From square sails to wing sails: The physics of sailing craft

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Through the ages

Most of the surface of our planet is covered with water, and over this water blow winds. From earliest times man has harnessed the power in the wind to transport people and goods over the water with far less effort than over land. And for centuries, sailing vessels were the only way in which distant lands separated by oceans were first discovered and later linked. Today, the most prevalent form of such transoceanic travel is to leave the water far below and to fly high above it. The direction and strength of the winds aloft still affect passage times as they did long ago, but now only in a trivial way. Given the differences in appearance, materials of construction, altitudes and speeds of operation of these two modes of transportation, one ancient and the other very modern, one could be forgiven for thinking that they could not possibly have much physics or technology in common. However, the task I have set myself here is to show you that there is in fact an intimate scientific link between them.

Let me start with a type of sailing craft in use four thousand years ago in Egypt on the Nile River which flows from South to North, while the wind blows from North to South. The sail was hoisted, as in Figure 1 to go South against the current, but was taken down when drifting North with the current. Even then, boards had to be lowered into the water, *transversely*, not longitudinally, to get a better grip on the current in order to overcome the effect of the wind blowing the opposite way on the portion of the craft above the surface (hull windage). This instantly illustrates that in this interesting system of interacting solid, liquid and gas, the speed and direction of the solid part are determined by the balance of the over and underwater forces.

These forces include underwater drag, the unwanted contributors to which are skin friction, form drag, and wave-making drag. Even though the first two grow as the square of the boat speed, they can be kept in check with a smooth and streamlined hull, and it is the third which really kills. Water waves are dispersive and propagate at speeds proportional to the square root of their wavelength. This causes the resistance due to wave making to increase very rapidly after a certain point and effectively to limit the maximum possible speed of any displacement hull to that of a wave as long as itself. This phenomenon discovered by the English engineer William Froude in the last century is depicted in Figure 2. This is why the famous Transatlantic ocean liners like the two Queens and the United States had

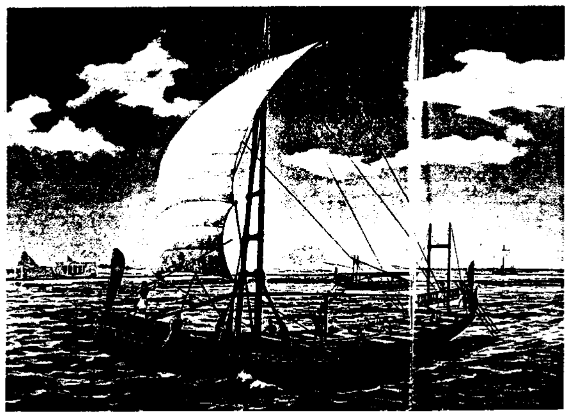

Figure 1. Ancient Egyptian square rig used on the Nile river as early as 2000 B.C.

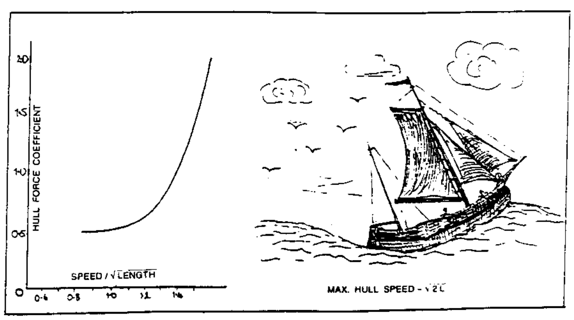

Figure 2. Wave-making drag increases catastrophically with speed as discovered by William Froude. It effectively limits the speed (measured in knots) of displacement hulls to the square root of twice their waterline lengths (measured in feet).

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to be as long as they were to do over forty knots, and why any conventional sailboat of ten meters length can barely reach seven knots, even with a twenty knot wind pushing it. This barrier can be beaten by 'getting the hull out of the water,' using the dynamic force of the water hitting a sloping under-surface or submerged foils to violate Archimedes' principle, or by having two or more hulls with a superstructure over them. In the latter case, the stability comes from the separation of the buoyant volumes, and they can be made more slender to slice through the speed barrier.

The Vikings who built boats like the one in Figure 3 evidently appreciated the need to have their craft smooth and sleek and long to minimize these unwanted kinds of underwater resistance. But I suspect they rowed more than they sailed, and it was the Chinese first and the Arabs next who built and voyaged extensively with what I would call proper sailing craft, which are not just like leaves blown along by the wind, but for which the destination is a matter of choice. Such a craft can get from A to B even if the wind is blowing directly from B to A. Junks and Dhows (Figure 4) are still being built and sailed in China and the Arabian Gulf,

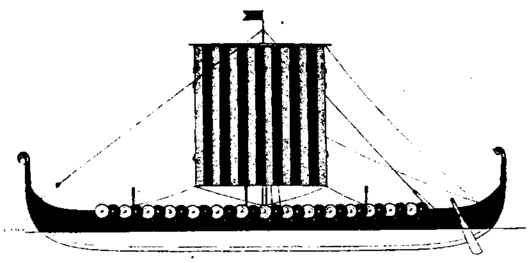

Figure 3. Viking Longship with square sail from a thousand years ago.

but to appreciate why and how these craft could make progress to windward we must first understand how sails work.

