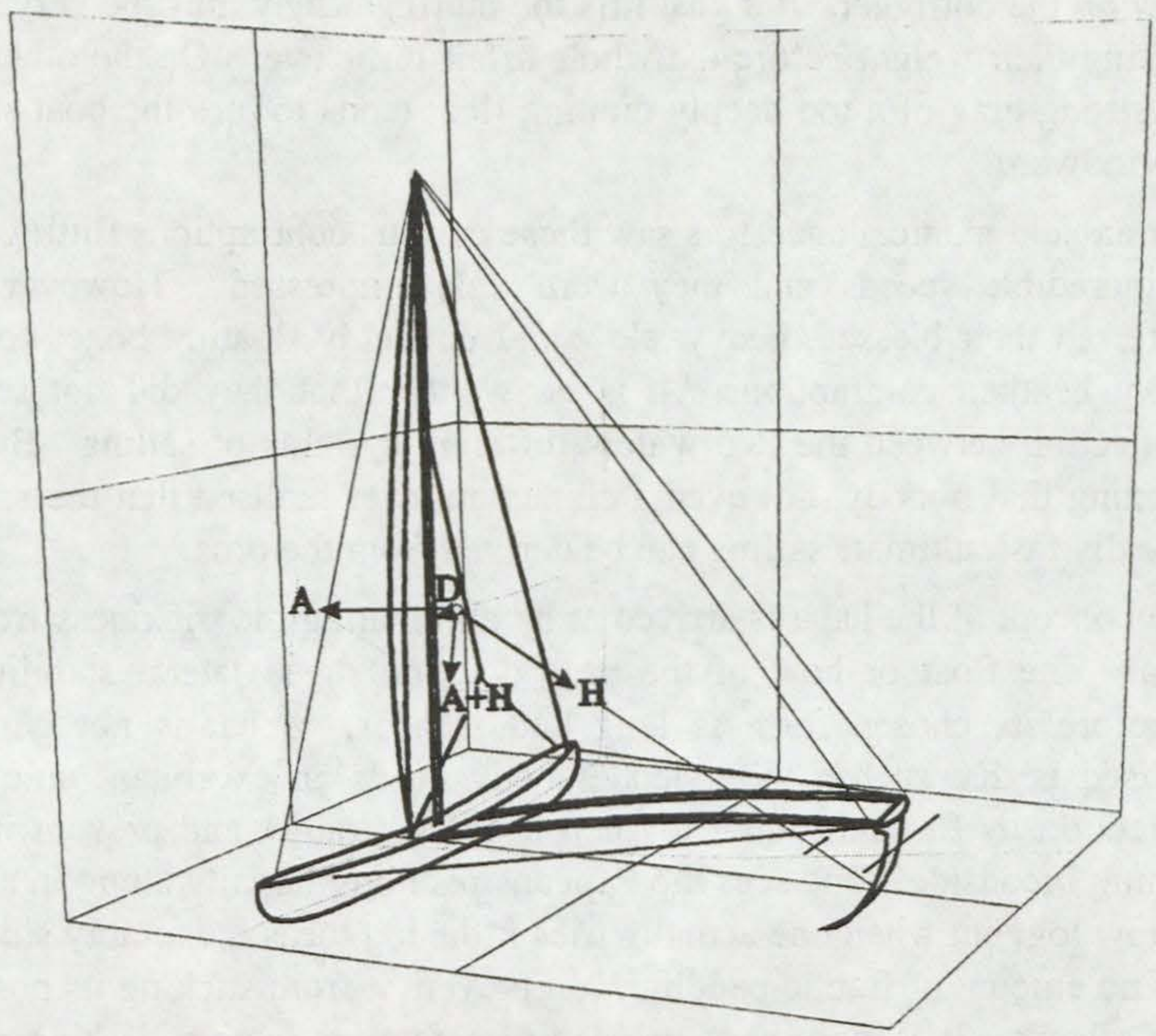


Figure 3 – The hapa automatically cooperates with the sail to form a stable sailing system.

This is illustrated in figure 3. Boat and sail are symmetrical fore and aft. The whole system can sail equally well in either direction with the outrigger to windward. The two outrigger arms pivot on vertical axes at both ends so that the orientation of the hapa in regard to the boat can be varied by changing the lengths of the lines connected to both ends of the boat. Such a linkage system is one possible way to obtain the correct angle of attack for the hapa when the boat travels in the direction of its long axis.

The hapa itself, that curiously curved symmetrical dagger, has to be curved in order to arrive at a stable system so that the forces *H* and *A* will provide couples to restore equilibrium as the hapa either dips down or is lifted. The approximate centre of curvature must lie somewhere between boat and hapa and a working compromise must be chosen: a smaller radius of curvature will give greater stability but less hydrodynamical efficiency and vice versa.

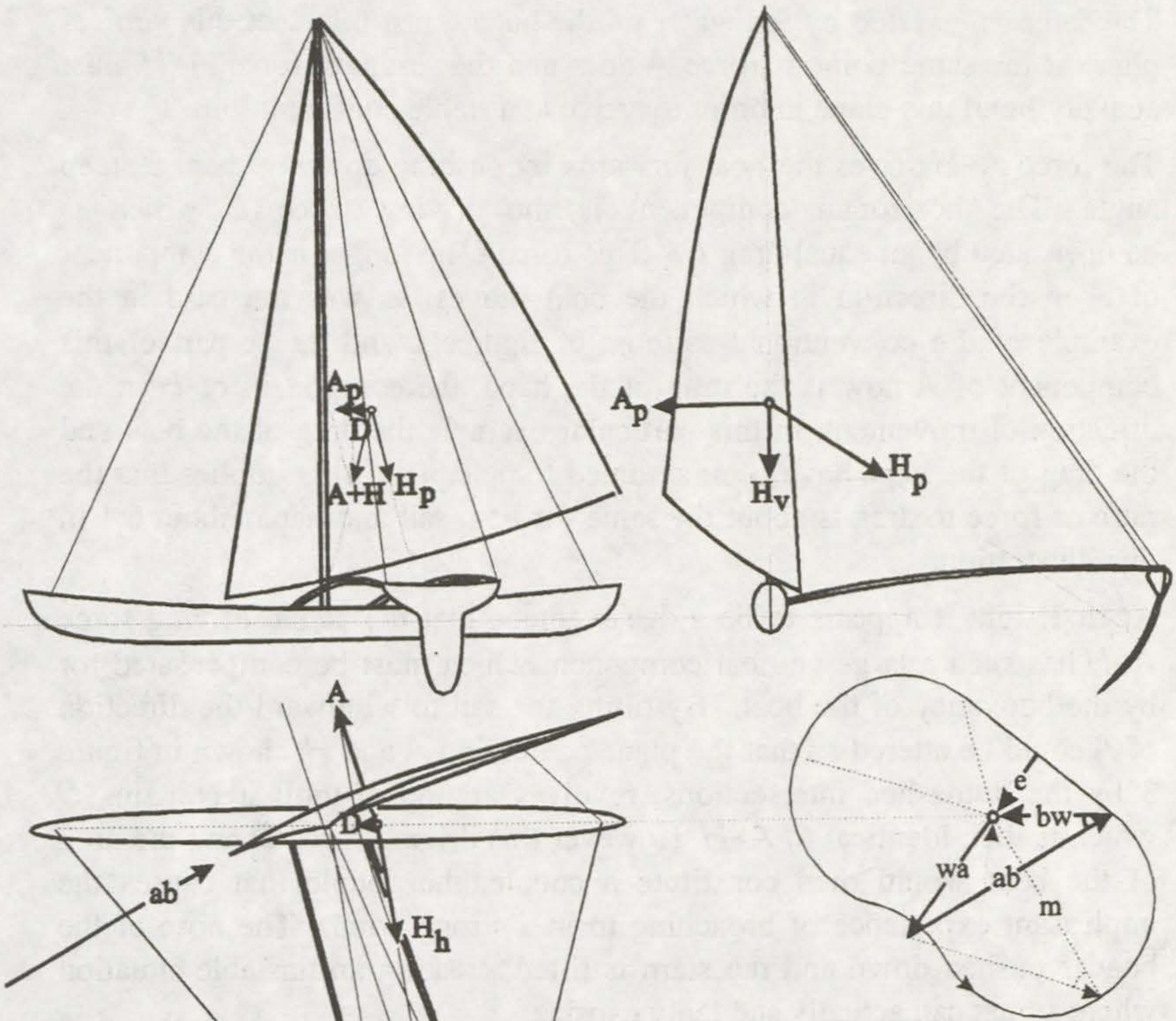


Figure 4 – Three projections of the system with Hapa with hypothetical diagram of velocities and a comparison with a waterskier.

In figure 4 three mutually perpendicular projections of this system are presented. Force *A*, the resultant force due to relative air movement, has been extended back to the vertical plane through the axis of the boat. This vertical plane is shown in figure 3 by its intersections, the dashed lines. The force H, exerted by the water on the hapa, must intersect this vertical plane at the same point as force A does and the resultant force $A+H$ must actually lie in this plane in order to arrive at a stable configuration.

The force $A+H$ drives the boat forwards by pushing downwards at a steep angle. The horizontal component is the driving force D which is compensated by an equal drag D. This force D no longer is the component of A in the direction in which the boat moves, as was the case in the example of the conventional sailboat of figures 1 and 2. A part of this component of A now is the drag of the hapa, the component of H in the direction of movement. In this particular example the drag of the boat and the drag of the hapa have been assumed to be equal. This implies that the ratio of force to drag is about the same for both sail and hapa; about 6:1 in this illustration.

At first sight it appears to be a disadvantage that the actual driving force $A+H$ has such a large vertical component which must be compensated for by the buoyancy of the boat. By tilting the sail to windward the direction of A could be altered so that the plane containing A and H, shown in figure 3 by the dotdashed intersections, revolves around H until it contains D which is then identical to $A+H$. However this driving force D and the drag of the boat would then constitute a couple, the couple that causes the unpleasant experience of broaching to in a strong wind. The nose of the boat is pushed down and the stern is lifted, creating an unstable situation where a boat can actually suddenly capsize.

The requirement that such a couple must be avoided implies that there must be a vertical component to point the force $A+H$ down in a direction towards the centre of buoyancy of the boat.

This does not, however, mean that the buoyancy of the boat actually constitutes an unavoidable limiting factor, the sort of factor favouring larger boats. In practice a boat can be given a planing response so that it starts to slide on the surface as speed increases. This is illustrated in figure 3 by the analogous case of the water skier. This water skier obviously slides over the water by virtue of the steeply dipping resultant force due to the pull of the boat D and the weight of the skier M. Such a lifting force can also be introduced by foils, which are to be preferred when considerable waves are involved.

There is then good reason to suppose that a system as illustrated in figures 3 and 4 would behave quite satisfactorily, particularly in a strong wind. A rather optimistic diagram of velocities has been included in figure 4. The velocities *bw* (boat–water), *wa* (water–air) and *ab* (air–boat) refer to the situation depicted in these figures 3 and 4. The contraption is sailing close–hauled with a boat–water velocity *bw* that is nearly as high as the actual wind *wa*. Its effective velocity *e* to windward is half the actual wind *wa*. In this same sketch of velocities the diagram of all sailing situations has been included, referring to a fixed true wind *wa*. *m* is the maximum velocity on a reaching course and *r* is the velocity on that particular course where the boat has its maximal velocity component, in this case equal to *wa* ,in the direction of this true wind.

This is a purely hypothetical example which is only presented in order to indicate how such a fast system would be sailed in all directions. Any one of these directions can be arrived at by adjusting the relative positions of sail, boat and hapa. And in any one of these configurations it would sail on a completely stable course.

It would be very interesting indeed to be able to actually sail this type of contraption. It is safe to predict that the first test–sailer would be in for a number of surprises, both pleasant and not pleasant. Some of these surprises are more or less predictable but the unpredictable ones, the true surprises, could be very instructive.

Changing course to the other tack would involve moving both sail and hapa to their symmetrical position while keeping the outrigger to windward. In a strong wind this could be rather exciting. Probably it would be best to first pull the hapa to its new position so that the boat turns into the wind. At the same time let go the sheet at the mast so that the sail turns broad–side and stops the boat. Tighten the other sheet at its new position near the foot of the mast and, as the boat reverses direction and starts to turn around the hapa, pull in the sheet that is now aft until the new course is obtained.

It is quite probable that the first time this is attempted in a strong wind the whole thing will capsize at the point where the hapa is supposed to reverse its movement through the water. This can be expected to occur because the hapa can only exert a force by moving through the water. As the velocity of the hapa decreases towards zero and starts to pick up speed in the reverse direction, force *A* must be in the direction of the boat or sufficiently compensated for by weight on the hapa.

It is clear that the actual villain in this narrative is the boat, because it cannot move sideways easily enough. Without the boat the system sail–hapa would present no difficulty in reversing course, because the hapa would describe a loop through the water and always automatically exert the right compensating pull. The system of figures 3 and 4 would be better off with two shorter boats in tandem, which can both move freely in all directions like casters.

The long narrow boats of the conventional proas, catamarans and trimarans are probably simply throwbacks to the original hollow log. The requirement of minimal wet surface is not obtained by a circular cross section in one direction only. The sphere, with its omni–directional symmetry, provides, the minimal surface for a given volume.

Figure 5 shows a comparison between a sphere and four bodies, all of which have the same volume as the sphere. The four bodies, with values of length/max.diam. of 2, 4, 8 and 16 respectively, have all been derived from the same form by proportional change in length and in diameters. Consequently, length times diameter squared (ld^2) is the same for all four, while their shape is fully determined by their "slimness", i.e their value of length over diameter (l/d).

The fulldrawn curve in the logarithmic graph of figure 5 is the resulting relationship between surface/volume (s/v) and "slimness" (l/d). As the body gets slimmer, s/v tends to become proportional to $(l/d)^{l/3}$ because the surface then tends to become proportional to ld while ld^2 is always constant; $ld/ld^2 = (1/d)^{l/3}\,(ld^2)^{-1/3}$. The value of s/v for the sphere has been chosen to be 6, because that is the value of s/v for unit diameter $(\pi/\pi/6)$. Thus, the vertical scale has units of $(ld^2)^{-1/3}$.

One body with a certain l/d can be divided into two bodies with the same l/d and each with half the volume. Total surface/volume of these two bodies will then be twice $2^{-2/3} = 2^{1/3} = 1.26$ times the value of s/v for the original single body. The resulting relationship between s/v and l/d, for two bodies instead of one, is shown in the graph of figure 5 by the dashed curve, which is the original curve shifted upwards by a factor 1.26. The dashed curve can also be regarded, approximately, as the original one shifted horizontally by a factor 1/2. It means that a slim boat can be divided into two boats with half the slimness, with half the value of l/d, without increasing wet surface. By substituting two boats such as the one in figures 1 an 2 (l/d approx. = 3) for the one in figures 3 and 4 (l/d =15) the wet surface would be decreased by about 20%. Also from this point of view it could be attractive to substitute two caster boats for one long narrow one. In this manner resistance and restraint could be abated at the same time.

A fine example of the advantage of getting rid of cramping restraints is La

Cierva's autogiro, which invention actually also made helicopters workable contraptions. Ever since Da Vinci, man tried to fly with revolving wings and was foiled by gyroscopic forces. La Cierva eliminated almost all restraint of the revolving wings, making use of centrifugal force instead, and suddenly his flying machine no longer flopped and crashed.

The connection between hapa and boat by the two rigid arms also constitutes an unsatisfactory restraint. Then the very long and slim boat of figures 3 and 4 is replaced by one or two caster boats, these arms no longer have to turn on pivots and can be replaced by only one arm. The relative position of sail and hapa, which determines the course, can be adjusted by only changing the position of the sail while the boat or boats follow passively. A rigid arm is, however still necessary in order to be able to counteract the twisting force exerted by the hapa. It is the couple due to the resultant drag on the hapa being located approximately halfway its length below the rigid arm. This arm is located above the surface of the water in order to avoid unnecessary resistance. In principle, only a pulling member such as a rope in the direction of force H would be required.

In actual practice it would be quite impossible to connect the hapa of figures 3 and 4 to the boat by a single rope. So many guy–ropes would have to be incorporated in order to make the,hapa behave that their resistance would be prohibitive.

The idea of a hapa on a flexible leash is, however, so attractive that it was considered well worth pursuing. It would have to be something like a paravane, the sort of contrivance used for minesweeping. It will be obvious that this is where the name "hapa" originated from. It sounds polynesian and it can only be hoped that it doesn't happen to be a dirty word.

It turns out to be frustratingly difficult to realise a hydrodynamically efficient hapa that can be pulled on a line,like a kite. The thing must follow a stable course just below the surface of the water. This is even more difficult than in the case of a kite in the air, because the thing is so near the radical transition air/water. The first experimental models indeed either jumped out of the water or dove down to the bottom, even when walking.

As a further approach, use was again made of La Cierva's principle of attaining stability by getting rid of restraints. The hapa was made to behave, at least to running speeds, by making it symmetrical around an axis and free to turn around that axis. In that way it can never exert a couple around that axis even if it strikes an obstruction.

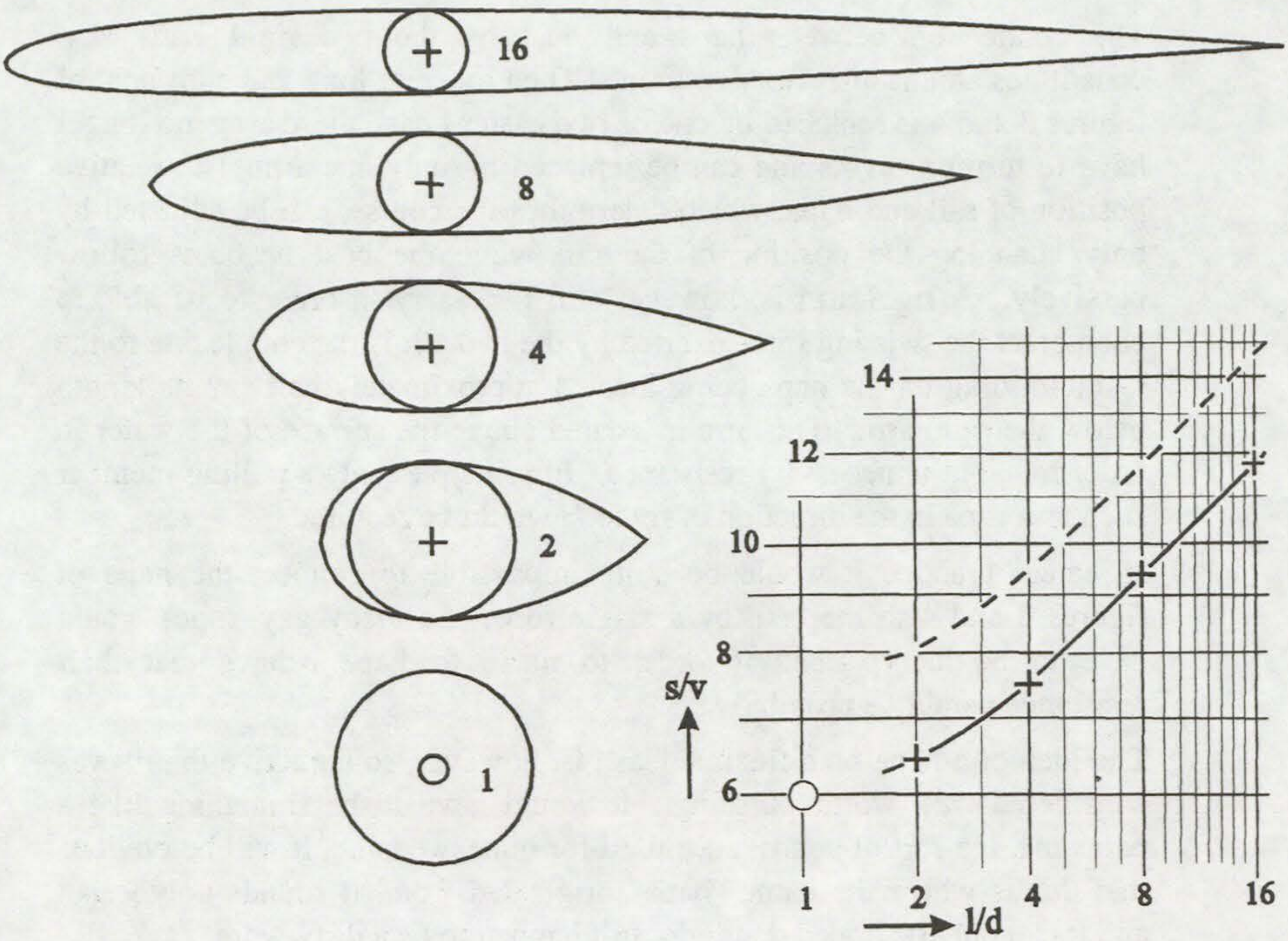


Figure 5 – The relationship between surface and volume of proportionally elongated bodies.

This attractive solution obviously imposes very drastic limits on the shape, which has to be hydrodynamically efficacious as a foil. For one thing, it fundamentally has an aspect ratio of only one which compares unfavourably with the hapa in figures 3 and 4 and also with leeboards, centreboards and keels in common use.

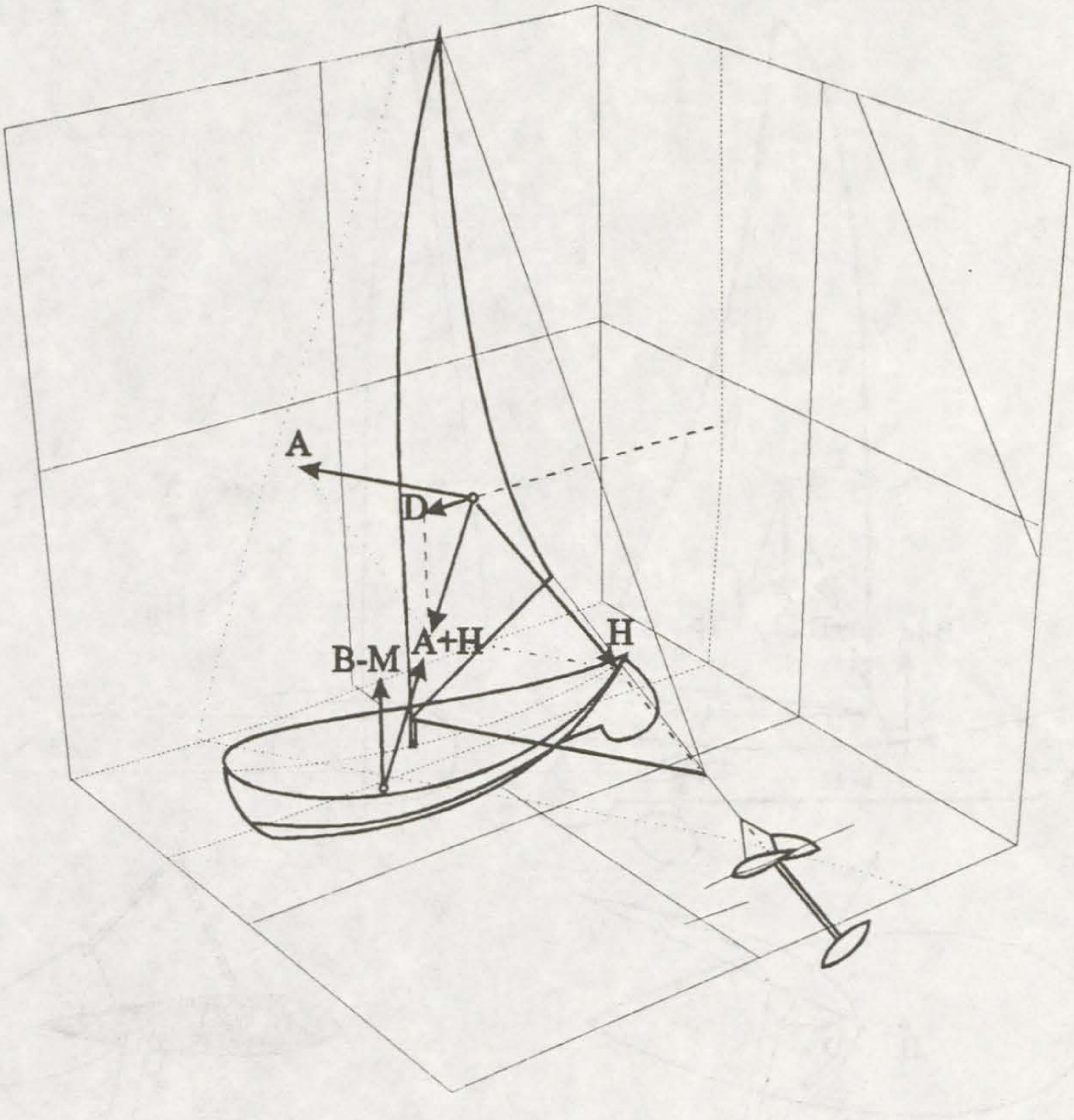


Figure 6 The Hapa can be a towed paravane connected directly to the sail, with the boat following passively.

This type of hapa is presented in figures 6 and 7, harnessed to a boat and sail very similar to those in figures 1 and 2. It is made of epoxy reinforced with glassfibres. The essential body of the hapa has a lens–like shape, slightly concave on one side and convex on the other. The hollow inside this lens fills with water, so that its actual weight only has to be a fraction of the total volume in order to give it approximately neutral buoyancy both in fresh and in seawater. The handle or haft can turn freely in a double race ball bearing around the axis of symmetry of the lens. The fulcrum point at the other end of this haft, in the float, is about 5% forward of the axis of the lens in order to obtain the maximal pull/drag ratio of the hapa.

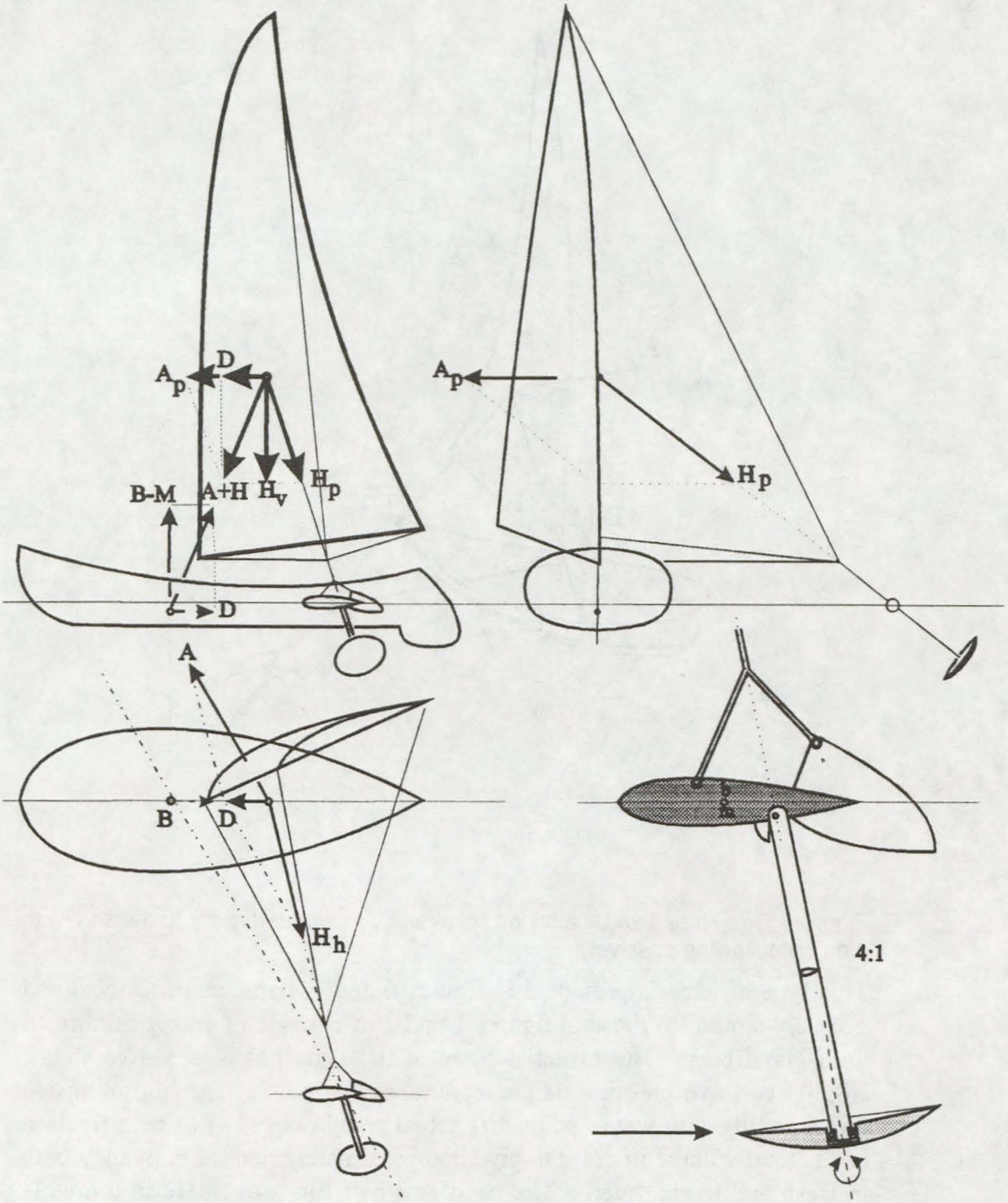


Figure 7 – The three projections of the boat with towed Hapa with a 4:1 scale drawing of the actual Hapa.

Such a haft is an essential requisite and a contrary troublemaker. It takes the place of the customary three, or sometimes only two, lines attached to a normal kite, which are adjusted to obtain the correct angle of attack, or lift/drag ratio. For a hapa, a kite in the water, it appears preferable to use a central rigid shaft or haft instead of ropes which would have to be attached somewhere near the rim of the lens. This appears to be an attractively unrestrained system but it would be very vulnerable to obstacles and it would be technically difficult to have the lens turn freely.

The main difficulty with this one central haft is that it must be quite rigid and strong, so that it has to be thick. The shaft of the hapa in figures 6 and 7 has a fairly slim cross section (1.5 by 5 cm) with quite small resistance but this has been obtained at the expense of symmetry. Actually this shaft has the same pernicious preference for travelling broadside as the Papuan's dugout. A compromise must be chosen between the inadmissibly high resistance of a symmetrical, consequently circular, haft and the instability introduced by a hydrodynamically ideal cross section.

This unavoidable instability must be counteracted by the float, the torpedo with the fishtail. This float, or some other means of keeping the system running near the surface, is just as indispensable to the system as the haft and maybe even more bothersome.

In principle, the float of the hapa in figures 6 and 7 has a weight equal to half the totally immersed buoyancy and the centres of mass (*m*) and buoyancy (*b*) are well forward of the attachment of the hapa to the float. This results in equal turning couples towards its correct, half submerged, position when it either comes out of the water or submerges. The two ends of the forked towrope are attached at points on body and tail that constitute a hinge line which is such that the haft tends to be turned so as to restore haft and lens to their correct position in line with the towing rope.

This clumsy–looking contraption actually behaves better than one would expect at first sight. It has a pull–over–drag ratio of about 5 and it is stable up to about 10 Km/h. It must be borne in mind that this is the very first model that starts to perform acceptably. Obviously,it will have to be improved and developed a lot further.

This particular hapa can only travel in one direction, but it has a central plane of symmetry through the axis of the torpedo so that it can be flipped over and travel equally well in the reverse direction. This may certainly not always be desirable because an accidental flip–over that is not automatically corrected may cause some rather awkward situations. For ocean sailing both a left–and a righthand hapa might will be safer. Another solution is a hapa with float and haft symmetrical in regard to a central vertical plane so that it can be made to travel both ways without flipping over. This presents a host of stability problems. A sort of double–ended waterski could be visualised as stabiliser but these things are no good in choppy sea. A torpedo with a fair lengthwise moment of inertia behaves much better because it punches right through the waves. But it would have to be a torpedo that can contribute stability while travelling either way.

The boat and sail in figures 7 and 8 are only meant as an illustration to be able to visualise one of many possible ways of sailing with a hapa that is towed like a kite. The mast does not have the usual stays because the system mast–sail is fully supported by the three lines connecting the three corners to the hapa. A rudder would obviously be absolutely useless. A change of course can be effected by veering out or pulling in the line at the foot of the mast. On a tacking course one could go about in the normal way by pulling the hapa in by the front line and launching a second hapa on the other side at the appropriate moment. One could also probably gybe by flipping over the hapa and veering the front line. Both manoeuvres could be rather exciting the first time in a strong wind.

During all these manipulations the boat would follow passively because it can turn freely around the mast. It has been tentatively provided with an enlarged tail fin but that may even not be necessary. In principle, the connection between mast and boat could be a universal joint, because the force $A+H$ passes right through this point. In practice some elastic restraint will be desirable, particularly when carrying out complicated manoeuvres.

It is surprising to what a large extent the boat, which is always considered to be the main constituent in conventional sailing, has been degraded by the evolution due to the introduction of the hapa. It has been stripped of keel, rudder, ballast, stays, etc. Actually it is just a superfluous nuisance, contributing unnecessary resistance and instability .

The inevitable next last step is the total elimination of the boat and an investigation of a symmetrical system of two kites, one in the water and one in the air. In the horizontal projection in figure 7, for example, the combination hapa–sail appears to actually be such a system.

There are innumerable types of kites to choose from, but there are only very few that can be considered efficient and safe for carrying a man. It is incredible that airplanes should already have wings with sophisticated airfoil sections for more than half a century while most kites and sails are still made of solely one thickness of cloth like the antique wings used by Lilienthal and the Wright brothers. These thin sections still persist notwithstanding their obviously staggering inefficiency. The reason for this, besides the usual conservatism and even mystical faith, is the technical difficulty of realising efficient and collapsible "wingsails".

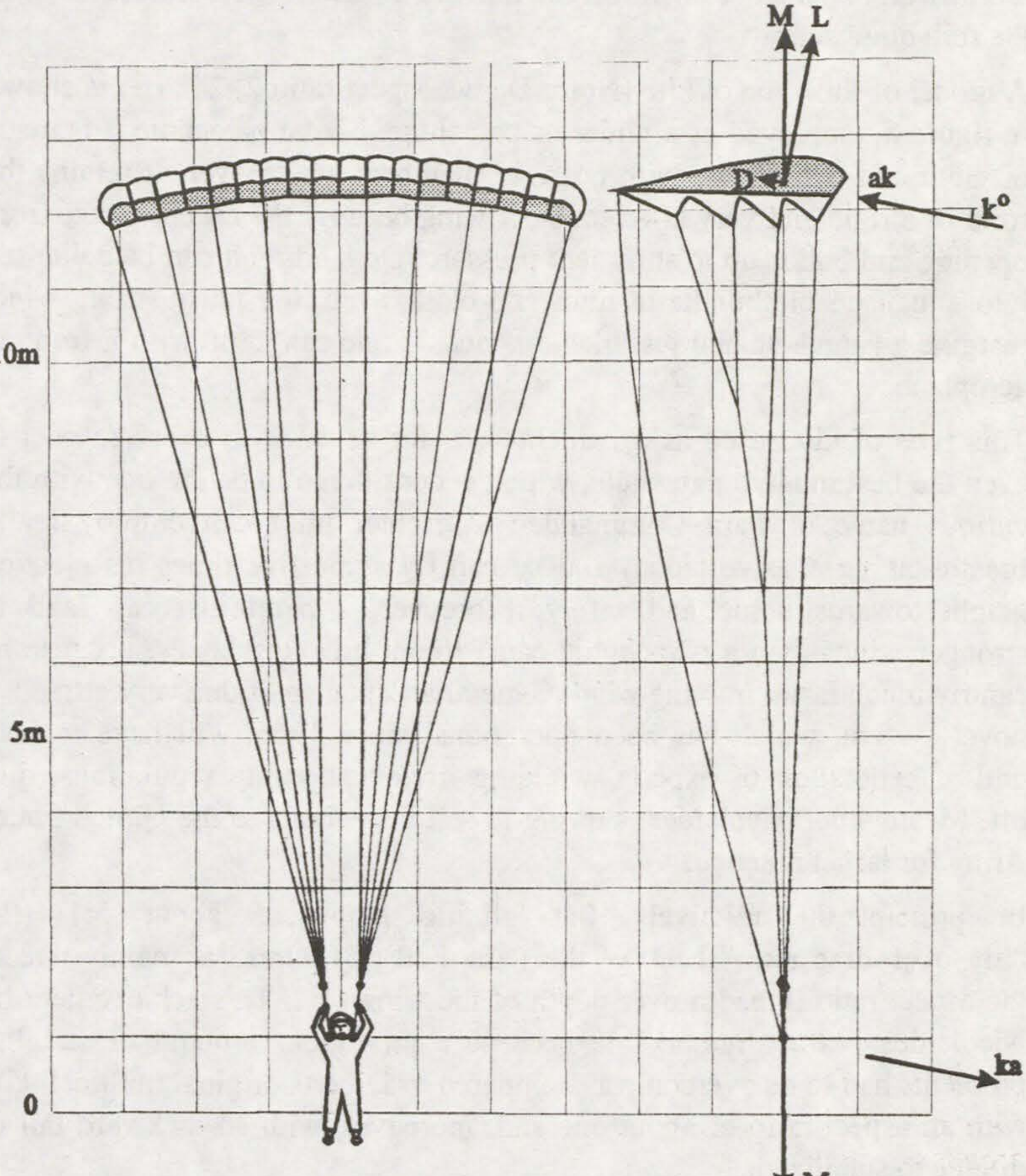


Figure 8 – Front view and median cross section of the 242 ft^2 Notre Dame Para-Foil with an aspect ratio of two, employed as a glider or parachute.

For this very purpose an outstanding invention, a real break–through, was introduced by D.C. Jalbert at Boca Raton, Florida. It was developed to a safe operational realisation by J.D. Nicolaides, head of the aeronautical department of the University of Notre Dame, Indiana. Jalbert originally called it an inflatable multicell airfoil, but it is now called Para–Foil, a philological joke due to "para" being very much the fashion since the last world war. A parachute will foil the fall and a parafoil will presumably foil the foil, quite simply.

A model of this type of kite (Notre Dame, aspect ratio 2, 242 ft^2) is shown in figure 8, employed as a glider or parachute. Like a parachute it is made of cloth and nylon rope with no rigid members whatsoever. It retains the form of a rigid and very efficient slow wing because the air enters the front opening and builds up to sufficient pressure. On landing it can be collapsed into a manageable bundle of lines and cloth, even in a fairly strong wind, just like a parachute and just like a parachute one can jump with it from an aeroplane.

This type of kite, used as a parachute, is far superior in every respect to even the best modern parachute, which is considered to be the one with the curious name of Para–Commander. A fighter pilot can employ really breath–taking evasive tactics and he can fly some five times his ejection height towards home and safety. Moreover, a parafoilist can land in stronger winds than a parachutist can without breaking bones, because he can fly much faster into the wind. General acceptance of this very attractive novel system, which has been operational since 1966, will have to wait until a generation of experts, wielding irrelevant safety regulations, dies off. Meanwhile, Nicolaides is trying to sell Para–Foils to the United States Army for target practice.

In principle,the relatively flat gliding slope of about 5:1 (the "lift–over–drag ratio" L/D) of the Para–Foil of figure 8 is mainly due to the aspect ratio (breadth over depth of the wing of 2. This achievement by Nicolaides is truly remarkable because a prodigious amount of stability problems had to be overcome as compared to Jalberts original multicell kite with an aspect ratio of about one and, moreover, with an awkward tail or drogue to stabilize it.

It seems unbelievable, at first sight, that such an unwieldy "mattress", with more than 300 metres of 0.3 cm thick shroud–lines attached to 40 triangular flares, will actually fly so well and so safely.

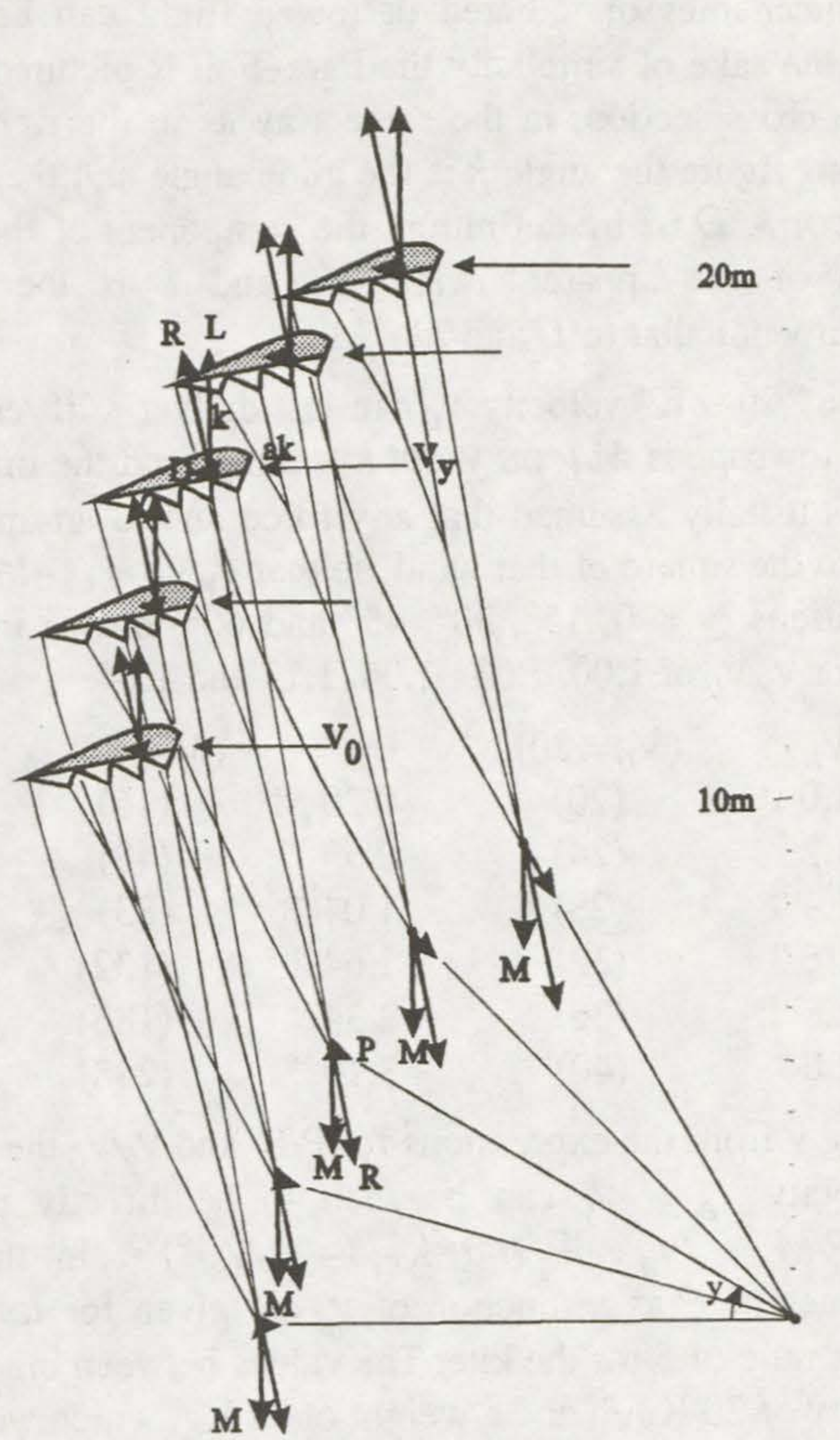


Figure 9 –

The forces and velocities involved when the Para-Foil is tethered or towed.

It must be borne in mind that a parachute or kite is relatively easy to stabilize for free flight, because the attached weight tends to automatically revert to its correct vertical position below the kite. It is much more difficult to achieve stability when the kite is tethered or towed. The Para–Foil of figure 8 is quite stable even under these circumstances. It was tested a number of times by towing it, with a dummy weight attached, to make it airborne. When launched correctly it gained height and flew quite stably.

The simple mechanics of tethered or towed flight can be derived from figure 9. For the sake of simplicity the Para–Foil is pictured schematically as its median cross section, in the same way as in the right hand side of figure 8. In this figure the angle k is the glide angle and the lift–over–drag ratio L/D is $\cot k$. D is, by definition, the component of the total force in the direction of the apparent wind ak, and L is the corresponding component perpendicular to D and ak.

In figure 9 the "lift–off" velocity v_0 can just deliver a lift equal to M. The pull P on the towrope is $M/(\cos y \cot k - \sin y)$ and the lift L is $M/(1-\tan k \tan y)$. It is usually assumed that any force due to an apparent wind is proportional to the square of that wind, so that $v_y/v_0 = (1-\tan k \tan y)^{-1/2}$. The five positions (y = 0, 15°, 30°, 45° and 60°) drawn in figure 9 then have values for v_y/v_0 of 1.00, 1.03 , 1.06, 1.12 and 1.24.

V_a	(V_0= 20)	p	(M= 80)
1.0 v_0	(20)	0.20 M	(16)
1.2 "	(24)	0.53 "	(42)
1.4 "	(28)	1.04 "	(83)
1.6 "	(32)	1.64 "	(132)
1.8 "	(36)	2.34 "	(186)
2.0 "	(40)	3.10 "	(248)

By eliminating y from the expressions for P/M and v_y/v_0 the pull P and the apparent velocity $v_a = v_y$ can be seen to be directly related by the expression: $P/M = (v_a/v_0)^2 \ (\tan^2 k+(1-(v_0/v_a)^2)^{1/2}$. In the table some numerical values of P as a function of v_a are given for $\tan k$ = 0.2 or a lift–over–drag ratio of 5 for the kite. The values between brackets refer to a lift–off velocity of 20 Km/h and a weight of 80 Kg, which would just about be the actual values for the case of a man suspended below the ND2(242) Para–Foil.

Figure 10 illustrates a transition from the free–flying condition of figure 8 to the tethered, or towed, condition of figure 9. It depicts a hypothetical descent over water with a surface wind (22.5 Km/h, only slightly higher than lift–off velocity (20 Km/h). The man is approaching the surface of the water "backwards" along the dashed line with a velocity kw (5 Km/h), the resultant of the true wind wa and apparent wind ak.