The energy to overcome various types of resistance comes from the relative motion of the air over the water. But to extract that energy to do things of our choosing, we need a foot in the water, so to speak. To see what I mean, think of a wind generator located on a balloon. It can generate power from the wind only if the balloon is tethered. If you cut it loose, the whole assembly will drift with the current of air; the generator will feel no apparent wind, and the rotation will stop.

Square sailing

The title of this lecture mentions square sails as the starting point, so let us look at a picture (Figure 5) of a big ship well equipped with this kind of sail. Most of the area is in the rectangular sails, which are hung from spars above. Such a sail works like a parachute, and a poor one at that, and generates a force in the direction of the wind flow called 'drag'. To go anywhere with such a rig you need a wind more or less from behind you and moderately strong. It needs to be strong because as you pick up speed and move with the wind, the apparent wind gets weaker. The force which is proportional to the square of this apparent velocity now drops, while the drag on the hull, as we saw earlier, goes up even faster than the square of the water speed. This means that if you want to approach your hull speed in moderate winds, you need the enormous area of 'air anchor' that you see in the picture. This is the above-water analogue of the Egyptian transverse board and the equivalent of the gigantic spinnakers carried by displacement yachts.

The bad news is that as the wind speed picks up beyond some safe value, the pressure cannot be taken

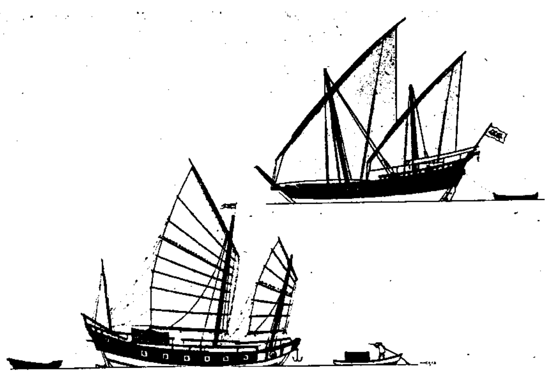

Figure 4. Arabian Dhow and Chinese Junk, among the earliest craft that could sail to windward.

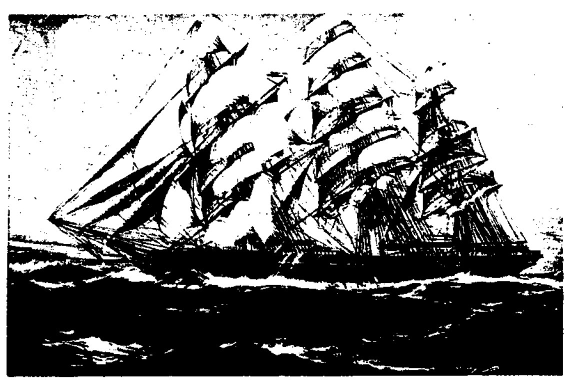

Figure 5. A three-masted square rigger, among the biggest ships that crossed the oceans under sail.

off by the ship running faster before the wind because it is already close to its limiting speed. So the power available for destruction goes up as the cube of the apparent wind speed, and we have in reality the proverbial confrontation of an irresistible force with an immovable object. Reducing the sail area is the only escape, but as seen in the next picture (Figure 6), this is a dangerous operation in impossible conditions, as witness the average loss of one crew member overboard for every rounding of Cape Horn.

A large piece of canvas flapping in a storm is like a thing possessed and totally uncontrollable. Two of my yachting friends have been flicked overboard like flies when trying to subdue a sail in a strong wind, and in both cases it was a near miracle that they were able to be rescued. Fear of the damage that a sail can and will do, and the hurry to reduce its size or to put it away altogether are still as much a part of the mental makeup of most yachtsmen today as they were of the poor souls who manned the square riggers that look so pretty in a moderate wind on a smooth sea, or even better as a picture on the wall. I have very little patience with the romanticizing that goes on about these vessels. To me their very design made superhuman demands on the crew which led inevitably to the brutality that characterized the maintenance of discipline on long voyages. It is no surprise that they are no longer in use for carrying any type of cargo anywhere in the world.