The man in figure 10 is dangling a sea anchor with which he hopes to get a grip on the water and thereby acquire the third, tethered position shown on the left in figure 10. The middle figure shows what he will have to do to get the towrope stretched out before he gets his feet wet. It is only included in

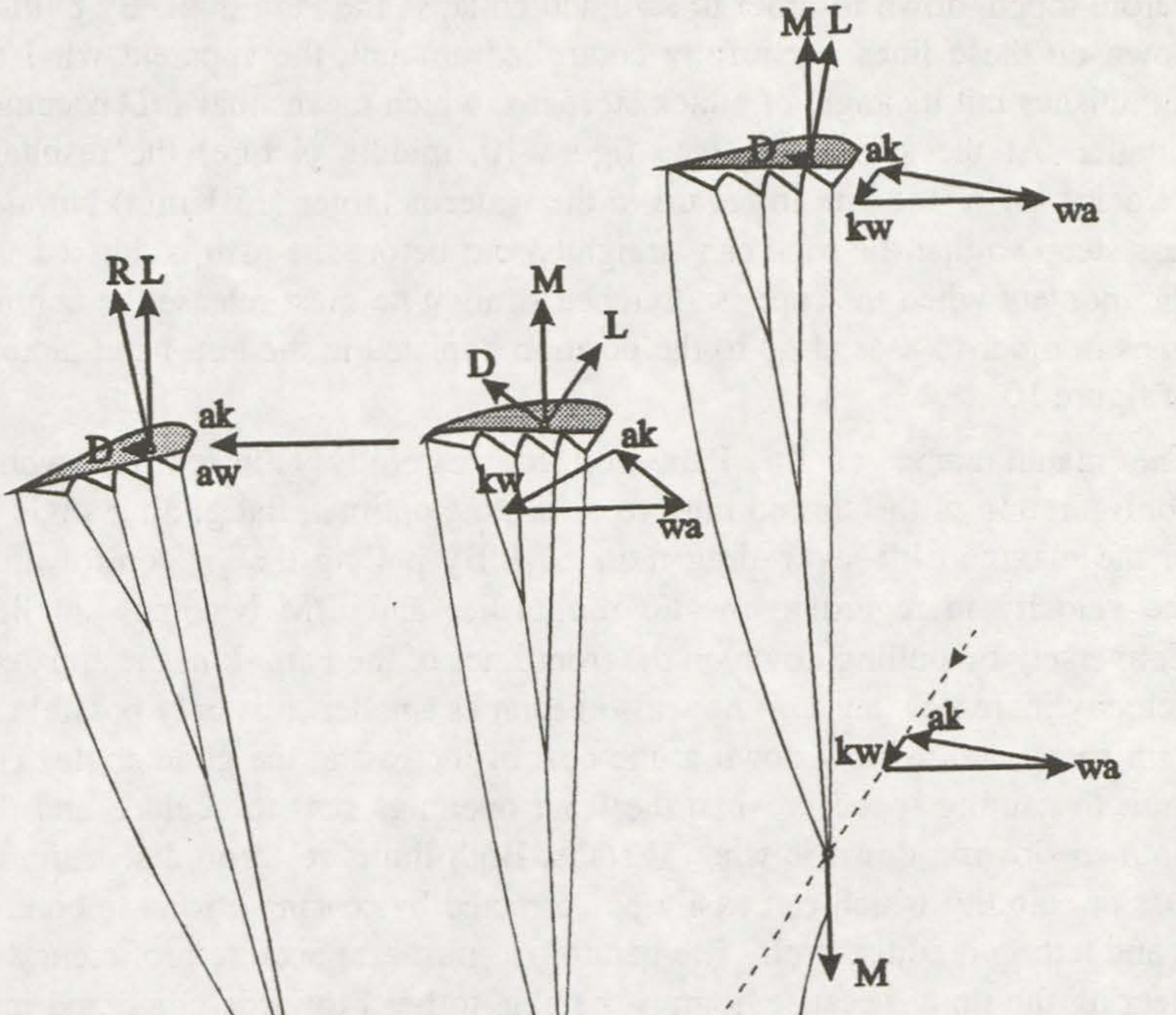


Figure 10 – A hypothetical descent over water, resulting in a stable position tethered to a sea anchor.

order to illustrate the function of the two control lines attached to the trailing edge of the Para–Foil. They provide a braking or stalling action when pulled. When landing on land they are pulled down all the way just before touch–down in order to stall and collapse the Para–Foil. By pulling down on these lines a carefully controlled amount, the apparent wind ak diminishes but its angle of attack steepens, which means that *L/D* becomes smaller. At the same time (see figure 10, middle picture) the resultant velocity *kw* of the kite in regard to the water is larger (15 Km/h) but also less steep so that the rope can straighten out before the man is dunked. At the moment when the rope is stretched straight he must release the control lines in order to ascend up to the position depicted in the left–hand picture of figure 10.

The manufacturer of the Para–Foil has carefully adjusted the whole configuration of the shroud lines to obtain the optimal, flat gliding angle *k*, or the maximal lift–over–drag ratio *L/M*. By pulling the aft control lines the velocity in regard to the air diminishes and L/M becomes smaller. Conversely by pulling down on the front lines of the Para–Foil the apparent velocity increases, but *L/M* now also becomes smaller. It is only possible to gain speed and to slow down at the cost of increasing the glide angle. The limit to gaining speed is when the front openings start to occlude and the limit to slowing down is when it stalls. Both limits result in a sensational loss of stability which can easily be corrected by ceasing efforts to control it and letting it adjust itself. The parafoilist must also acquire proficiency in steering the thing because he must be able to head towards home and into the wind when landing. To turn a parafoil and, even more important, to stop it turning, the man must pull down on the appropriate one of the two rear webbings attached to his harness, to each of which half of the rear forked shroud lines are connected. It is amazing how delicate this control is. It is always good to remember how the inventor of the bicycle must have wobbled at first and must have had grave doubts as to its possible stability.

The aviator in figure 10 has been left hanging high and dry in the air and he wants to start moving, become an aquaviator, and not wait until somebody, perhaps the enemy, comes to pick him up.

It is simple to imagine what would happen if his sea–anchor were the ingenious hapa, introduced in figures 6 and 7. As the rope straightens, the pull *P* is exerted on the hapa and it starts to move off sideways. The man must adjust the parafoil to follow the hapa so that the whole system moves on a desired and possible course.

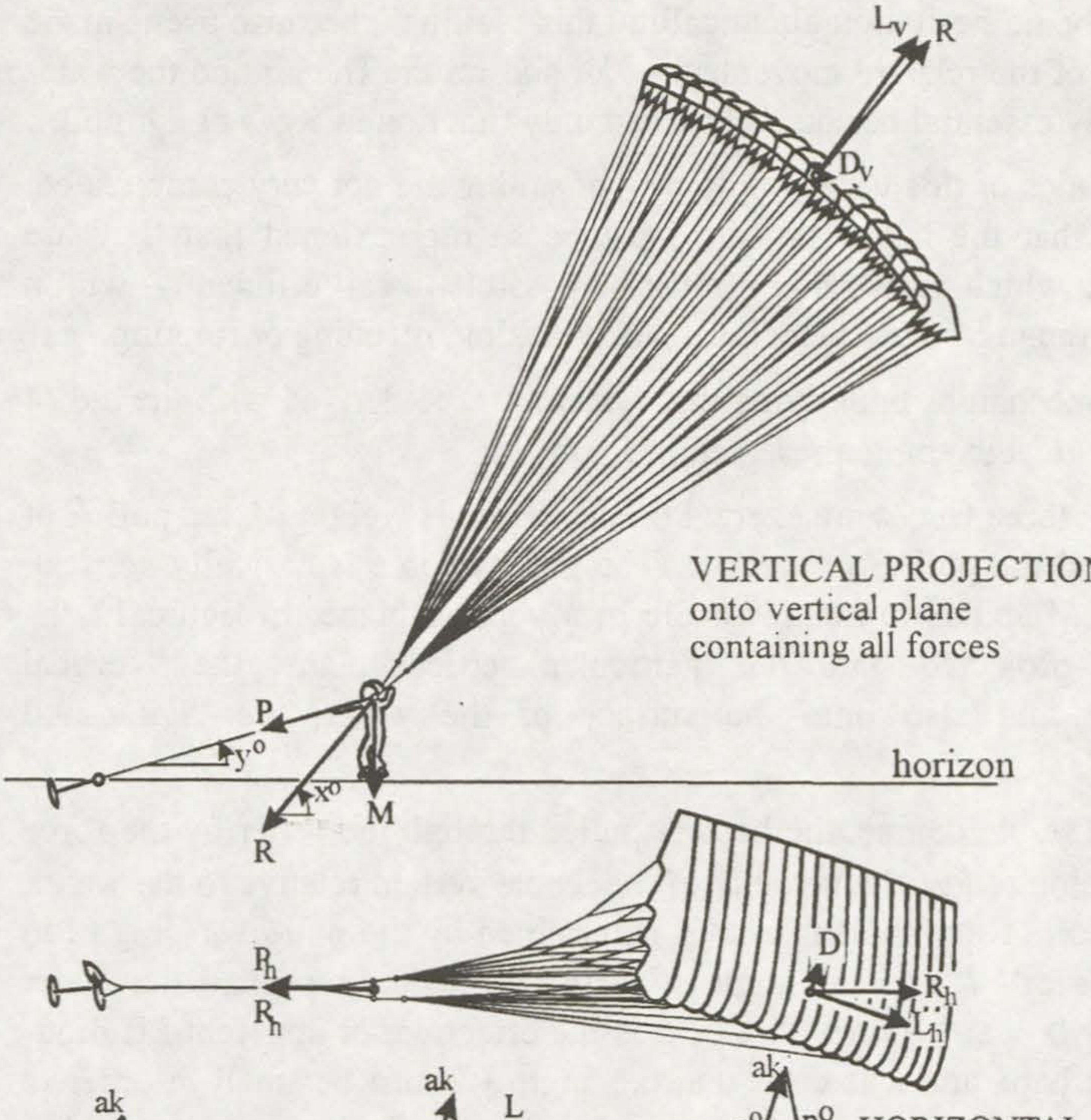


Figure 11 – Derivation of forces and velocities for a system hapa-mass-kite.

This, then, is ultimate sailing: the absolute minimum of kite–man–kite and no more than necessary in the water, the medium with the high resistance. There can be no hesitation about calling this "sailing", because use is made essentially of the relative movement of air and water. The air and the water are basically essential because a kite can only function in a gas or a liquid.

The mechanics of this very simple way of sailing are not very complicated. It is clear that the hapa and kite must be so dimensioned that they are compatible, which means that it must be possible to sail efficiently, within a practical range of wind velocities, when tacking, reaching or running.

The basic mechanics underlying this system can be derived with the aid of the hypothetical example presented in figure 11.

Essentially, three forces are exerted on the man: his weight M, the pull P of the hapa and the pull R of the kite. The gravity force is basically vertical, so that P, M and R must always lie in a vertical plane. In figure 11 the system is projected onto this particular vertical plane, the "vertical projection" and also onto the surface of the water, the "horizontal projection".

When on a stable course, the hapa is pulled through the water by the force P with a velocity kw, the velocity of the whole system relative to the water. The direction of kw, the angle $p°$,is determined by the pull-over-drag ratio of the hapa $cot\ h$ and the angle $y°$ between the towrope and the water surface $sin\ p = sin\ h / cos\ y$. $Cot\ p$ is the effective, or apparent lift-drag-ratio of the hapa and it is clear that the angle $y°$ must be small in order to approach the optimal value where p approaches h. The hapa of figure 11 is assumed to behave efficiently down to a minimum slope of the towrope of $tan\ y = 0.3$.

The next step is to assume a certain value $x°$ for the angle between force R, exerted by the kite, and the surface of the water. The three forces P, M and R must cancel, so that P and R can be written as functions of M, y and x:

$$P = M/(cos\ y\ tan\ x - sin\ y)$$

$$R = M/(sin\ x - tan\ y\ cos\ x)$$

The movement of the kite in regard to the air is fully determined by size and direction of R. This is the crucial fact underlying the behaviour of the kite. A minimum relative velocity kite-air, the lift-off velocity v_0, can keep a weight M suspended in the lowest position shown in figure 9, where the lift of the kite is $L = M$, the drag $D = M\ tan\ k$ and the resultant of L and D is $R = M/cos\ k$. The velocity ak of the kite in regard to the air in figure 11 is determined by the size of R in figure 11 compared to the minimal value of $R = M/\cos k$ in figure 9.

It is generally assumed that a motive, or resultant force is proportional to the corresponding velocity squared, so that:

$$(v_{ak}/v_0)^2 = \cos k/(\sin x - \tan y \cos x)$$

This simple expression produces the magnitude of the apparent velocity, but its direction must also be determined. This direction can be found by the simple observation that the direction of this velocity must be horizontal, parallel to the surface of the water, in order to arrive at a stable sailing configuration where forces and velocities are essentially constant.

By fixing the value of $x°$ the direction of R in the vertical projection in figure ll is fully determined. The only remaining degree of freedom is a rotation of the kite around R. During this rotation both L and D remain in the median plane of the kite. Moreover, D and the apparent velocity ak are, by definition, in the same direction. This means that the aquaviator must have turned the kite in such a way that D is horizontal.

This "rotation"-procedure is illustrated in the lower "2:1" diagram in figure 11. The dashed lines present the same median cross section as in figure 8, with the same L, D and R, only R being full-drawn because it is invariant, being the axis around which rotation takes place. Furthermore,the observer is looking at a vertical projection of the manipulation. This means that rotations around R result in a movement of any point restricted to the perpendicular to R. Thus, the arrow point of D moves along the dotted line to D_v, determined by the fact that D_v must be horizontal (the vertical projection of a horizontal line is horizontal). In this way the actual vertical projection of the median cross section has been determined.

Now that the vertical projection of D and the corresponding median cross section has been obtained, the next step is to determine the horizontal projection with D_h (dot-dash lines). For this there are two evident, logical facts. In the first place, the relation vertical-to-horizontal projection of a point implies that the two projections lie on the same vertical line. And in the second place, D_h is actually equal to D itself because D is horizontal. Thus, the arrow D_h in the "2:1" diagram of figure ll is fully determined because its length is equal to D and its point is on the vertical dotted line through the point of D_v. $D_v/D = \sin k / \cos x$ because the angle between D and the dotted line to D_v equals $k°$ and the angle between D_v and R equals $x°$. Furthermore $\sin q = D_v/ D_h$ and $D_h = D$. This results in:

$$\sin q = \sin k /\cos x$$

In this way the direction of the apparent wind *ak* is determined as a function solely of the angles *k* and *x*.

The example in figure 11 can be brought to life by assigning numerical values to the different forces, velocities and angles. By assuming M= 80 kg, $tan\ y$ = 0.3, $tan\ x$ = 1.2, $tan\ k$ = 0.2 and v_0 = 20 Km/h, the resulting apparent velocity v_{ak} = 26 Km/h and the force P = 93 Kg. The velocity of the hapa through the water, which is the velocity *kw* of the whole system in regard to the water, has been assumed to be 22.5 Km/h at an angle $p°$ determined by a choice of $tan\ h$ = 0.2.

This latter assumption implies that the hapa has been dimensioned in such a way that a pull of 93 Kg will actually give it a velocity of 22.5 Km/h through the water. Here then is an illustration of what "compatibility" implies. The system presented in figure 11 can only function in the manner depicted if the hapa is the right one. The logic of the thing must necessarily be rounded off in this way. Use of maximal lift-over-drag ratios and a shallow angle y can only be efficiently made if the hapa is the right one for the given circumstances.

In the case of the practical example corresponding to figure 11 ,the hapa must run 22.5 Km/h when pulled with 93 kg, so that, if again velocity squared is proportional to the exerted force:

$$v^2 = 5.5\ P$$

The hapa could be described as having the characteristic constant of·5.5 (Km/h)^2 per Kg force.

In the particular example presented in figure 11, the velocities *ak* = 26 Km/*h* and *kw* = 22.5 Km/h will form part of a completely compensated triangle by adding the velocity *wa* = 13 Km/h. This latter velocity is the corresponding actual velocity of the water in regard to the air, or the true surface wind velocity. The surprising fact emerges that the example in figure 11 refers to a physically possible case of a man remaining in the air and even moving quite fast (22.5 Km/h) relative to the water, when the wind is well below (65%) liftoff velocity (20 Km/h). The example is an absolute minimal situation; a wrong control adjustment, a momentary slight lull of the wind, etc, will result in an irremediable dunking and, moreover, it is impossible for the man to reverse his course. It would, however, appear logical to choose a hapa that is dimensioned to obtain optimal performance under these minimal circumstances.

Mathematically, the two equations governing size and direction of the apparent wind $v_a = v_{ak} = a$:

$$(v_a/v_0)^2 = \cos k / (\sin x - \tan y \cos x)$$

and

$$\sin q = \sin k / \cos x$$

present the relation between va and q with x as parameter, which can be eliminated, resulting in:

$$v_a^2 = v_0^2 \cos k \sin q / ((\sin^2 q - \sin^2 k)^{1/2} - \tan y \sin k)$$

This is a curve in "polar coordinates" *va* (radial distance) and *q* (angle). It sounds a bit involved but it expresses a very simple possible way of obtaining a clear visual picture of the movements of such a system kite–mass–kite under a wide variety of circumstances.

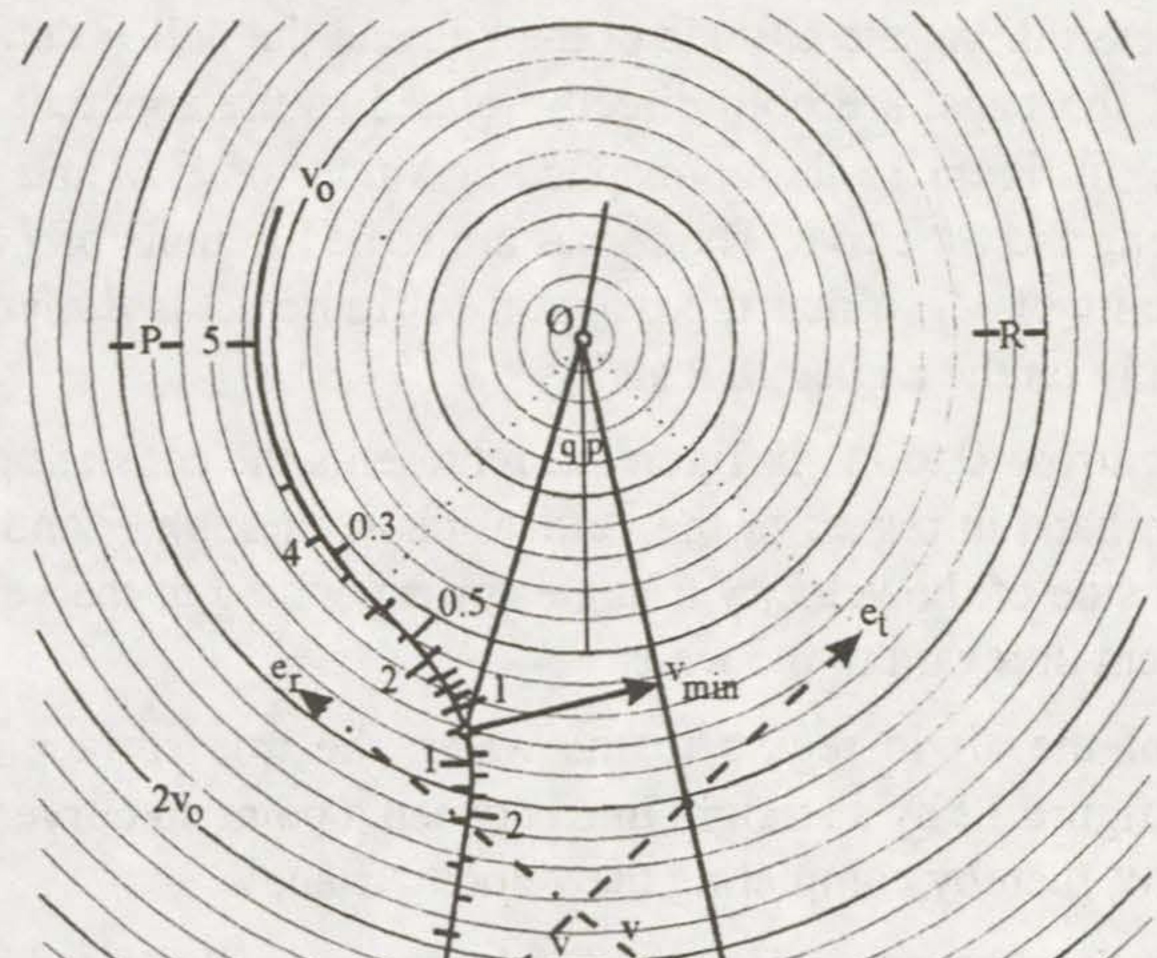


Figure 12 – Polar vector diagram of the velocity ka in regard to the air and the velocity kw in regard to the water for lift-over-drag ratio of 5 for both kite and hapa and the towline at a slope of 3 to 10.

Such a polar diagram is shown in figure 12. The only underlyingassumptions are that lift–over–drag ratios of both kite and hapaare 5 *(tan* h = *tan* k = 0.2) and that the angle $y°$ is such that *tan* y = 0.3. These are the same values used in figure 11 and, actually, the same triangle of velocities of figure 11 will be recognised as the full–drawn triangle in figure 12, with the true wind wa reversed and called vmin. The straight line through P, O and R corresponds with the vertical plane through P and R in figure 11, because figure 12 is, in essence, a horizontal projection.

The curved line ka in fig 12 was obtained by calculating pairs of corresponding values of $v_a = (ka)$ and q from the formula. Any arrow from the origin O to a point of this curve is a possible apparent velocity of the kite.

The angle x, determining the attitude of the kite and the pull P determining the velocity of the hapa, are both directly related to the apparent velocity vak of the kite. In figure 12 the corresponding values of P/M and of *tan* x are marked along the ak curve. The forces are scaled in units of M and the velocities in units of v_0 so that the diagram in figure 12 is dimensionless and depends only on the angles h, k and y.

The rectilinear arrow 0 to kw in figure 12 represents the constant direction of travel of the hapa in regard to the vertical plane through P and R. This determines the side of the velocity triangle corresponding to the velocity of the whole system in regard to the water.

The velocity of the air in regard to the water, the true surface wind, is represented in figure 12 by a straight line between a point on curve ka and a point on line kw, thereby completing the velocity triangle.

It is clear from the diagram in figure 12, why the case illustrated in figure 11 is a minimal configuration. The true wind v_{min} is the shortest possible connection between curves ka and kw.

The diagram in figure 12 contains three further examples, each with a true wind v (22.5 Km/h) corresponding to figure 10, in order to see how the aquaviator could actually travel home.

The dashed v in figure 12 completes a triangle with k_a = 46 Km/h and kw = 30 Km/h. By trial and error this has been found to represent the maximum case for tacking into the wind. The velocity e_t = 16 Km/h is the best effective velocity into the wind obtainable. Here a force of P = 5.2, M = 420 Kg must result in a velocity of the hapa of 30 Km/h, or $v^2 = 2P$.

The dot–dashed v in figure 12 completes the triangle with k_a = 32 Km/h and k_w = 46 Km/h. This results in the maximum effective velocity er = 34 Km/h when running in the direction of the wind. Now P =180 Kg must result in a velocity of v = 46 Km/h, or $v^2 = 11.5\ P$.

The dot–dashed v results in the maximal reaching velocity of k_w = 54 Km/h, when P = 500 Kg, or $v^2 = 6P$

The necessary constant of the hapa ranges from 2 through 5.5 and 6 to 11.5, which means that the velocity kw, for a certain pull, ranges from 50% to 150% of the value corresponding to the case with minimal wind - figure 11.

This means that the choice of a $v^2 = 5.5\ P$ hapa is a rather good compromise. The hapa then is too fast for tacking into the wind and too slow for a reaching or running course. In order to be able to sail efficiently, it will be necessary to correct to a slower hapa and faster kite when close hauled, and to a faster hapa and slower kite when reaching.

The lift–over–drag ratio of both kites decreases, and thereby also their efficiency, when they are adjusted to velocities either higher or lower than optimum. From the performance figures of the ND2(242) Parafoil, provided by Notre Dame, it appears that a 25% change in velocity either way can be obtained by changing the angle of attack from about 0° to 15°, with a corresponding decrease in liftover–drag ratio of, roughly, from 5 to 3. This is probably about the maximum that can be obtained in actual practice without losing too much stability.

Corresponding values for a hapa are not yet available, but if it behaves in a roughly similar way, a combination of controls of hapa and Parafoil should just about provide the necessary variation in speed/pull from tacking to running. This control can be, in principle, a single manual control that changes the attitudes of hapa and kite simultaneously in opposite directions, always keeping the combined effect at optimal efficiency. In this way the man can fix his course while with his other hand he adjusts the rotation of the kite so that he flies at a minimal angle y with the water. The really keen competition sailor will probably eventually take along a fast, medium and slow hapa.

The beginner should obviously be given a relatively slow hapa, say about a $v^2 = 2\ P$ hapa, so that it cannot run away from him. It could actually be similar to the one in figure 7, which is adjusted to maximal L/D with a single towrope and consequently without velocity control. The student will have to learn to keep up with it by adjusting the controls of his kite so that the hapa either tends to be in a following position on a close–hauled course, or in a forward position on a reaching or running course. To attain the latter position he must let the hapa gain on him and then try to make it run faster by pulling harder, which means that he must pull the rear control lines sufficiently hard that he just doesn't get his feet wet.

The mechanics of this way of sailing are so clear and simple because the object to be moved, the man and his impedimenta, is moved through the air with a negligible resistance compared to the forces exerted by the kites. That makes it such an attractive approach, from this simplest type of sailing to the more complicated, but more normal and comfortable, systems of sailing with a boat.

It is now clear that the system sail–boat–hapa in figures 6 and 7 also implies the use of a mutually compatible pair of sail and hapa in order to arrive at an efficient system. Here also, the most efficient way to sail would be with a set of hapas and to control the speed of each hapa to both sides of the optimum within the limits set by an acceptable loss of pull–over–drag.

A fixed hapa, as illustrated in figures 3 and 4, can have a velocity/pull control based on a change of angle of attack, but also a further very effective control by a variation in immersion. Fully immersed it could be ideal for tacking, when, moreover, it should present its lowest profile to the wind, while it is lifted out more and more on reaching and running courses. With these provisions, such a sailing system with a high aspect ratio hapa could be a very attractive practical proposition, but then with one or two freely moving boats and, naturally, hydrofoils to reduce the resistance.

Again it must be emphasised that the usual sailboat sails are actually inefficient atavisms, certainly when compared to glider wings, but also when compared to an efficient kite like a Parafoil. It can only be hoped that somebody will soon take the obvious, imaginative initiative and develop a sail that is also inflated by the wind. The designer of such a sail has a marked advantage over the designer of a fully collapsible kite, because he can easily achieve a high aspect ratio by a sparing use of rigid members like mast and slats and still have a system that he can lower, stow away, replace, etc.

The hapa, the little brother to the sail, is also still very much in its first development stage. A tremendous amount of imaginative thinking, experimenting and designing will have to be carried out before the first aquaviator wins the transatlantic sailing race.

January 1971.

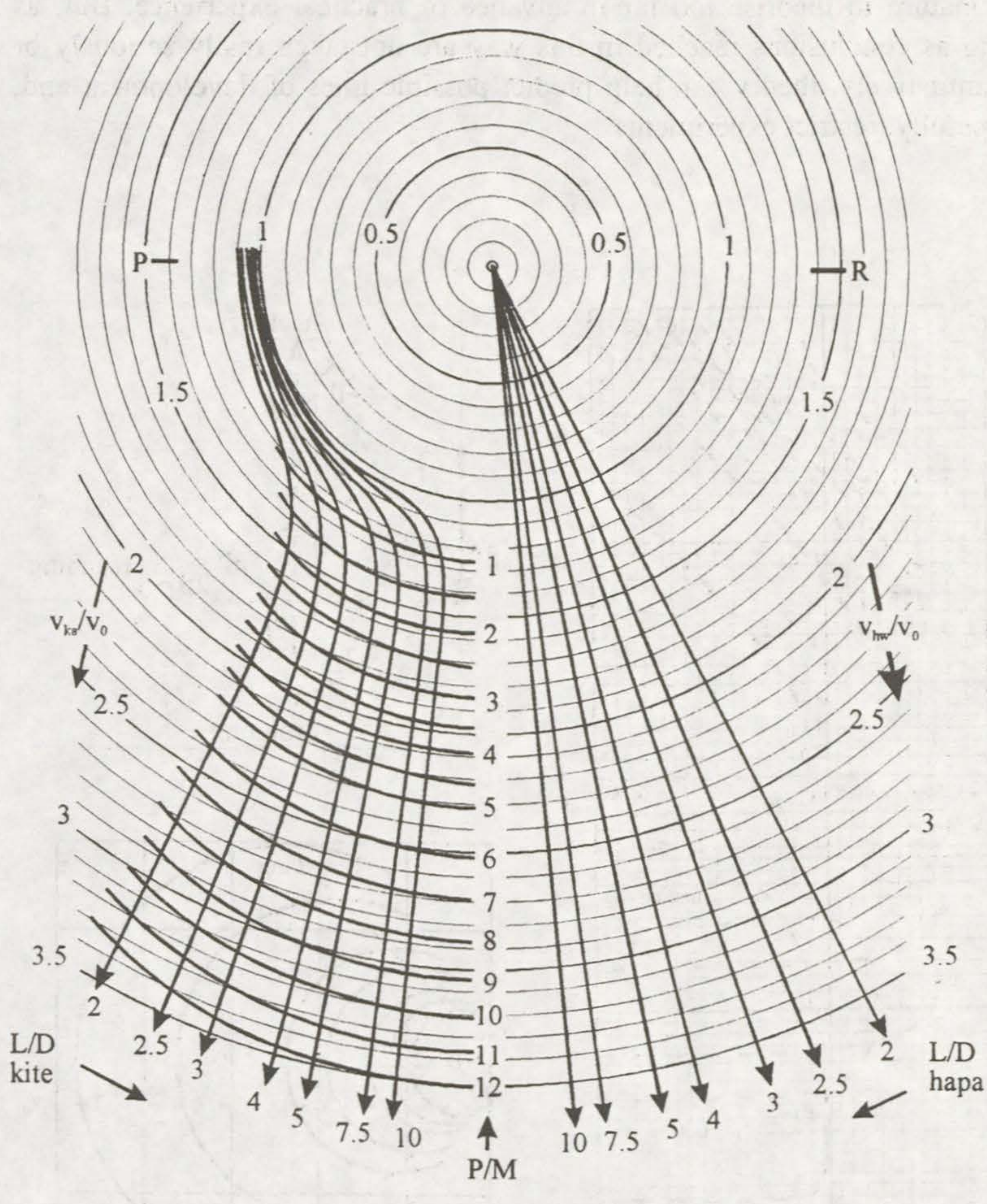


Figure 13 Polar vector diagram of the velocities in regard to air and water, also of the pull on the towline, for a range of lift/drag ratios from two to ten. The slope of the towline is 3 in 10 throughout.

Appendix

The main impediment to progress is the fact that the hapa has not yet been developed to behave stably at high velocities. It would therefore appear premature to theorise too far in advance of practical experience. But, as long as conclusions reached in this way are not taken really seriously or quantitatively, theory can help predict possible lines of development and, hopefully, restrict experiments.

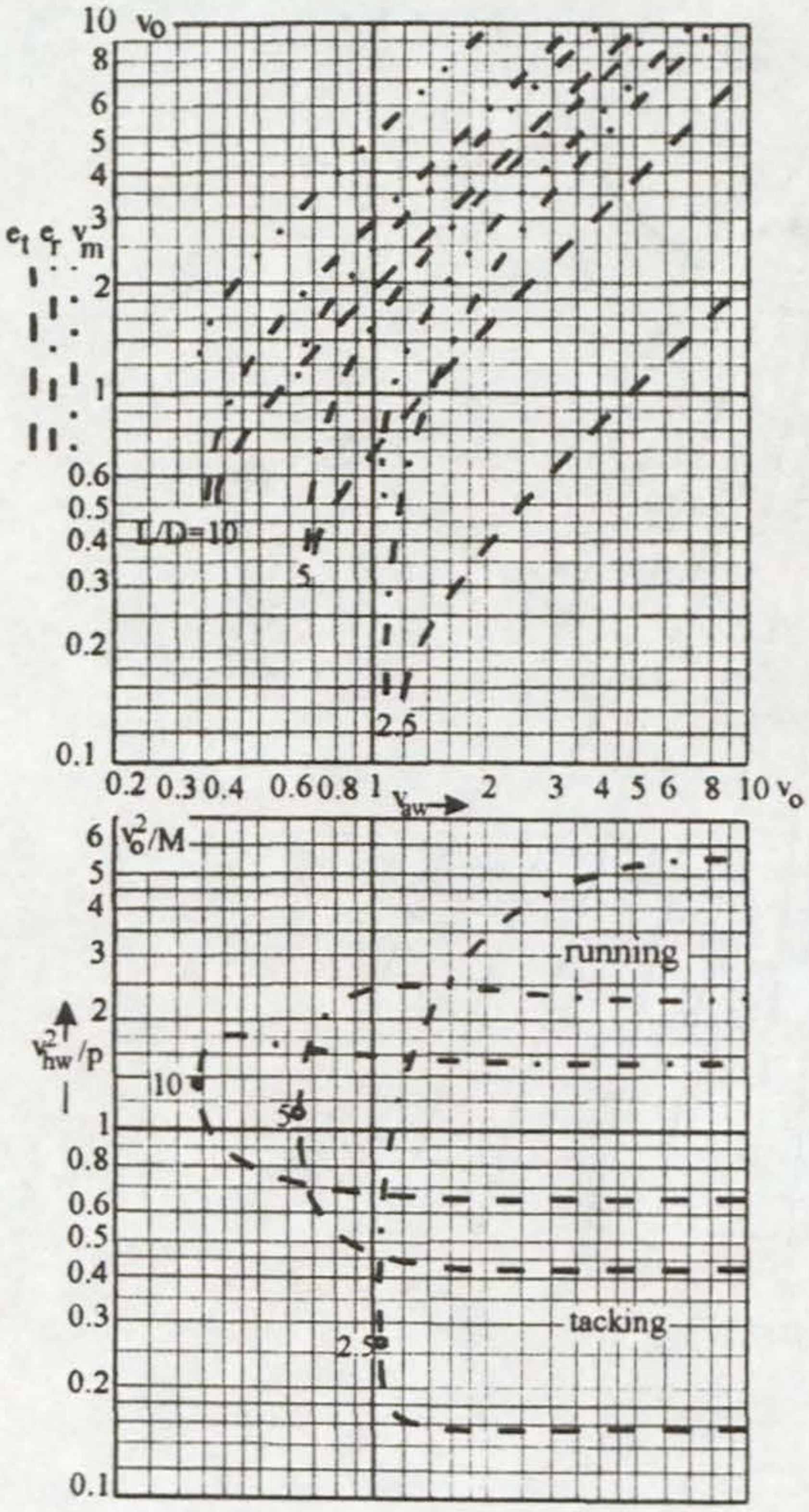


Figure 14 Velocities and pull as function of V_{AW}

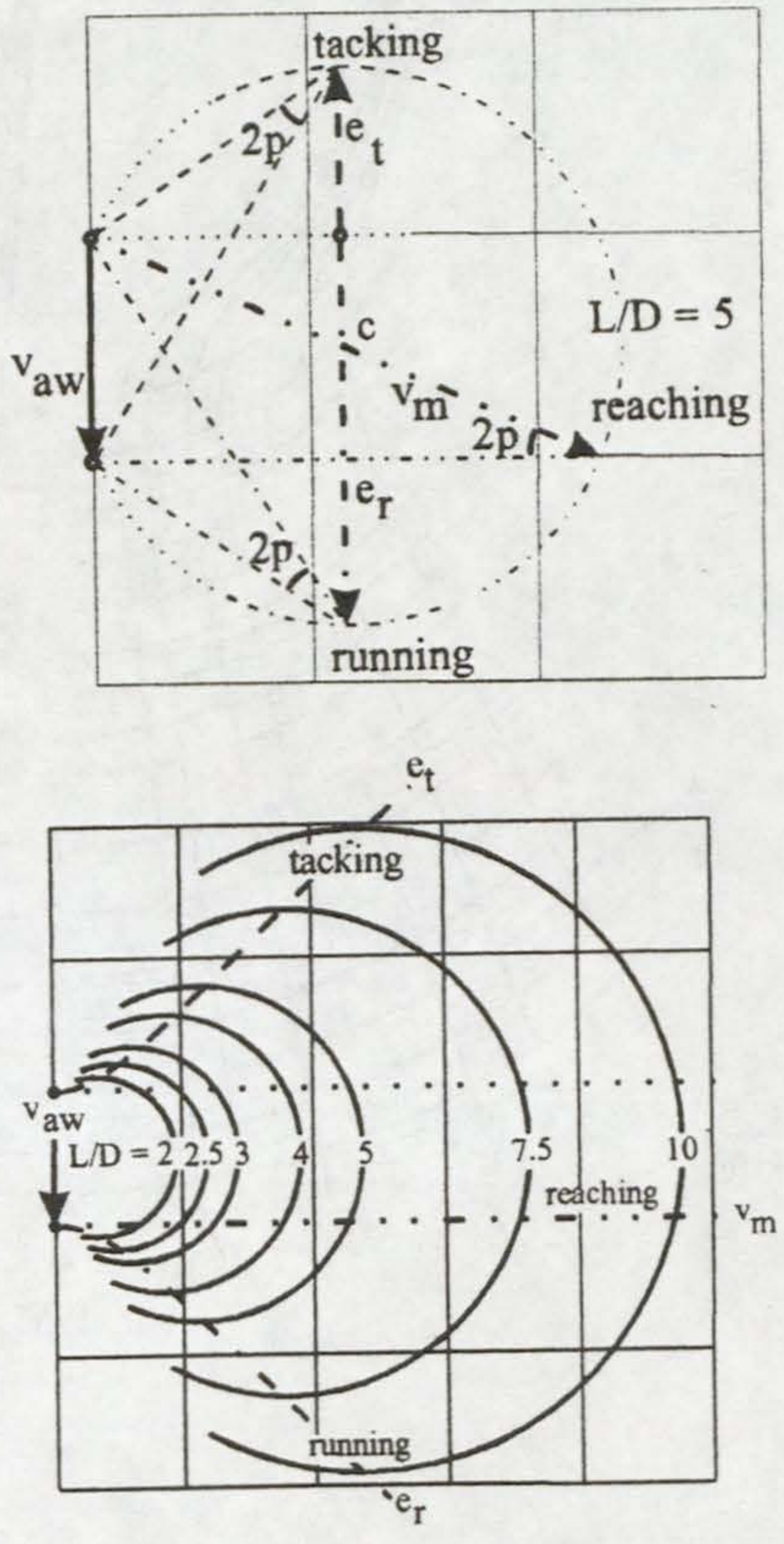


Figure 15 – ultimate velocity diagram for large velocities and the true wind fixed

Figure 12 is a polar diagram only for the case of a lift/drag of five for both kite and hapa. In figure 13 the polar diagram for a range of values of L/D, from 2 to 10, is presented. The directions of the relative velocities hapa-water (v_{hw}) are again given by $sin\ p = sin\ h\ /\ cos\ y$. Direction and size of the velocity kite-air (v_{ka}) is given by:

$$(v_{ka}/v_0)^2 = cos\ k\ sin\ q\ /\ ((\ sin^2 q - sin^2 k\ )^{1/2} - tan\ y\ sin\ k)$$

In order to introduce the corresponding values of the pull on the hapa, it is convenient to combine this relationship with an expression for sin q derived by eliminating x from the two equations:

$P = M/(cos\ y\ tan\ x - sin\ y)$ and $sin\ q = sin\ k\ /\ cos\ x$, Which gives:

$$sin\ q = sin\ k\ ((P/M)^2 + 2\ (P/M)\ sin\ y + 1)^{1/2}\ /\ (P/M)os\ y$$

This expression for sin θ can then be introduced into the relation between v_a/v_0 and $sin\ q$, resulting in:

$$(v_{ak}/v_0)^2 = cos\ k\ ((P/M)^2 + 2\ (P/M)\ sin\ y + 1\ )^{1/2}$$

This gives separate expressions for v_{ak}/v_0 and $sin\ q$ with P/M as parameter. One value of P/M, combined with different values of L/D $(= cot\ k)$ will then provide one line of constant pull in the diagram.

The velocities in figure 13 are again scaled in units of the lift-off velocity v_0 and the pull P in units of the mass M. This means that the polar diagram in figure 13 can be used for any system kite-hapa, with the only complication that the angle y must have a finite and acceptable value. Luckily, the diagram is not very sensitive to variations in y around the chosen angle of about 17° ($tan\ y = 0.3$).

The two graphs in figure 14 were derived from this polar diagram of figure 13. They are plotted on logarithmic scales because that gives a convenient and clear visual appreciation of ratios rather than absolute values. The horizontal scale is the actual wind vaw in units of v_0.

In the top graph of figure 14 the three most important velocities have been plotted for the three cases,marked $L/D = 2.5$, 5 and 10, the lift/drag ratios of both kite and hapa in each of the three examples. et is the maximal effective tacking velocity into the wind (dashed curves), er is the maximal running velocity in the direction of the wind (dot-dash curves) and vm is the maximal reaching velocity (dot-dot-dash curves).

The lower graph in figure 14 gives the ranges of the required characteristics of the hapas that must be employed to actually obtain the velocities in the top graph. One point on a curve in the top graph corresponds to a velocity triangle in the diagram of figure 13. Such a triangle is determined by connecting a point on a v_{ak}-curve with a point on a v_{hw}-line by a line segment with a length corresponding to the surface wind v_{aw}. The point on the v_{ak}-curve determines the value of P/M and the point on the v_{hw}-line the value of v_{hw}, which two values are then combined to give the desired characteristic value v^2_{hw}/P of the hapa.

In figure 12 it can be seen that, when tacking, the surface wind (dashed v) connects a larger vak with a smaller v_{hw} and, conversely when running, the surface wind (dot-dash v) connects a smaller v_{ak} with a larger v_{hw}. It is clear that, for a certain surface wind, the largest v^2_{hw}/P is required when running and the smallest when tacking. This is the reason why only these particular values have been plotted in the lower graph of figure 14.

By scaling the values of v^2_{hw}/π in units of v^2_0/M, the graph is made Dimensionless, so that it can be used for evaluation of any system kite-mass-hapa. This can be considered to be an elimination of the compatibility, because v^2_{hw}/π is the hapa and v^2_0/M is the kite.

All curves in figure 14 are seen to converge to asymptotes as vaw increases. The velocities become proportional to v_{aw} and the hapa characteristics become constant.

What these limits actually mean can be clarified with the aid of figure 15. Here the unit is changed from the lift-off velocity v_0 to the actual surface wind velocity vaw and, moreover, this wind is given a fixed position. The top diagram in figure 15 is directly related to the diagram in figure 12 at high velocities. The curve ka in figure 12 obviously converges to an asymptote, the straight line through O with $q = p$. The velocity v consequently is a connection between two straight lines at an angle $2p$. In figure 12 these two lines are fixed and v is moved around. In figure 15 this vector v is fixed and the pattern, consisting of the two lines at an angle $2p$ with their intersection O, is moved around. Our Greek forebear Ptolemeus discovered that the locus of all points O is a circle through the ends of v. This leads to the attractively simple top diagram in figure 15. The actual surface wind v_{aw} is the common baseline of the three triangles, corresponding to the three most important sailing configurations: tacking (dashed lines), reaching (dot-dot-dash lines) and running (dot-dash lines). The relations are quite simple,because v_m must obviously be a middle line of the circle: $v_m/v_{aw} = l/\sin 2p$

$e_r + et = v_m = v_{aw} / \sin 2p$ or, $e_r/v_{aw} = ((l/\sin 2p)+1)/2$

$e_r - e_t = v_{aw}$ $\qquad e_t/v_{aw} = ((l/\sin 2p)-1)/2$

In the top diagram of figure 15 the value of p has been chosen to correspond to the lift/drag ratio of both kite and hapa of 5 ($\cot k = \cot h = 5$ and $\sin p = \sin q = (\sin k = \sin h) / \cos y$). In the lower diagram of figure 15 the suite of circles through the wind v_{aw} correspond to a number of different lift/drag ratios, in each case referring to both kite and hapa.

The limits of the characteristics $v^2{}_{hw}/P$, expressed in units of v20/M, can be derived in the following manner. From the expression

$$(v_{ak}/v_0)^2 = \cos k\ ((P/M)^2+2(P/M)\ \sin y +1)^{1/2}$$

it follows that the limit for large values of velocities and of P/M:

$$(v_{ak}/v_0)^2 = (P/M)\cos k, \text{ or } (v_{ak}/v_0)^2/(P/M) = \cos k.$$

This must be multiplied by $(v_{hw}/v_{ak})^2$ in order to obtain the desired value of $(v_{hw}/v_0)^2/(P/M)$. An expression for the proportion v_{hw}/v_{ak} can be obtained with the aid of the top diagram of figure 15. In the maximal tacking case, v_{ak} is the dashed line from the arrow point of v_{aw} and v_{hw} is the dashed line from the other end of v_{aw}. The two dot-dash lines from the ends of v_{aw} to the arrow point of er represent v_{hw} and v_{ak} for the maximal running case. v_{hw} for the running case equals v_{ak} for the tacking case and vice versa, so that the values of v_{hw}/v_{ak} simply are each other's inverse for the two cases. By applying Pythagoras' theorem that in a right-angled triangle the squares of the short sides are proportional to the projections on the hypotenuse:

$$(v_{hw}/v_{ak})^2{}_{tack} = (v_{ak}/v_{hw})^2{}_{run} = e_t/e^r = (1-\sin 2p)/(l+\sin 2p\ )$$

The limits for the characteristic $(v_{hw}/v_0)^2/(P/M)$ consequently are:

	$\cos k(l-\sin 2p)/(l+\sin 2p)$	when tacking
and	$\cos k(l+\sin 2p)/(1-\sin 2p)$	when running.

The conclusions arrived at with the aid of figures 13, 14 and 15 provide a fairly complete theory for the system kite-mass-hapa. It must, however, never be forgotten that this theory is based on some quite sweeping assumptions.

The complication due to a necessarily finite value of y, the angle of the towrope with the water, results in the difference between the v_{ka}-curves and the v_{hw}-lines in the diagram of figure 13 (and 12). In order to complete the picture a variation in y could be taken into account but this would tend to become a pernickety refinement. It is clear that optimal results, both as to velocities and small range of hapa characteristics, are obtained at minimal values of y, but improvement is largely related to $\cos y$ which is already close to its optimal value of unity at small angles *(cos* $y = 0.96$ when *tan* $y = 0.3$*)*.

The most sweeping assumption used is, however, that forces are always proportional to velocities squared. This is probably quite acceptable for the aerodynamical part where velocities are still very far below Mach one. The hapa, however, must travel through the water, which is some thousand times denser than air. The one direct advantage is that the hapa can be relatively small with an area that is only about one hundredth of that of the kite. But, on the other hand, its behaviour becomes more and more unpredictable by simple theory as speeds increase.

It is abundantly clear that there is a very exciting future in this type of sailing. There is no doubt that it will be possible to sail faster and faster in this way. Beyond the very attractive system of kite-man-hapa in figures 11 and 12 there already looms the vision of a very robust glider attached to a hapa, both with a lift/drag ratio of around 10. It can be done!

It is, however, also abundantly clear that this development can only be achieved by concentrating a lot of effort on evolving the right hapa and that this is primarily in pursuit of an elusive stability. The moon was also clearly visible, but rather a lot of effort was needed to get there.

SEADOGS FOR MONOHULLS

by Paul Ashford

Recent AYRS interest in hapas or paravanes has been aimed at high speed sailing with esoteric craft or gliders. My recent model experiments suggest they could be applied with benefit to more ordinary sailing boats. For this purpose we need an obedient device which will pull strongly to windward like a dog on a lead smelling a rabbit, or drop back to idle at heel on command. Didier Costes uses the apt name Chien de Mer, which translates as Seadog.

The basic ideas have been around for a long time. Professor J.G. Hagedoorn is an early exponent of the Hapa. AYRS Airs No 2, April 1972, p. 27 published his letter pointing out that foils to windward should be curved for stability, with further advantage from a hinged arm. In Airs 8, March 1974, p.51, Harry B. Stover suggests adding stability by a rope suspended foil, reversible for use on either tack. His sketches show a flat foil, with stability depending on weight and buoyancy of the supporting float. Didier Costes has since the 1960's produced practical seadogs using the stability of a curved foil. His elegant Chien de Mer 1989 is shown in AYRS 108 May 1991, p. 17.

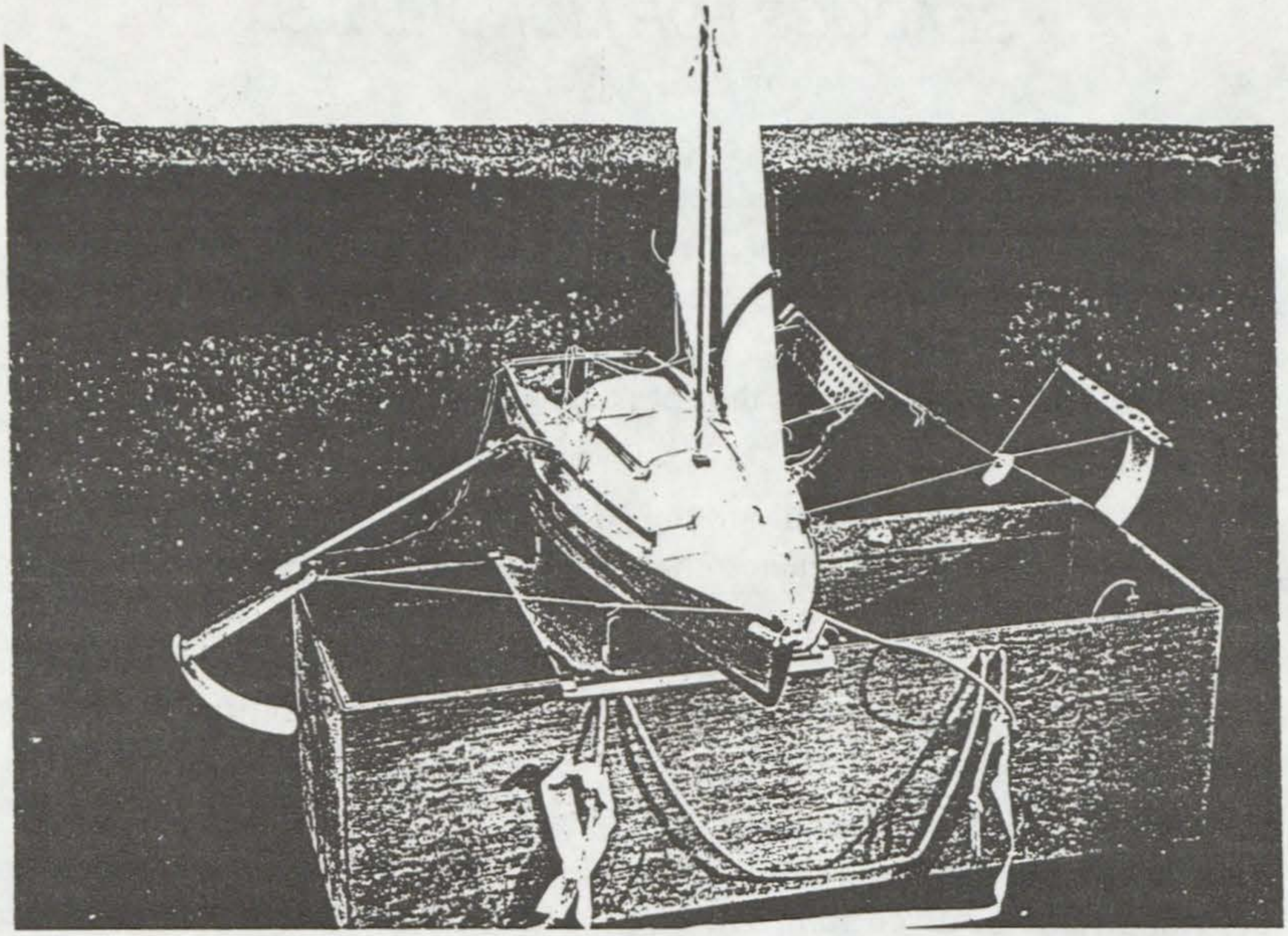
In 1986 I did some crude experiments to develop a stabilising paravane, reported in AYRS 107, p.17. The resulting model device looked so unfriendly to tow or stow that I returned to my original idea to turn my yacht Shalimar into a foiler. My foiler model experiments were reported in AYRS 106. Being daunted by the engineering effort needed and the capsize risk, I decided not to apply the results at full scale, but to try the model with seadogs.

SHALIMAR prototype statistics

Hull length 23'-6". Waterline length (LWL) 22'-3". Beam 7'-3". Draft 1'-10"/4'-3". Sail areas, square feet. Main 140. 1st reef 104. Working jib 69. Cruising displacement about 3600lb. Displacement length ratio 145. Ballast keel and centreplate 610lb. Inside ballast 240lb. Self righting from 135°. More details in AYRS 106.

Model details

The model is 1/8 scale, accurate in dimensions and weight, but not quite as stiff as the prototype as the mast is too heavy. There is radio control of the steering only.

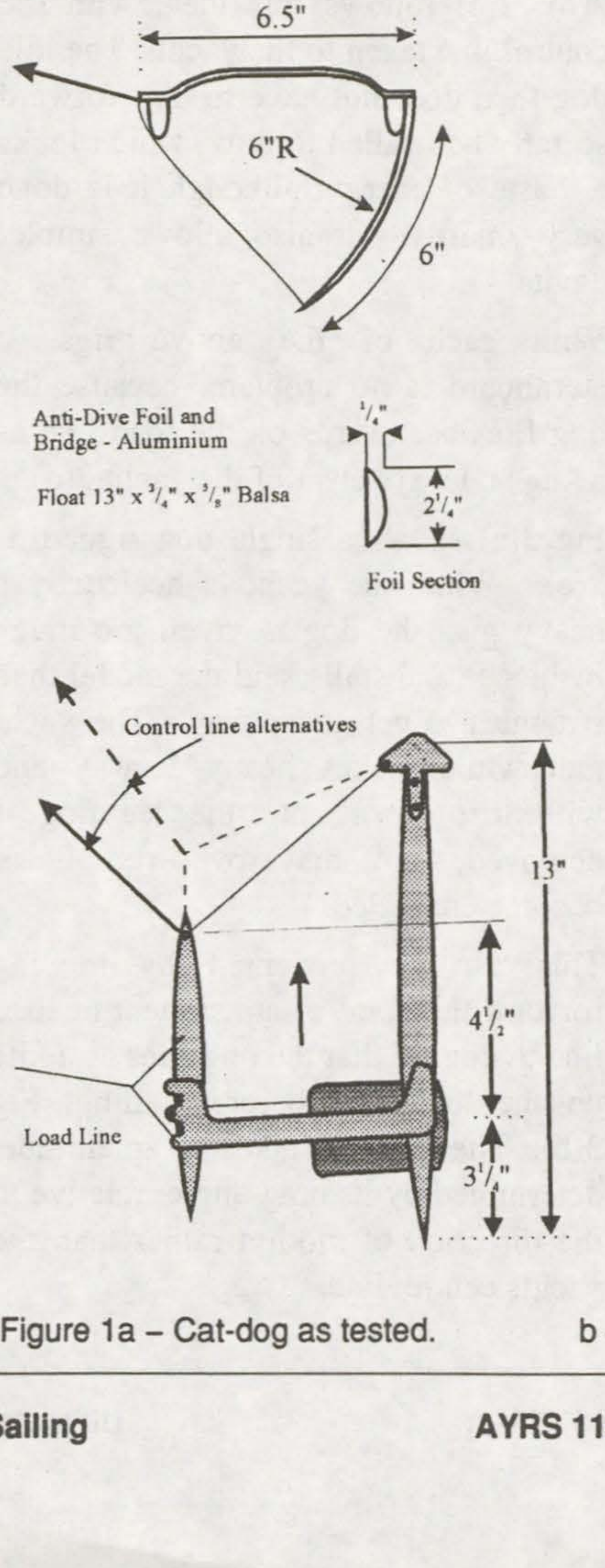


Model Tests

Tests started in Oct. 1991 with a new seadog linked with a cats cradle of string to the model hull and mast. For later tests the model was given pegboard davits so that points of attachment by toggle could be easily changed and recorded. About 8 variations of seadog, using identical main foils, have been deployed in various ways. The two most successful seadogs are shown in photograph 1.

From the outset of tests it was obvious that a seadog was a powerful stabiliser. So much so that the yacht could sail at 20° heel with one dog in a wind strength which would knock it flat if put about. For this reason, as well as for convenience in short tacking, one of my aims was to be able to sail the yacht with dogs deployed to port and starboard, with automatic transfer from idle dog to duty dog on tacking or gybing.

All the seadogs tested have been connected to the yacht by two lines. The aft "load line" conveys the main working load to the yacht. The forward "control line" is used to alter the incidence and loading of the seadog, to send it "to heel" when not needed, and at full scale should provide a means of bringing it alongside and on board without stopping the yacht. Their use is first illustrated for the type of seadog shown in Fig. 1(a). This I call a cat–dog, as the foil is mounted on a small catamaran. Lines are attached to the float nearest the yacht, which is roughly on the axis of the cylinder on which the curved foil lies. This prevents the foil lifting or diving whether towed by the load line, control line or both. When working hard this float can be lifted off the water without instability. The small anti–dive foil on the outer float has never appeared necessary when sailing the model and dog. Tests manually towing the dog alone have caused a dive without this foil, but with it the dog is stable up to my running speed, equivalent to a prototype speed of over 15 knots. The cat–dog has proved versatile and well behaved, except that the tow lines can wind around the projecting float ends. This could be prevented by connecting the floats by a bridge at each end as Fig. 1(b), with the forward one angled as an anti–dive foil. Although not yet tested, I have shown this in the diagrams of observed cat–dog behaviour, as it is simpler to draw.



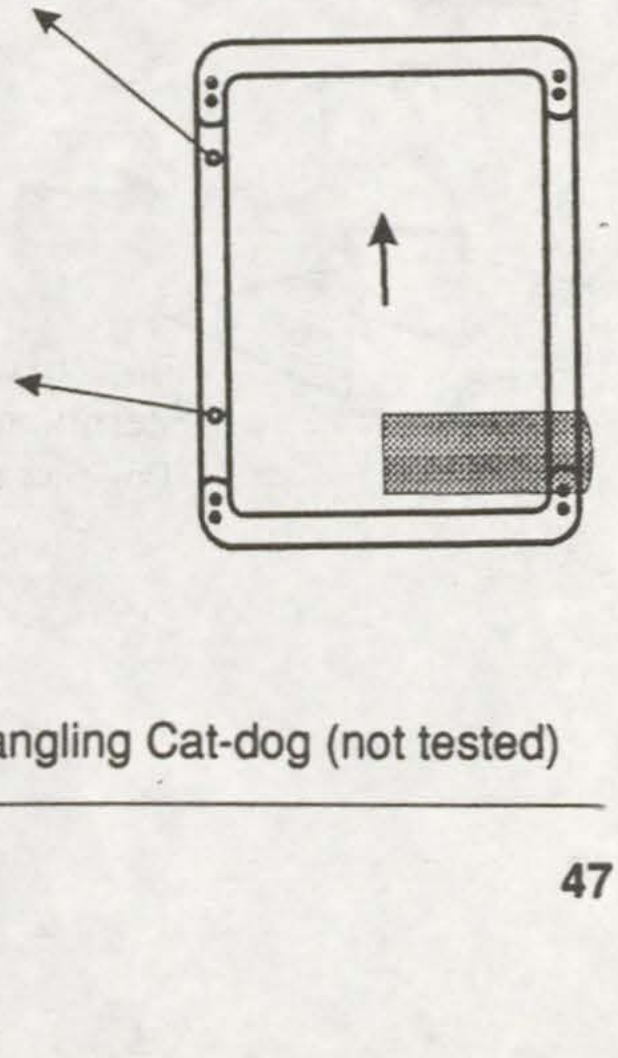


Figure 1a – Cat-dog as tested. b – non tangling Cat-dog (not tested)

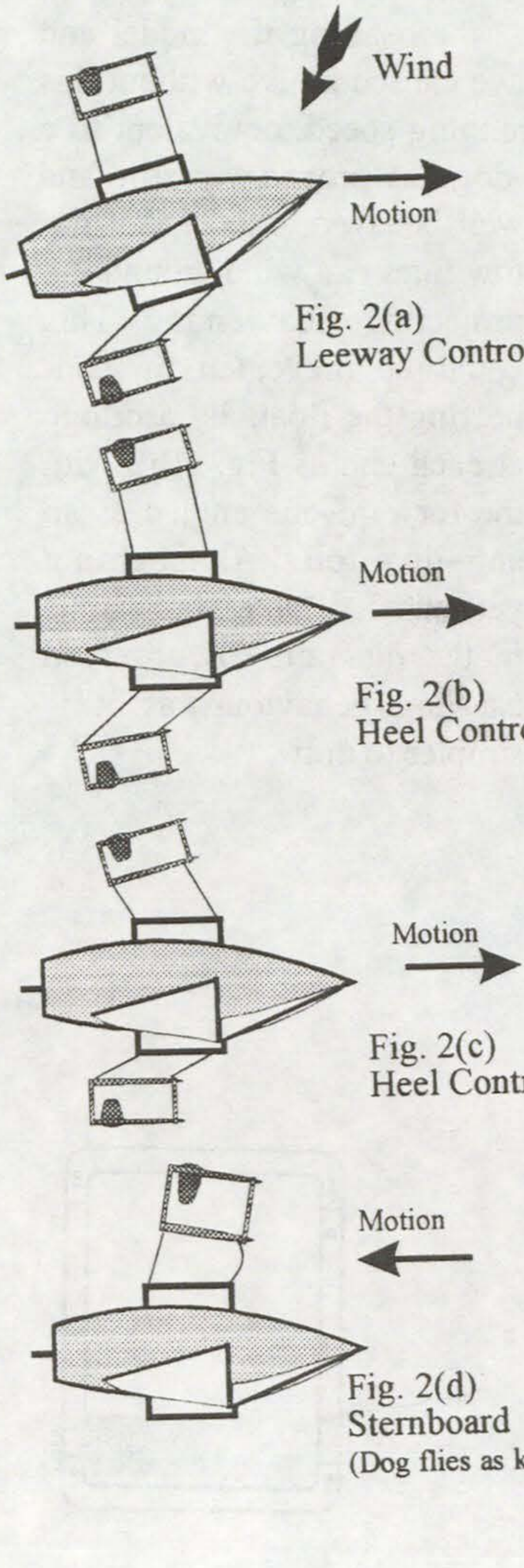


Fig. 2(a)
Leeway Control

Fig. 2(b)
Heel Control

Fig. 2(c)
Heel Control

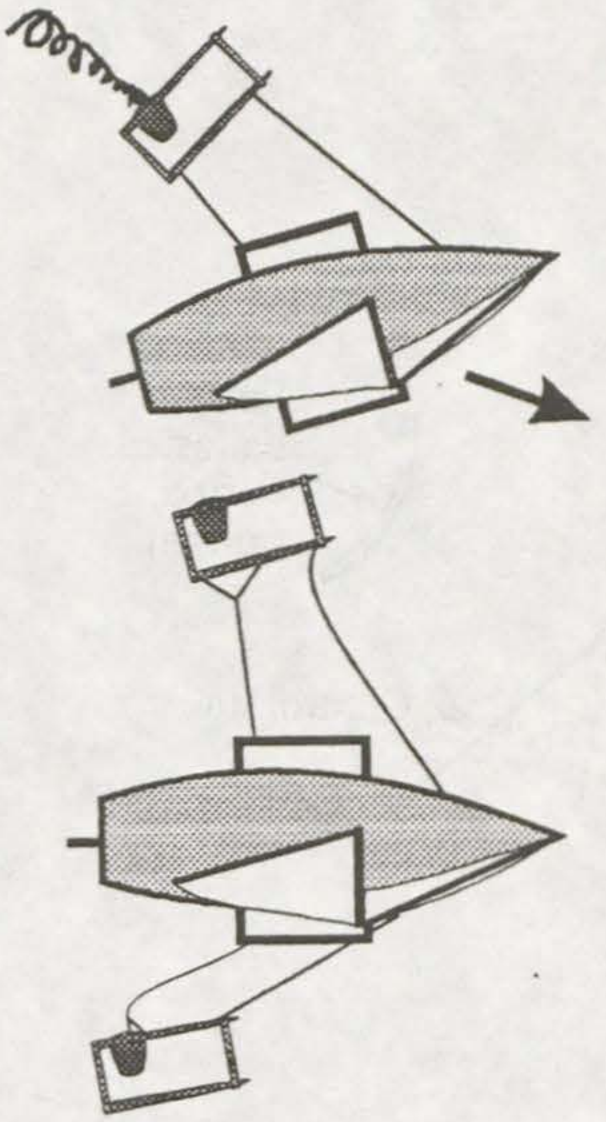
Fig. 2(d)
Sternboard
(Dog flies as kite)

Fig 2(a) shows the dogs connected to points parallel with the yacht axis. Foils stay parallel with the yachts centreline and are leeway activated. At full scale fine tuning would be possible by adjusting the control line. If the control line is attached to the yacht lower than and/or inboard of the load line automatic incidence control of the foils occurs as the yacht heels, as Fig 2(b). 2(c) follows this idea, with the control line taken to the yacht. The idle dog then does not have to dart forward so far when called to duty, which looks a waste of energy, although it is done very smartly. It also allows simpler davits.

With each of the above rigs, a sternboard is no problem, because the dog flies backwards on the load line as a kite and stays clear of the yacht,2(d).

Fig 3(a) shows a single dog rigged as 2(c). When the yacht is heeled by a heavy gust the dog is given too much incidence and stalls, and the model then struggles to get under way. The yacht meanwhile makes heavy leeway and will drift down onto the lee dog if deployed, and may over-run it or become entangled.

This can be prevented by moving forward the point of attachment of load line to dog, so that the dog flies as a kite on the load line before stalling, Fig 3(b). The dog then takes up an attitude, determined by its drag angle, relative to the direction of motion rather than the yachts centre-line.



If a gust induces heavy leeway the dog will actually pull forward of the beam and quickly get the model sailing. The only disadvantage is that if the yacht makes asternboard the dog will swing forward and hit the bow; in practice the model has never made a long enough sternboard for this to happen.

The two floats of the cat–dog are so much parasitic drag. My most refined one scales up to a prototype length of 8.6ft and a weight of 125lb. This gives plenty of scope for slimming at full scale. The float nearer the yacht should be light to lift off the water, buoyant not to be overrun, and resilient not to damage the yacht; inflatable? Stowage on board remains a problem, even with pantograph cat or foil to hinge under.

Single float dogs therefore appear attractive; the experiments started with the dog shown in Fig 4, connected to the yacht effectively as Fig 2(b). Note that for stability the bridle legs must converge beyond the axis of the foil cylinder, and that this condition must still apply when the lines are inclined forward to depower the dog. An additional allowance is necessary because the control line takes part of the load off the bridle. The control line is inclined downward relative to the load line, and this causes a pitching couple depressing the front of the float, requiring a large and buoyant float. (I later realised that Didier Costes had solved this problem by bringing bridle legs and control line through a common point, see AYRS 108 p.17). The tail fin seemed necessary to get this dog to take up load if the tow lines got too far forward. This dog became the first cat–dog by addition of a bridge and small inner float and discarding the tail fin; an improved and smaller cat–dog followed. These were used together.

The last dog made was essentially a cruder version of Didier Costes' chien de mer, see Fig 5(a). Stops on the load line, which slides through an eye where the bridle converges, allow it to be used in the same way as the kite flown cat–dog in Fig 3(b). This appears to give the best performance so far in straightforward sailing.

Fig. 5(a) Chien de Mer

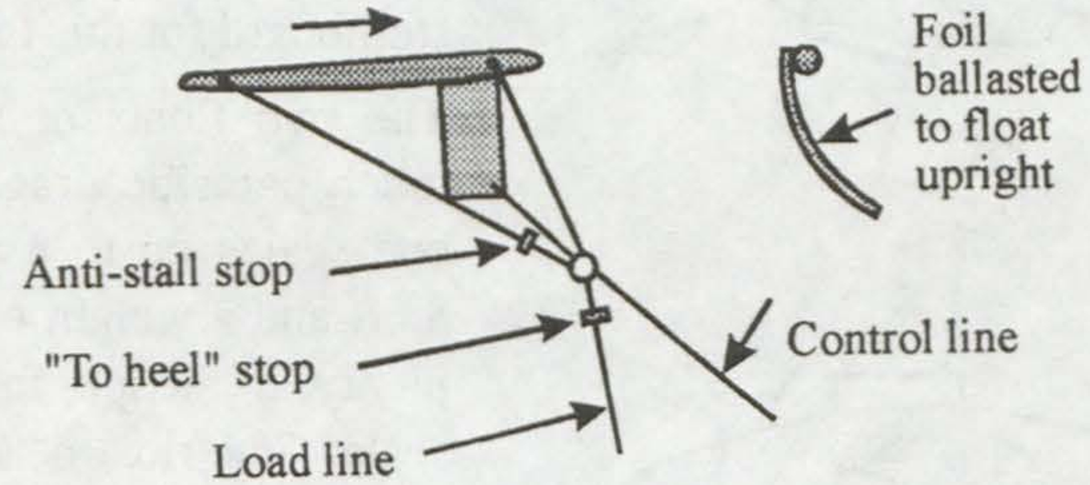
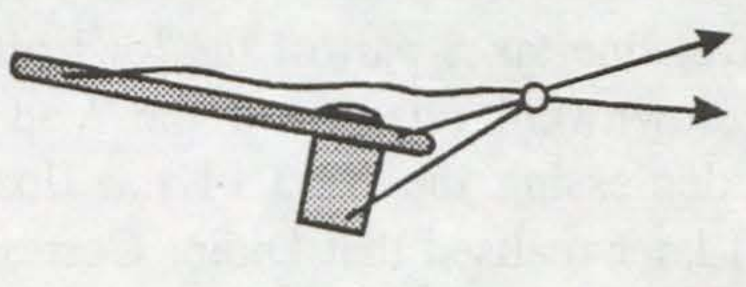


Fig. 5(b)



Figures4 5a & 5b

However, if it gets in the wrong attitude with the lines toward the back (Fig 5(b)), it does not sort itself out when towed, as the cat–dog does. To cure this I replaced the top bridle leg with a stiff wire hinged to the float, adding a small self aligning planing float to lift the wire off the water. This version is shown in the photographs. Unfortunately, while curing the original problem the additions encourage entanglement with the yacht davits etc, if driven onto the dog to leeward.

All the dogs have used the same size and design of foil, as in Fig 1(a).

The following test statistics are translated to prototype scale:

Typical position of attaching load line of kite rigged dog:

Distance from water line entrance	14.5 feet (65%LWL)
Distance off centreline	5.7 feet
Height above waterline	5.3 feet
Distance from centreline to dog foil when under load	17 – 19 feet
Yacht stub keel	5.0 square feet
Centre board	4.4 square feet
Total keel area	9.4 square feet
Dog foil	6.0 square feet

Steering balance

There is some latitude in the fore and aft point of attachment. The best point is difficult to judge as the radio control gives no helm feedback. Ideally it should be moved aft as the sheets are freed.

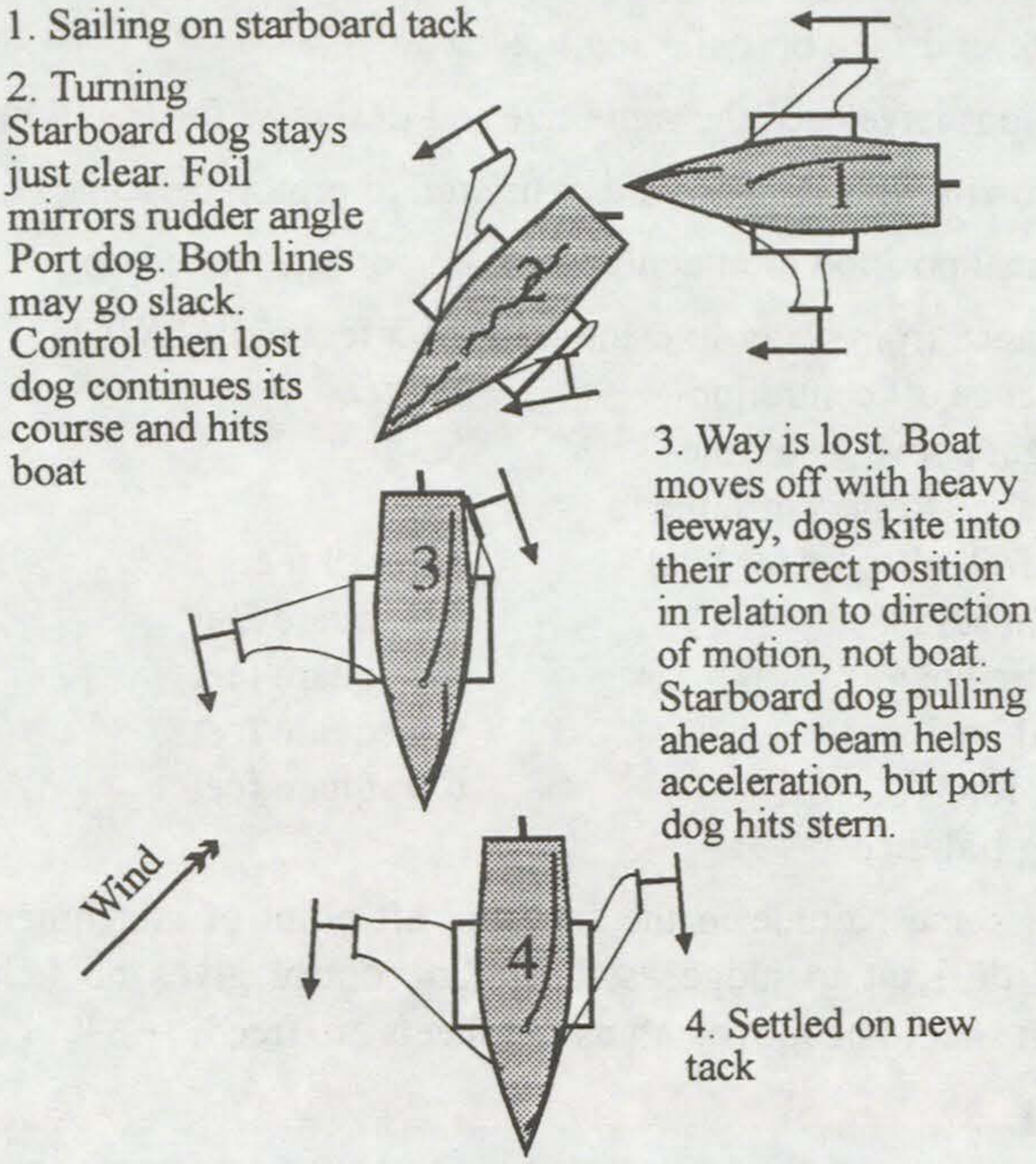
Stability

The increase and robustness of stability was most striking. The model has yet to suffer a complete knockdown with a dog properly deployed from the windward davit. Shalimar needs 1 reef for F4 (5kt model, 14 prototype). With a single seadog the model could sail under single reefed main and jib with the wind before the beam heeled 20° in 15kts of wind (proto. 42 kt. F9) and survive 20kt. gusts. As the wind force varies as the square of its speed this indicates a nine times increase in stability!

Speed

Timed runs in a wind rapidly varying between 5 and 18 knots with radio control in one hand and a stop watch in the other are not easy, but I am reasonably sure that the model has exceeded 3kts (proto. 8.5, $V/\sqrt{L} = 1.8$). This with the first cat–dog, single reefed main and jib. Subsequent tests have concentrated on manoeuvrability.

Fig. 6 Dog behaviour on tacking



Tacking

I wish I could report that I have been able to tack with two dogs without either hitting the yacht, but I cannot. The drag of the outside dog slows the turn, and may prevent a tack altogether. Given a favourable wind shift when head to wind the tack can be completed as shown in Fig 6. and described below:

Sailing on port tack.

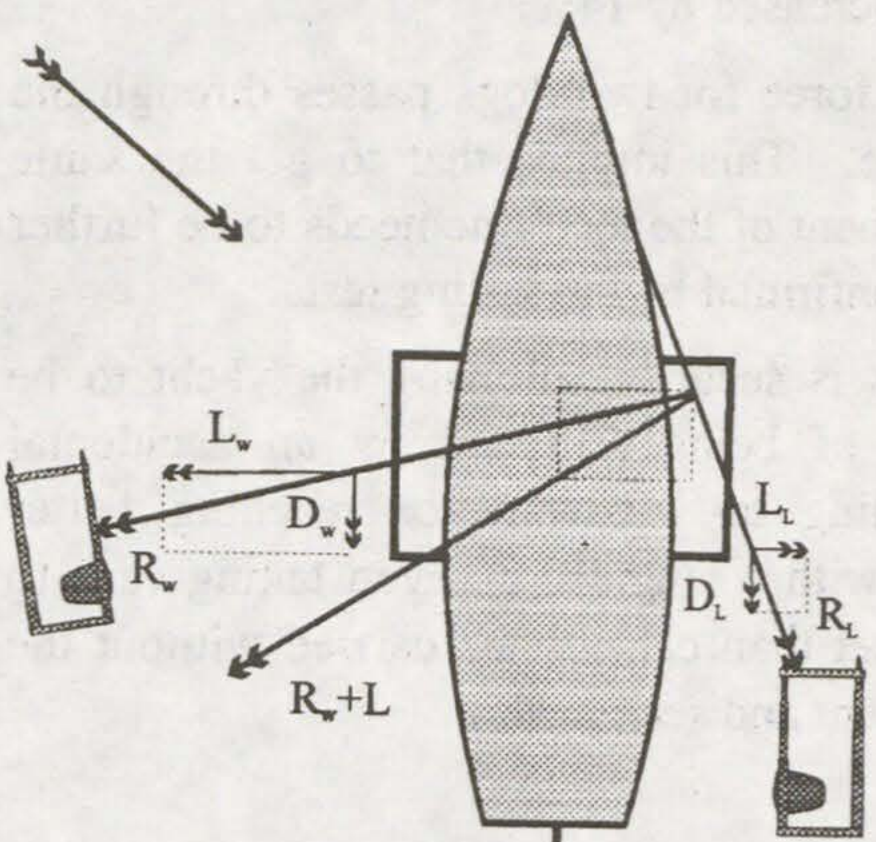
2. Turning. Starboard dog stays just clear, foil mirrors rudder angle. Both lines of port dog may go slack. Control is then lost, dog continues its course and hits boat (remedy, slack–rope–operated spoiler/rudder?).

3. Way is lost. Boat moves off with heavy leeway. Dogs kite

into their correct position relative to direction of motion (not centre line). Starboard dog pulling ahead of beam helps acceleration, but port dog hits stern.

4. Settled on new tack.1.

Fig. 7 Lee dog penalty



Shows windward load line and lee control line, rigged as Fig. 2(b).

Gybing

With no ability to square off the sails the model is a little reluctant to bear away onto a run. Once running it can by gybed without either dog touching the hull. The previous lee dog "catches" the yacht quickly with no more heel than the usual monohull gybe lurch, in winds strong enough to flatten the model without dogs.

Leeway

With a single dog properly trimmed leeway of the main hull could be virtually eliminated even when sailing to windward. The performance was then not obviously different whether the centre–plate was up or down. From this I conclude that seadogs can probably be used to improve performance of fixed keel yachts.

Lee dog penalty

Fig 7 shows the performance penalty for deploying two dogs.

L = lift, D = drag, R = resultant, Suffix $_W$ = windward. Suffix $_L$ = lee

From estimates of observed drag angles

$L_W = 4 x D_W$ $\quad$ $L_L = ½ D_L$

D_L is less than D_W because the lee foil is unloaded and less induced drag.

At a guess D_L = ½ DW

then $L_L = L_W/8$
$L_{W+L} = (1 - 0.125)\ L_W = 0.875\ L_W = 3.5\ D_W$
$D_{W+L} = 1.5\ D_W$ $(L/D)_W = 4$
$(L/D)_{W+L} = 3.5/1.5 = 2.3$

This, which may be based on optimistic assumptions, is a serious degradation of the lift/drag ratio. Note also that to get the same net lift and righting moment foil area must be increased by 14%.

Fig 7 also shows that the resultant force for two dogs passes through the yacht centreline aft of that for one. This implies that to get the same steering balance the point of attachment of the load line needs to be further forward with two dogs. This was confirmed by the sailing tests.

The benefit of deploying two dogs is security, allowing the yacht to be driven very hard without danger of being flattened by an accidental puttingabout or gybe. For sailing to windward or reaching better performance will probably be got with a single dog, even taking care to reef down so that no more sail is set than can just be carried without the dog. This will require good judgement and seamanship.

Dogger/Foiler Comparison

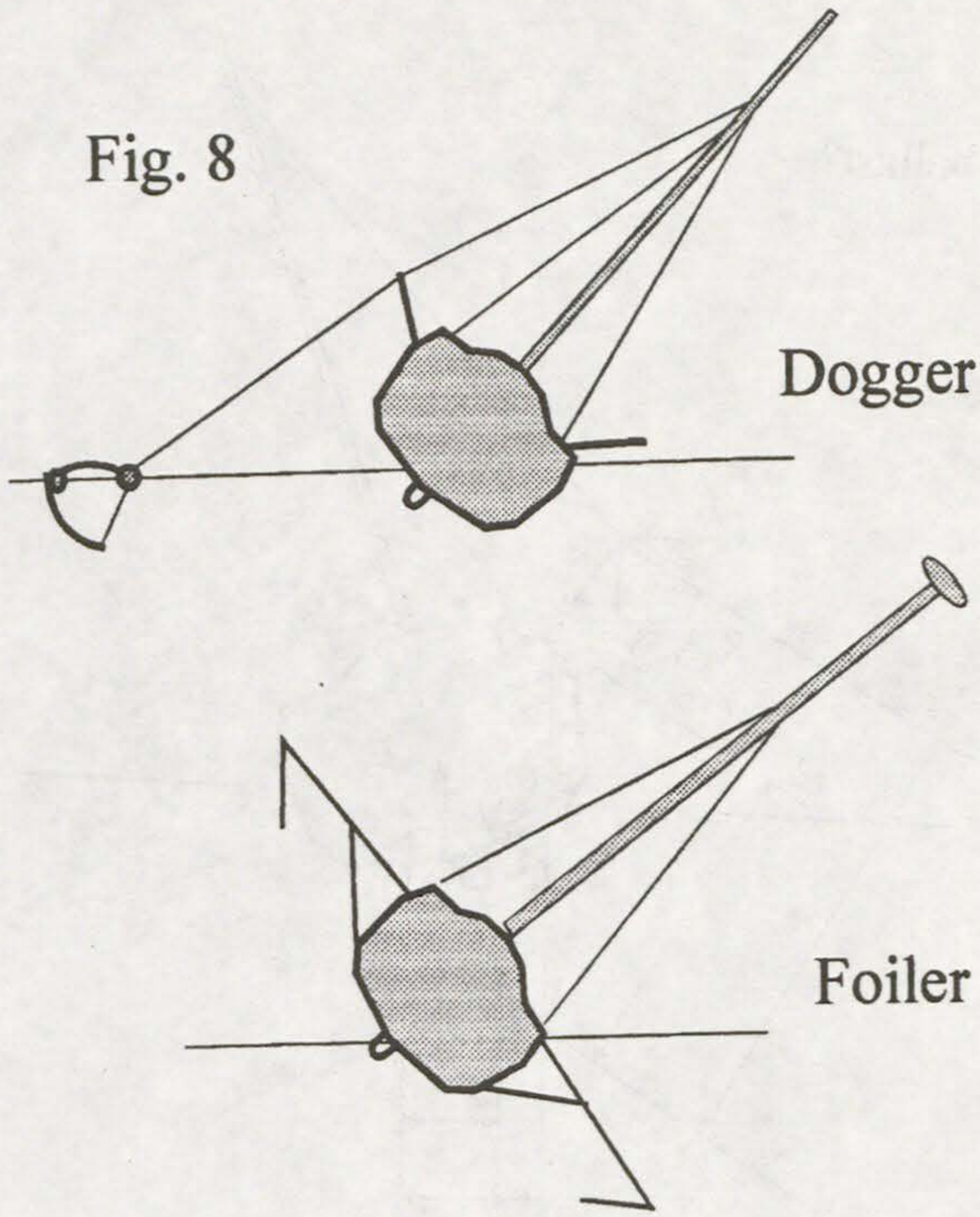
Dogger advantages:- The dogger has more robust stability which grows through heel angles large enough to shed the wind loading on the sails (Fig. 8(a)). The foiler at (b) at the same angle is being tripped by the foils and likely to capsize to at least 90°, or 180° if it has no masthead buoyancy. Its draft is increasing, and in shallow water it could end up with foil and masthead stuck on the bottom.

The dogger can give faster sailing with a smaller foil area, because the foil is always fully immersed, and can be worked further from the centreline.

In the foiler tests (AYRS 106), the areas of foils tested varied from 13 to 18 square feet (prototype equivalent); all were at times driven under to capsize. All the seadogs had foils of 6 square feet.

Fixed foils will only work on a suitable hull, preferably without a keel, and light enough to accelerate away in a gust rather than submerge its foils. The relative proportions of foil and hull must be right. Seadogs can probably be applied to a much wider variety of hulls, including self righting keel yachts. The foil size may determine the amount of performance gain, but is not critical to whether the dogger works at all.

Fig. 8



Foiler advantages

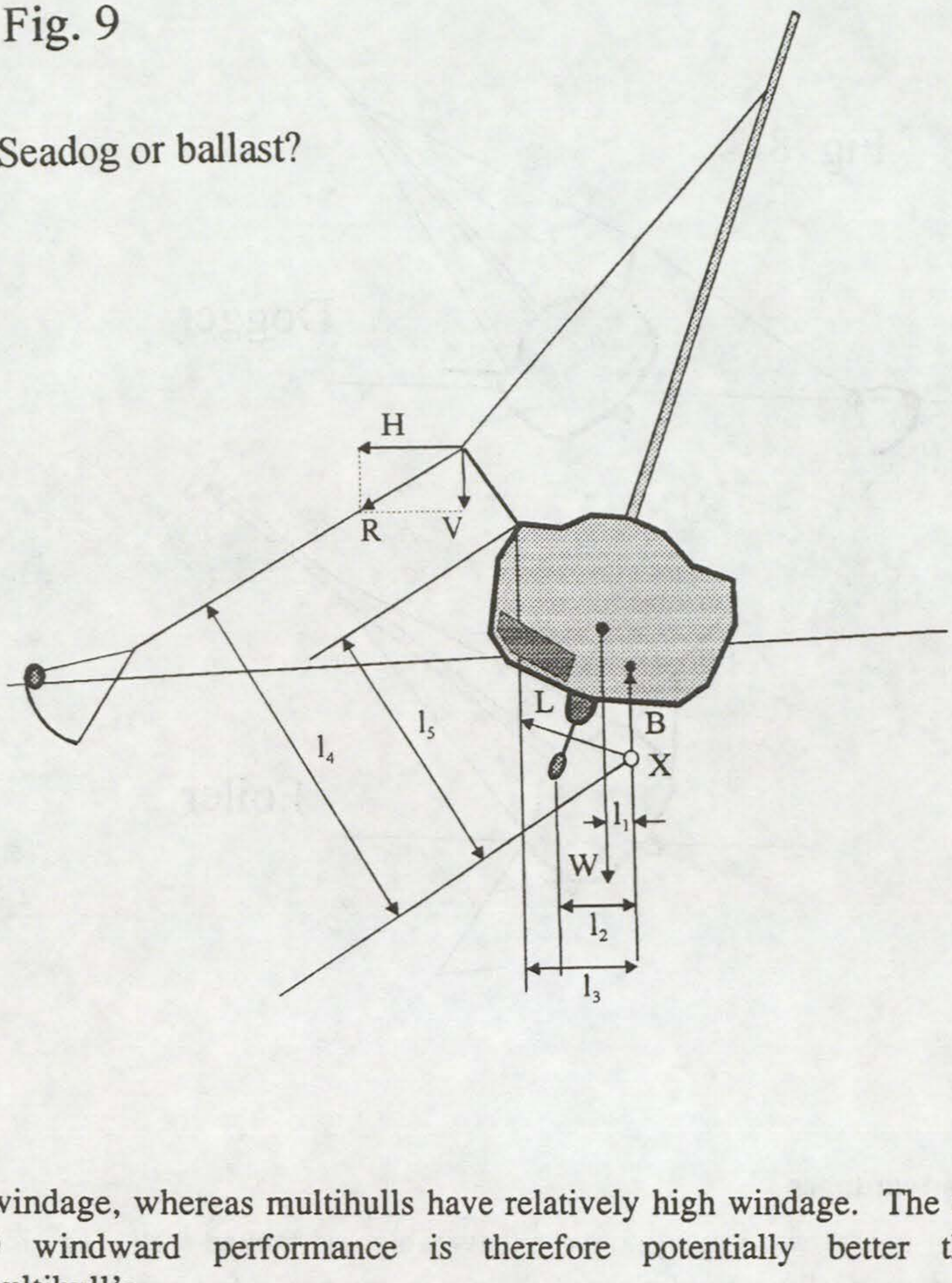
The foiler model was much more manoeverable and tacked well. The idle foil is automatically carried clear of the water, but ready for immediate use on gybing or tacking. The foiler's theoretical advantage of lee foil lift did not show up in higher speed in the model tests.

Dogger versus multihull

Seadogs can probably help monohulls sail faster and more upright, benefits normally associated with multihulls, while retaining the ability to use normal marina berths. A deployed seadog adds very little to the monohull

Fig. 9

Seadog or ballast?



windage, whereas multihulls have relatively high windage. The doggers' D windward performance is therefore potentially better than the multihull's.

Seadog versus ballast

Fig 9 shows why a seadog is a very effective way of adding power to carry sail. Starting with a yacht of weight W sailing at around 20° of heel, we can add ballast or a seadog. Any of these will increase the buoyancy force B, and may change the keel or centreboard lift L, but we can eliminate these by taking moments about their intersection at X. We can add bulb keel ballast at lever l_2, movable water ballast or additional crew to sit on the deck at lever l_3, or fly a seadog at lever l_5. l_5 is about 4 times l_2, therefore the dog pull R need only be a quarter of added keel weight to achieve the same stability. Displacement and its drag will be increased 6 to 8 times as much by added keel ballast as by the vertical component of dog pull V. Movable water ballast in the bilge is only a little better.

The penalty is induced drag of the dog foil. But the horizontal component H of its lift reduces the keel lift needed. The dog foil is more inclined than the keel, but can be a highly efficient asymmetric section. The net increase in induced drag should be small.

Even attaching a seadog to raised topsides, lever l_4, could be worthwhile. I suspect that attachment high up the mast, as has been proposed from time to time, is for smooth water only.

Ballast and gravity act constantly. Dog pull $R = 2.77 \times C_l A V^2$, where R is in lb, A is foil area in square feet, and V is in knots. We can get a reasonable lift/drag ratio at a lift coefficient Cl up to say 0.8. 6 square feet of foil can then give the following:

Speed kt	5	7	9
Foil pull R lb	332	652	1078

Attachment

Fig 10 shows some simple ways of attaching a seadog. Ropes abc allow fore and aft adjustment. be is an optional strut universally hinged at e. Note the increase of lever arm between Figs. (b) and (c). For angles of heel beyond Fig. (c), without the strut ropes ab or bc collapse and the lever arm reduces. In model testing the davits gave quicker recovery from extreme angles of heel than an all string rig. At model scale storm force gusts are relatively frequent. The all rope rig should be satisfactory at full scale, at least for initial trials.

SUMMARY

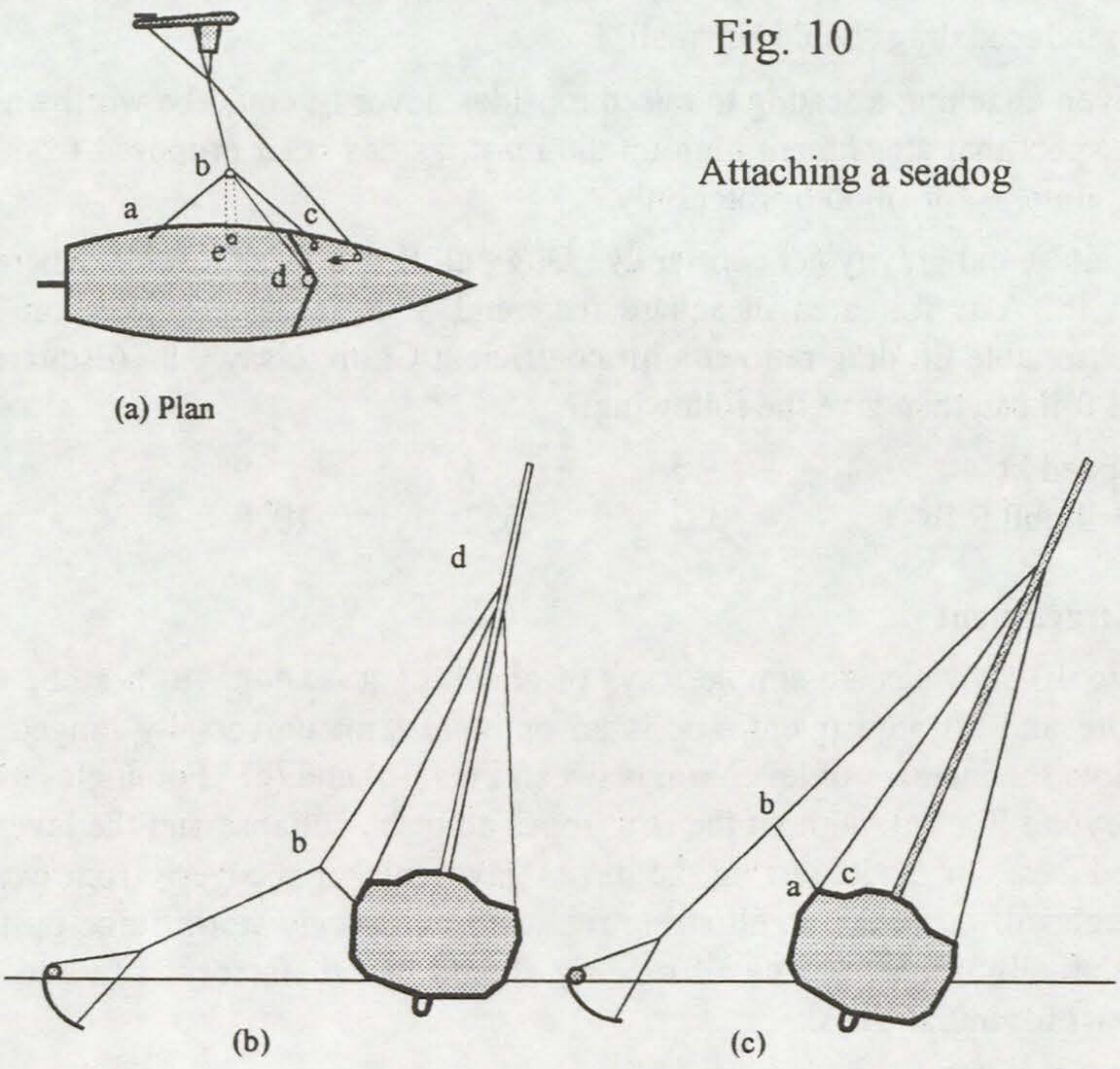
Model tests and theory suggest that seadogs can be used to enhance monohull performance, and give more comfortable upright sailing. The foil size tested may give more stability than can safely be used with a single dog to windward, as accidental putting about or gybing can cause a knockdown. A second dog to leeward can guard against this, but the penalty is reduced efficiency. More conservative use of a single smaller dog may give worthwhile gains in performance.

Where next?

I intend now to move from small scale models to prototype tests. I shall probably start with a dog foil area of 2 or 3 square feet, rather than the 6 square feet modelled. This will minimise as yet unsolved problems of stowage and deployment while allowing realistic tests of control, and measurements of dog pull and drag angle. It may well be big enough to give a worthwhile gain in performance.

Fig. 10

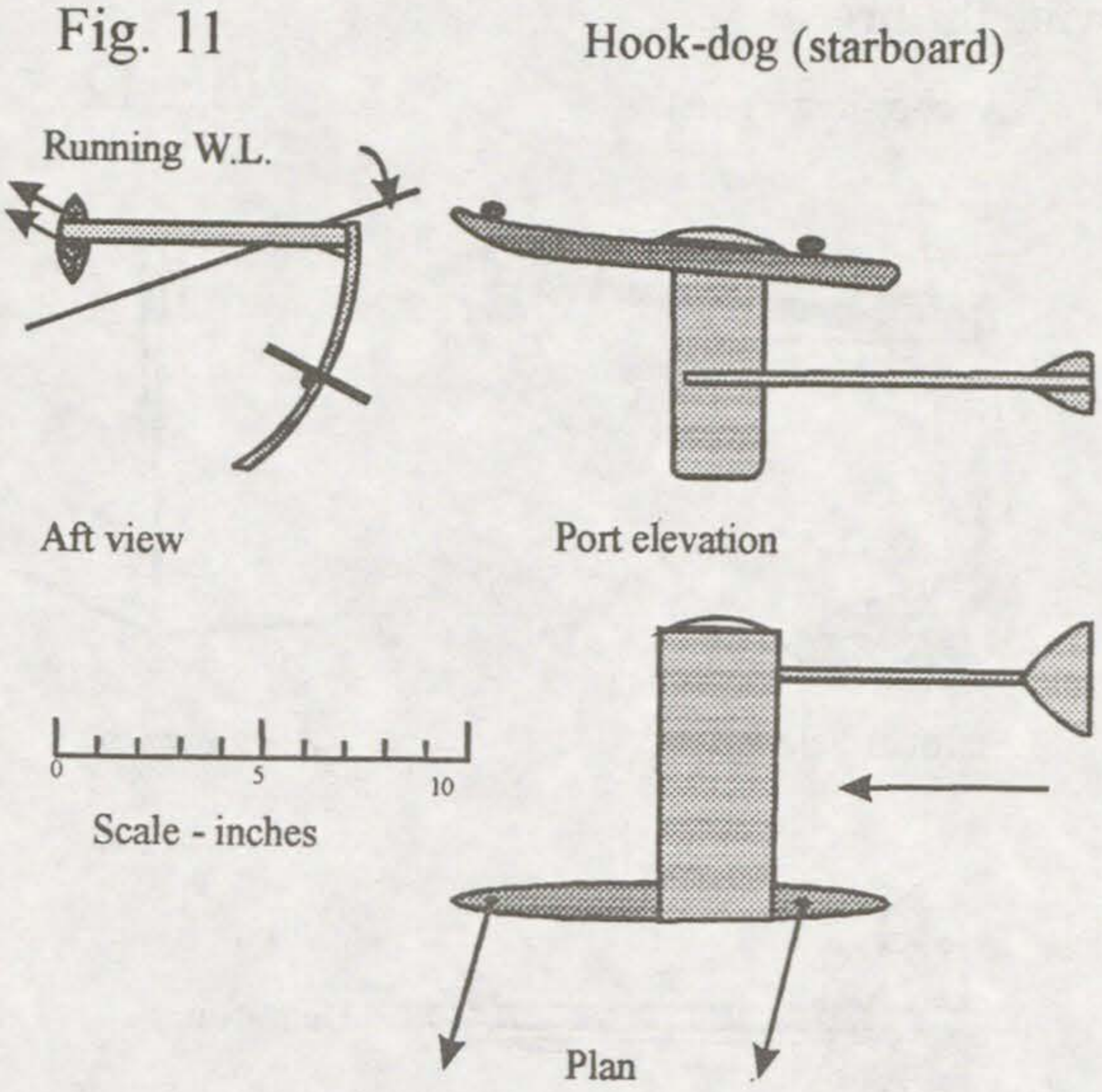
Attaching a seadog



Join the fun

It needs relatively little effort to make and attach a small seadog to a sailing boat in the dinghy size range. I hope that AYRS members will join me in this line of research. It might just be the next breakthrough for light displacement fast cruising. *June 1993*

Fig. 11



P.S.Health Warning – Seadogs in Waves

Towing the model dogs from the full–sized yacht has exposed them to more speed and wave action than previous tests in the model yacht pond. The cat–dog in Fig 1(a) was first kite rigged as Fig 3(b). Towing on 4 foot lines through wind wavelets and motor cruiser wash at any speed over 2kt (5.6 proto) produced some very erratic behaviour, including leaps and aerial back–somersaults and rolls. The dog is readily displaced in yaw by small waves, causing snatching. Just as a waterskier swings in a wide arc behind his tow boat to get maximum speed at a jumping ramp, so the dog can swoop above the tow speed and leap off a wave. Switching to parallel line towing as Fig 2(a) had a calming effect allowing smooth towing without leaving the water up to 4.4 kt (12 proto) both under load and to heel. Between 1.8 and 4.4 kt a drag angle of 12° was achieved (L/D = 4.7).

My version of the Chien de Mer, Fig 5(a), was towed with disappointing results. Apart from being inherently kite rigged, with tendencies described above, other problems were revealed. Because centres of buoyancy and gravity are aft of the foil the dog can run in 3 modes:

1.Level, as intended

2.Head–up with the foil part out of the water and the tail dragging on the surface

3.Head–down, dived, with body floating up and preventing recovery.

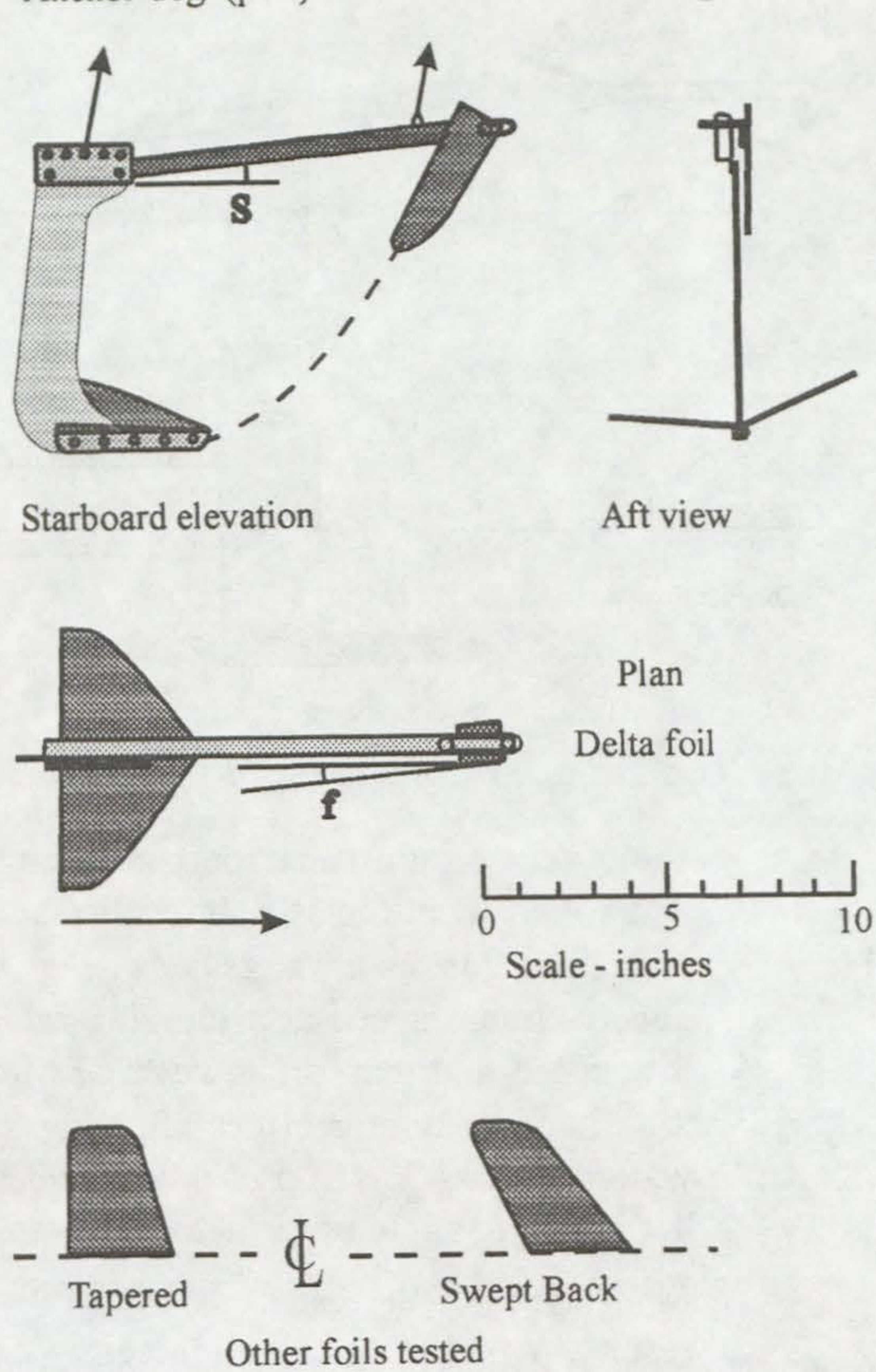
Waves trigger switching from mode 1 to 2 or 3. In spite of adjustments to the bridle this dog did not work at speeds above 1.7 kt (4.8 proto). Previous satisfactory tests with the model yacht were in relatively light winds and smooth water. *July 1993.*

P.P.S. Four months on – improving the breed

Several new model dogs have been made and towed under power, the latest having much improved behaviour.

Cat–dog was followed by hook–dog, Fig 11. This runs with the float lifted off the water. The foil is stabilised in pitch by a submerged tail, and its curvature causes it to follow a wave profile. A stronger bridge eliminates need of the underwater stay line which adds resistance and would collect seaweed etc. The float has to extend forward to the foil to allow the contro 1 line to operate, and with the tail the total length is greater than the stabilising length in the water. Stowage would be awkward. In waves behaviour was better than the cat–dog, but the flat bridge foil caused som l line to operate, and with the tail the total length is greater than the stabilising length in the water.

Fig. 12



Stowage would be awkward. In waves behaviour was better than the cat–dog, but the flat bridge foil caused some wave slap and splash. Fluctuations in line pull were considerable as the foil immersion varied. This encouraged a completely new approach with a submerged main foil.

Anchor–dog

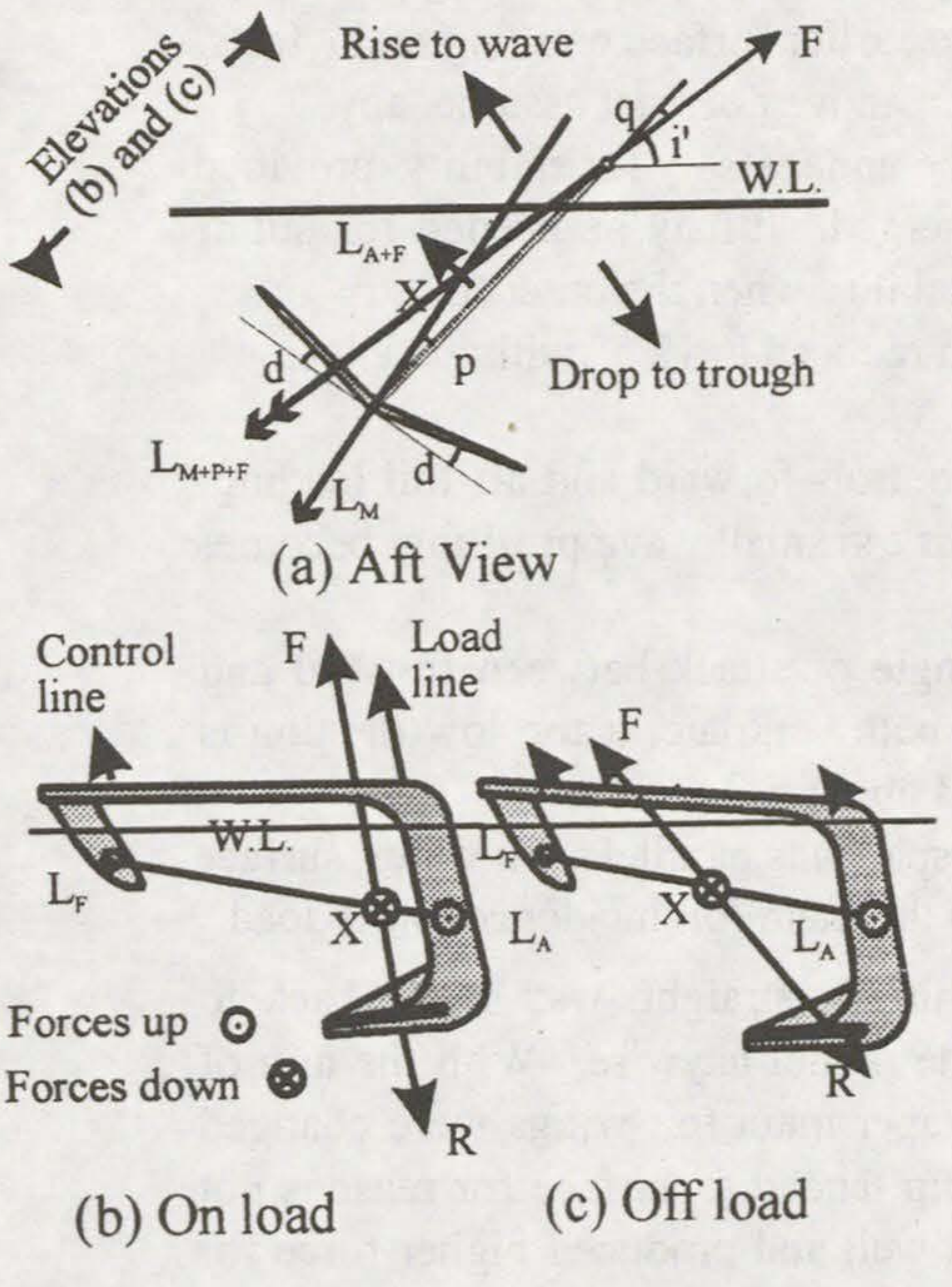
So called because it looks like an anchor. Fig 12 shows the last model tested. It comprises a submerged main foil supported by an offset surface piercing aft foil and a small forward foil. The aft foil must have its centre of effort behind the main foil's line of force. The forward foil is given a higher angle of attack than the aft foil, the difference being f.

Fig 13 shows how it works. L denotes lift and suffices M,A & F refer to the main, aft and forward foils. F is the resultant force of the load and control lines resolved in the plane of each view. View (a) shows the aft foil inclined toward the yacht by an angle p to offset the line attachments relative to the plane of symmetry of the main foil. The three foil lifts can be resolved into a resultant through X directly opposed by F. If the angle q changes F no longer passes through X and a couple is set up which rolls the dog to restore q. The heeling angle of the dog is therefore controlled by the inclination of the lines i'. In elevations (b) and (c) R is the resultant of the lift of the main foil and drag of all three foils. The resultant of F and R, equal and opposite to L_{A+F} in view (a), is the fulcrum about which L_A & L_F must balance. If L_F is too big the dog yaws left and rises to a new waterline where L_F is proportionally smaller, if too small the reverse occurs. The same action allows it to negotiate waves and troughs. The main foil is steered sideways with little change of incidence, and the rapidly changing forces of L_F & L_A are nearly at right angles to the plane of the towing lines, so waves cause relatively small changes in F.

On shortening the control line the angle of attack and lift of the main foil reduce and the forces adjust as shown at (c), with the aft foil at very low incidence. X is raised and q increases to suit. The above is somewhat simplified, as an additional side force can occur from a yawed main foil. Its significance depends on the dihedral angle d.

Fig. 13

Forces on Anchor-dog (port)



Model & performance

For ease of making and adjustment the model is all aluminium and therefore a sinker. As soon as way is on it turns outward and rises to the surface. At speeds over 2 kt. the spar is lifted clear of the water. The dog runs very cleanly with little wake and spray (happily for the crew as dog will be up–wind of the cockpit).

Its ability to profile waves keeping the main foil submerged is excellent. The cat–dogs rely on gravity to drothe front foil into a trough; at some critical speed this is not fast enough and they take off. The front foil of anchor–dog is moved by foil forces which rise as the square of the speed, and the faster it was towed up to the yacht's 7½ knots maximum the better it followed the wave profile. It is also better than hook–dog because the forward foil gives the main foil advance warning of the next crest or trough.

The model is adjustable and the following variables have been investigated.

- d. (fig 13). Dihedral angle. Initially set at 23° to approximate the curvature needed by the earlier surface piercing main foils. The analysis of forces given above does not assume any dihedral and it appears to be unnecessary for stability provided he main foil is fully submerged. It may be needed for initial hook on and to maintain stability when the outer foil tip surfaces. It has so far been reduced to 12.5° without adverse effect.
- p. (fig 13). Offset angle. Controls forward and aft foil loading. If too large foils ventilate, if too small wave profiling becomes soggy. 10° about right.
- f. (fig 12). Difference in angle of attack between forward and aft foils. If too high they both ventilate, if too low the dog is slow to rise to waves. 3° is about right.
- s. (fig 12). Spar angle. The spar runs parallel with water surface with s 5.5°. This indicates the main foil incidence under load.

Foil plan forms. The forward foil, initially straight, was swept back to throw off floating leaves which sent the model haywire. With the aim of shedding rubbish quickly the original taper main foil wings were changed to swept back. The swept back outer tip tended to surface for reasons not understood. The delta form performed well and produced higher force for a given span. Its best drag angle was within a degree of the taper form. Other benefits are strength and stall resistance.

The aft foil can still catch rubbish, but with less adverse affect on performance. Whether this will be a serious nuisance at full scale remains to be seen. A wire guard, shown pecked in Fig 12, was only partially successful in deflecting small rubbish. It did however allow the dog to surmount a floating rope more often than not, and a guard could give some protection against picking up a drift net at night. To reduce resistance and air entrainment the round wire could be replaced by a narrow streamlined foil pivoted to be hydrodynamically neutral.

Tow force geometry

Fig 14 shows forces produced by a dog at E attached to a yacht at A and being towed toward C.

F = total force in towing lines

D = drag   L'= lift of dog

L = horizontal component of lift

a = drag angle in azimuth

a'= drag angle in plane of tow lines i = angle of F to horizontal (force inclination)

i'= angle of L' to horizontal

L, D and a are relevant to yacht's windward performance and Fig 7.

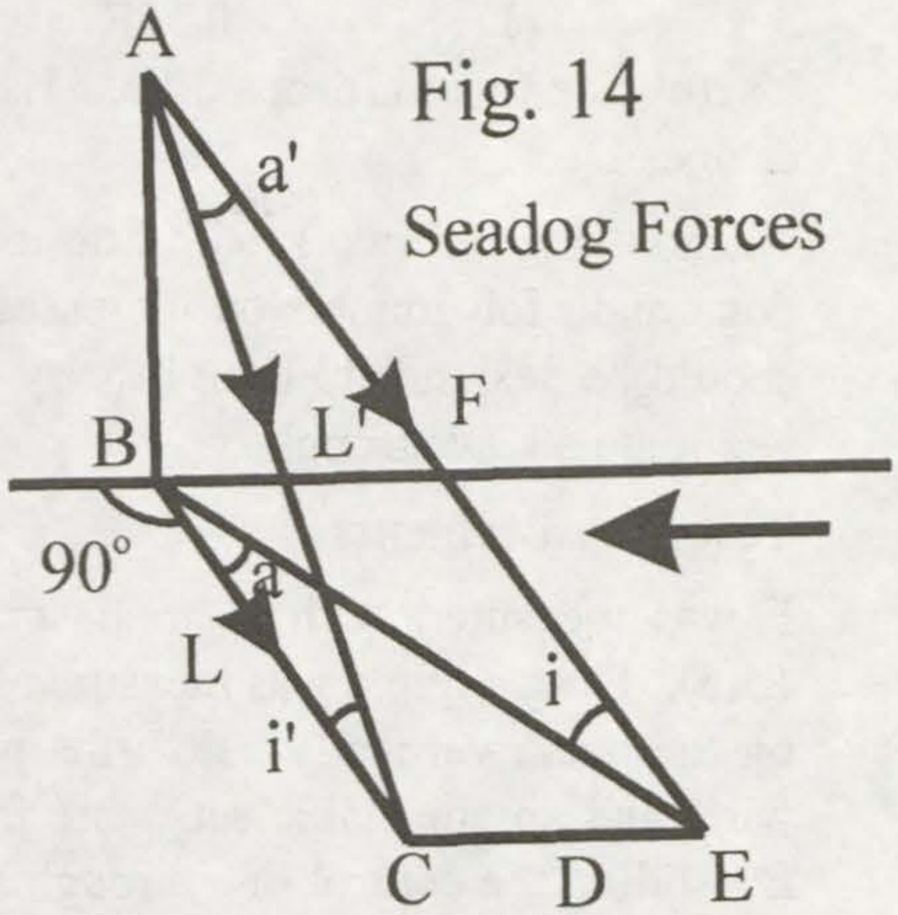


Fig. 14

Seadog Forces

L',D and a' are useful in comparing the dog performance with foil theory. L' and i' can be used to calculate gain in power (as Fig 9, in which R = L').

During tests a and F were measured. Height of tow point and length of tow line were set to give a chosen value of i. Remaining parameters can be calculated as follows.

$$BE = F.\cos i$$

$$D = BE.\sin a = F.\cos i.\sin a \quad (1)$$

$$\sin a' = D/F = \cos i.\sin a \quad (2)$$

$$L = BE.\cos a = F.\cos i.\cos a \quad (3)$$

$$L' = F.\cos a' \quad (4)$$

$$\cos i' = L/L' = \cos i.\cos a/\cos a' \quad (5)$$

Equation (2) can be rewritten

$$\sin a = \sin a'/\cos i \quad (6)$$

It is likely that a' is more or less independent of i and that a increases with i, and tests seemed to confirm this. In practice i will probably need to be in the range of 35° to 45°. Below 30° a main foil tip breaks surface, at 35° it shows a surface wake which disappears above 45°. For most of the systematic testing i was set at 35°. The following table shows the calculated influence of i when the dog is working near its best drag angle.

i	35°	40°	45°
a'	9°	9°	9°
a	11.0°	11.7°	12.8°
L	0.80F	0.75F	0.69F
L'	0.99F	0.99F	0.99F
D	0.16F	0.16F	0.16F

Useful side force L drops off as i rises, but righting force L' stays the same, as does D.

Anchor–dog will work with i up to 90° in smooth water; unlike the other dogs main foil immersion increases as i rises. In practice tow line length should be designed to limit i to say 60° at maximum heel, to leave scope to negotiate a wave trough.

Test Measurements

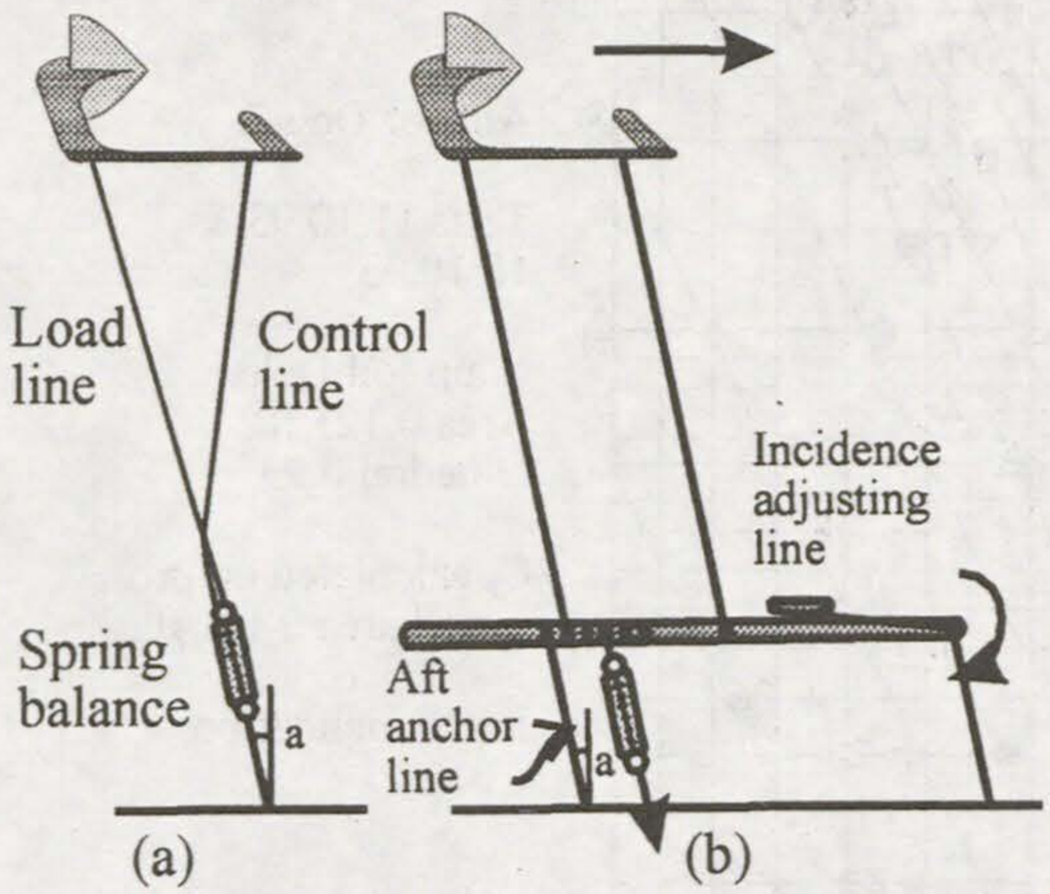
F was measured with a small spring balance, initially as shown in Fig 15(a). Drag angle a was measured by sighting the combined line to a mark on the deck, vertically below the point of attachment to the yacht's guard wire, and an adjustable setsquare fixed to a plank square across the yacht. By sliding the control line through a clove hitch in the load line the relative lengths were adjusted. With a short control line the dog drops back to large a and small F. As the control line is lengthened F increases and a reduces to a minimum, around 10° to 12°. Any further lengthening causes a sudden increase in a to about 27° to 30°. With the corresponding increase in angle of attack the dog is then stalled.

This kite rig just allows the dog to be flown at the optimum drag angle which probably corres-ponds to an angle of attack of about 5° and CL (coefficient of lift) about 0.4. It does not allow use of the reserve of CL available up to 0.6 or more, which is useful to absorb gusts or waves without stalling. Since some reserve is necessary, in practice it may not even allow use of the optimum. This is a powerful argument for use of a parallel line rig as Fig 2(a) or 2(b).

To explore the previously blind arc a parallel line and steelyard system was set up as shown in Fig 15(b). After setting incidence and speed the point of balance was found and the spring balance hooked into the nearest hole aft. It was then extended until the aft anchor line just went slack, taking care not to change incidence. Force in the incidence adjusting line was then negligible, and the spring balance gave F.

Successive small adjustments were made to the incidence line and readings of a and F taken at different speeds. Fig 16 shows a plot of a series of readings. High readings of a above $C_F = 0.5$ show stall, while those below $C_F = 0.2$ show the dog off load. Anomalous readings occur below 2 knots, which is too slow to lift the spar and various drag making attachments clear of the water.

Measuring Seadog Forces Fig. 15



The plot suggests a working range of C_F between 0.3 and 0.6 with a drag angle a of between 10° and 13°.

The maximum coefficient of force C_F at the upper speed range is relevant to strength requirements and engineering design when scaling up to prototype. Reynolds number will increase at full scale and this may delay stall, and raise maximum C_F from 0.9 to say 1.2. This is a bit academic as the maximum speed is more significant and unknown.

The above results are obtained with thin plate foils, the main foil given a slight camber. Larger dogs will be given thick foils of appropriate section. They will be built to float, ballasted if necessary.

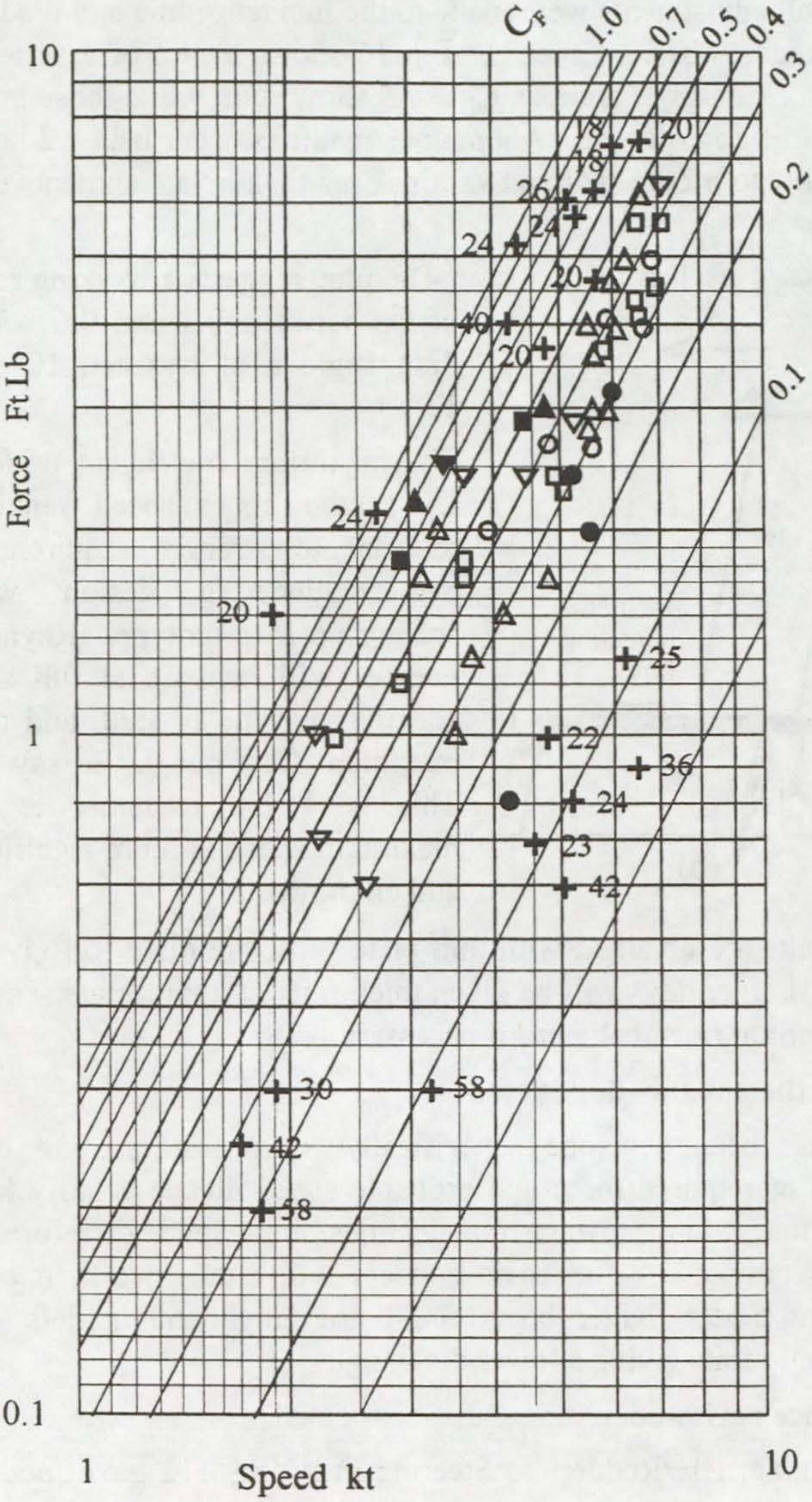
Variations on the anchor–dog theme

My version has been developed specifically for a fast cruising boat. Considerations of required force and probable speed dictate a fairly large area of main foil, while stowage practicalities limit span, therefore the aspect ratio is only 2.8. The basic concept will surely work in other proportions, and faster lighter boats could use greyhound models with higher aspect ratio foils giving a lower drag angle.

Steering balance reviewed

Henry Gilfillan's article Rudderless Steering in AYRS 112 gave food for thought. Because a seadog gives lateral resistance well to windward of the centreline it will need quite a large shift aft to maintain balance on

Fig.16



Anchor Dog 2.

Tests 11.10.93 & 18.10.93

Main foil Delta, Area 0.121 ft^2, Dihedral d 23^0

C_F calculated on projected area 0.111 ft^2.

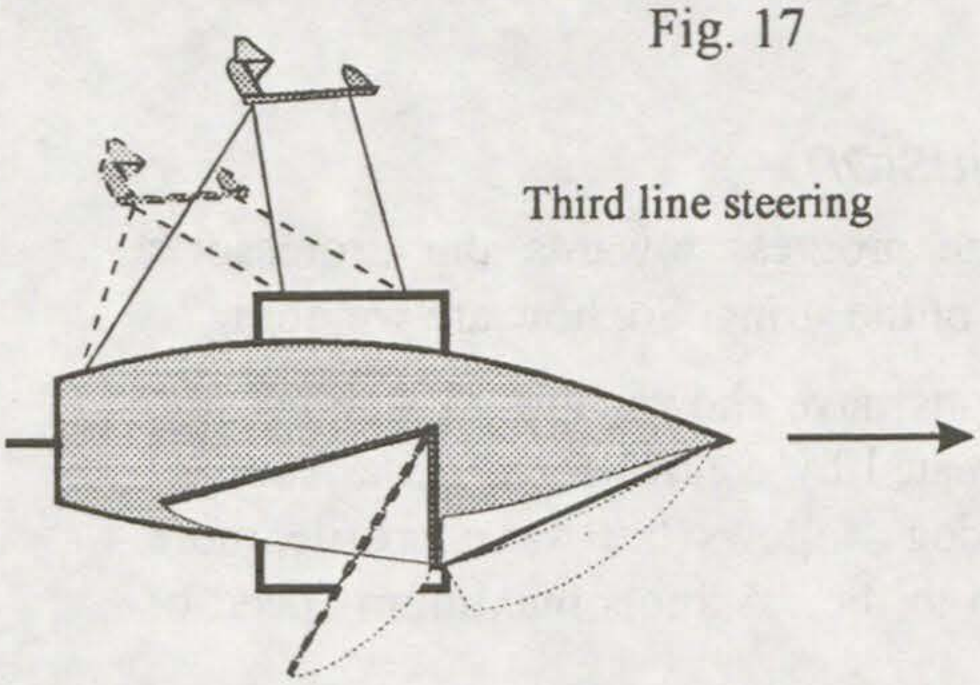
Force inclination, i 35^0

Key:
Drag angle in azimuth.

10^0 ○
11^0 □
12^0 △
13^0 ▽
14^0 ●
15^0 ■
16^0 ▲
17^0 ▼
18^0 & over +

(0.5^0 measurements rounded down.)

Fig. 17



changing from close hauled to reaching. Fig 17 shows how this might be done. Tests have confirmed that the model dog can be hauled aft by a third line without changing the incidence set by the control and load lines. Perhaps this will give self steering on various courses. Problems in tacking the model yacht with two dogs have been referred to earlier (Fig 6). The first was that the outside dog slowed the turn. By hauling in the third line and letting out the control line it could probably be used to positive advantage as anextra rudder. The initially windward cat-dog ran on and hit the yacht. This seems unlikely to occur with anchor-dog, which has less mass and a built-in tendency to turn away from the yacht. Another strategy is to let out enough control line to stall it, providing a pivot for the turn. It may even be possible to tack and carry out other manoeuvres without using the rudder.

Stowage. As shown in Fig 18, anchor-dog and its davits can be made to fold and carried with minimal increase in beam.

Summary. Model tests to develop a better dog have delayed any full scale work but have been very worthwhile. Overall the project still looks good. *November 1993*

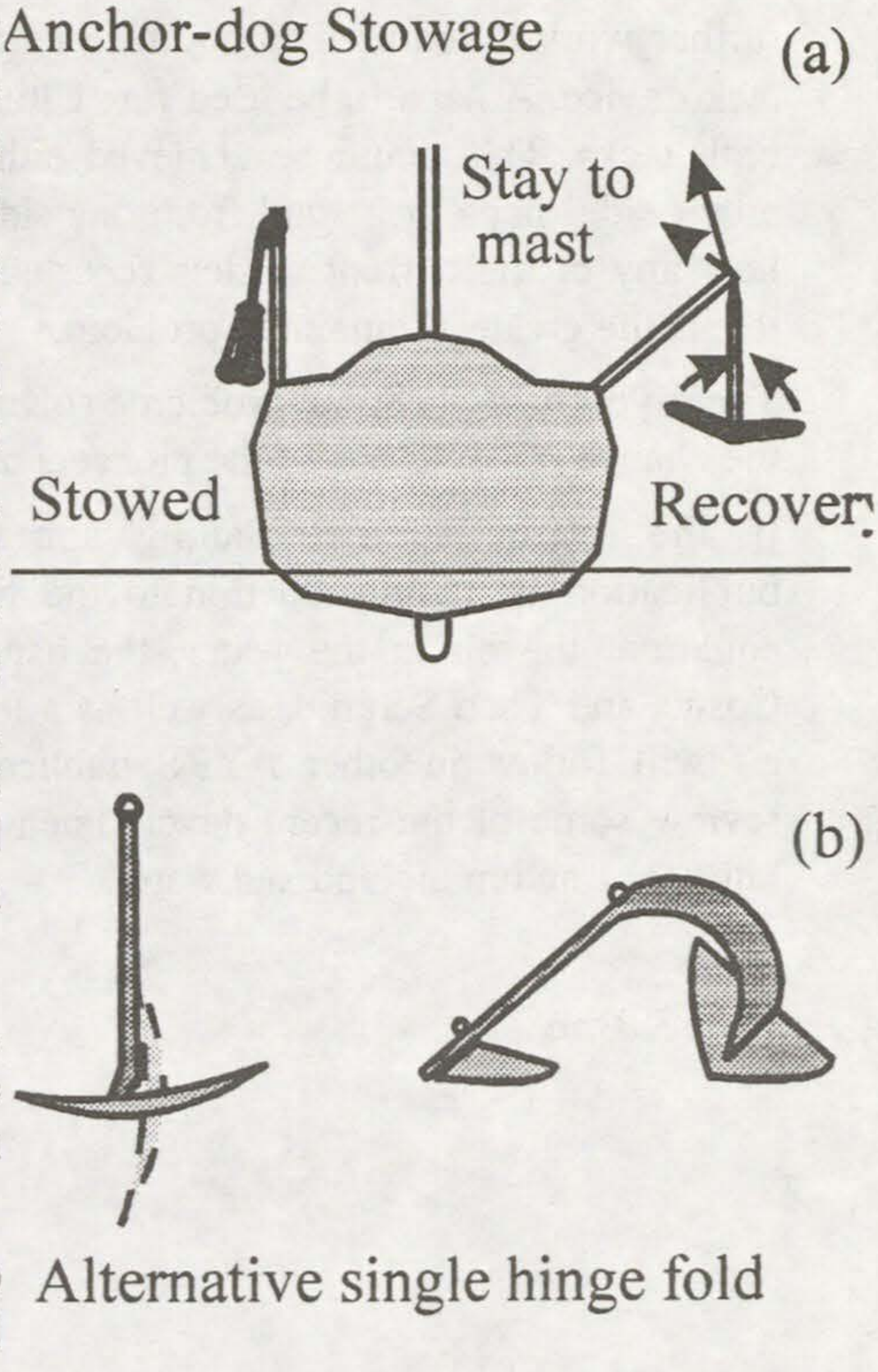


Fig. 18

Conclusion

The papers published here show the progress towards the professor's 'ultimate' goal, at least at the wet end of the string. So, how are we doing?

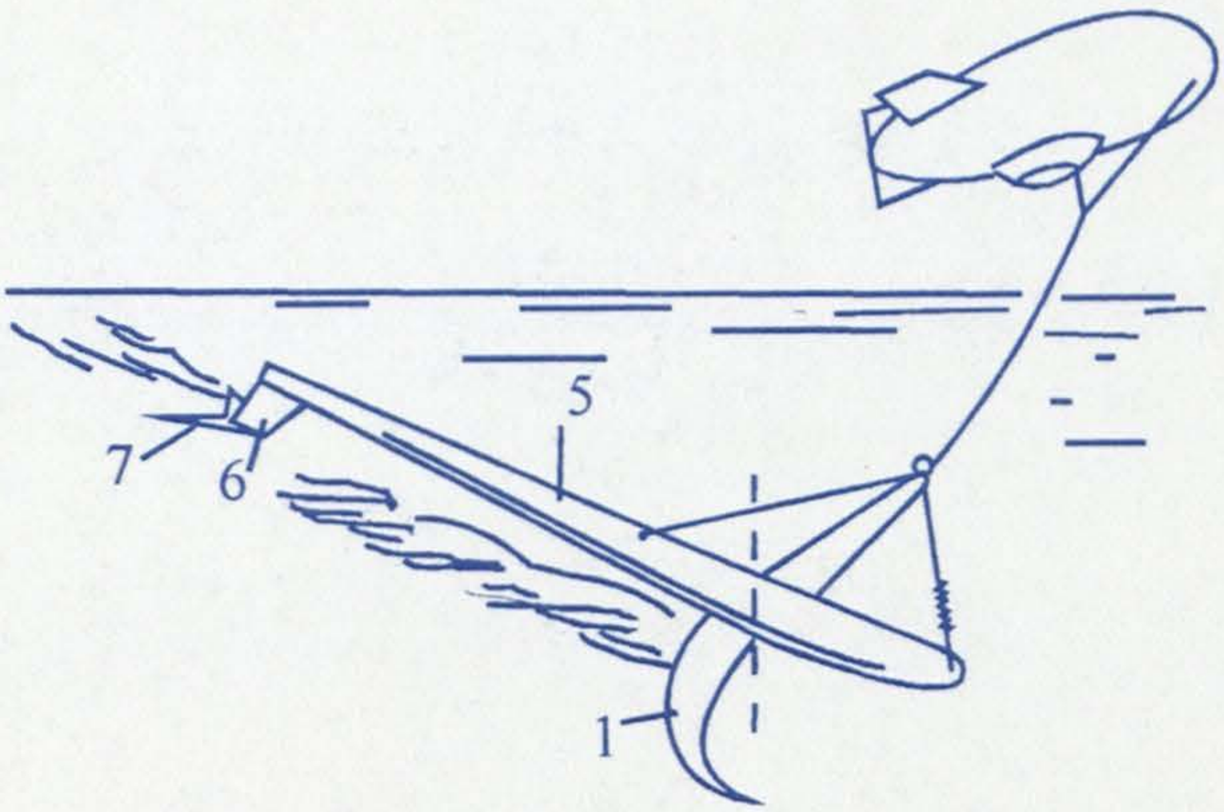
Paul Ashford's most successful designs have shown how to stabilise the hapa by using the dynamic forces created by control foils. As a result of this Paul reports that the 'Anchor–dog' follows the wave profile more accurately the faster it is running (up to the 7.5 knots maximum speed of his trials). One problem solved.

Paul has taken reliability as his main aim rather than high efficiency. Some further work is required to optimise performance and make a pratical two tack device. A hapa to be used for 'Ultimate Sailing' will need to work on both tacks. This could be achieved either by a 'one direction, pull from either side' hapa or a 'pull from one side, proa' hapa. It is difficult to see how any of the current models reported could easily be adapted. Perhaps this is the greatest remaining problem.

There you have it. Some problems solved and some for you to solve, with the chance of being one of the pioneers of the sport of the '90s.

If the idea of 'Ultimate Sailing' appeals to you, watch this space. This publication is an introduction to the first part of the 'ultimate sailing' equation, the bit in the water, the hapa. More information from Didier Costes and Theo Schmid, as well as a look at the other half, the bit in the air will follow in other AYRS publications soon. 'Kite Traction' will review some of the recent developments in the design and application of kites for traction on land and water.

Tony Kitson *Editor*



CONTENTS