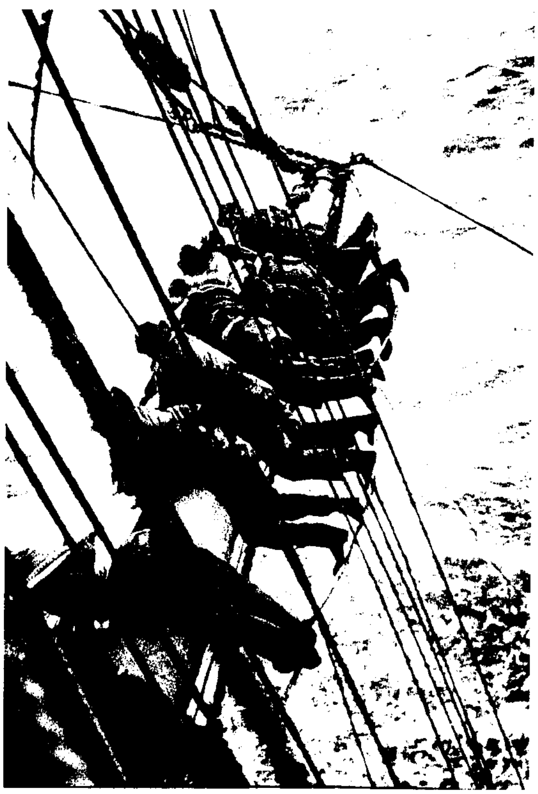

Figure 6. Furling sail in a square rigger, hanging on to the yardarm high above the water in a heaving sea.

Aero and nautics

The Chinese junks I mentioned earlier had ingeniously designed sails (Figure 7) which could be hoisted or collapsed progressively like a venetian blind from on deck by one person. More importantly, the material and the shape of the sail were such that they enabled the craft to make effective progress into the wind many hundreds of years before the western world learned how to do it. To understand how, one must now make the connection with aeronautics that I promised at the beginning.

The magnitude and direction of the force generated by a fluid flowing at a small angle to a lamina was a problem that has challenged many great physicists, starting with Newton. According to a theory attributed to him, the prediction was that at small angles, the force would be negligible, increasing only as the square of the sine of the small angle. Lord Rayleigh, in a remarkably perceptive paper written over a century ago,

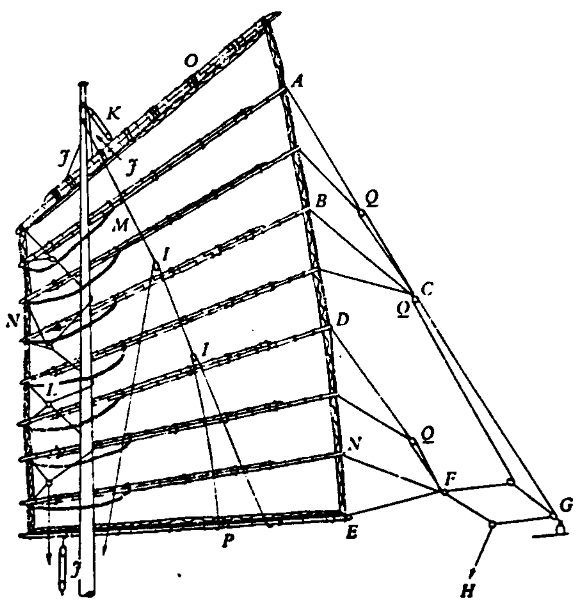

Figure 7. A Chinese mainsail, which could be hoisted or lowered from on deck by one person.

dismissed this conclusion, because '... it is known to practical men to be very wide of the mark especially for small values of the angle.' He goes on to make a statement clearly presaging the concept of the force called 'lift' in aeronautics, a science yet to be born. Describing as an example the dipping action adopted by Chinese oarsmen to greatly enhance the force obtained by pulling their oars through the water, he stated in 1876:

> The fact that the resistance to the broadways motion of a lamina through still fluid can be increased enormously by the superposition of an edgeways motion is of great interest. For example, it will be found to be *of vital importance in the problem of artificial flight* (emphasis mine).

Incorporating this idea, he calculated a much higher value for the force at small angles, which we know today to be even greater, and given correctly by the circulation theory of airfoils developed by many great minds at the turn of the century and later. It is this force which enables a bird to glide down with a vertical speed far smaller than achievable with a parachute of an area equal to that of its wings. And it is what holds planes up in the sky with a force proportional to the real area of the wing even though it is moving *edgewise* through the air.

To return to our present concern, it is such a lift force, perpendicular to the flow, that a sail set at a small angle to the wind has to produce to enable the boat to move to windward. But as seen in the sketch (Figure 8), this force will have a component trying to push the boat sideways which is far greater than the forward component. Thus enters the essential requirement on any proper sailing craft for an underwater arrangement which makes it hard to move the boat sideways while leaving it easy to move forwards. It is to serve this function that the Chinese invented leeboards which even today are a common sight in the Netherlands on traditional Dutch boats. The same function is served by retractable or fixed fins of various shapes and sizes on wind surfers, dinghies, and larger sailing craft.

The most important aspect of the functioning of these fore and aft surfaces in the water is one that Rayleigh, and Froude apparently, understood better than most yachtsmen do today. To quote again from his paper,

> As a proof that an edgeways motion of an elongated body through water is not without influence on the force necessary to move it with a given speed broadways, Mr Froude says, 'Thus when a vessel was working to windward, immediately after she had tacked and before she had gathered headway, it was plainly visible, and it was known to every sailor, that her leeway was much more rapid than after she had begun to gather headway. The more rapid her headway became, the slower became the lee-drift, not merely relatively slower, but absolutely slower.'

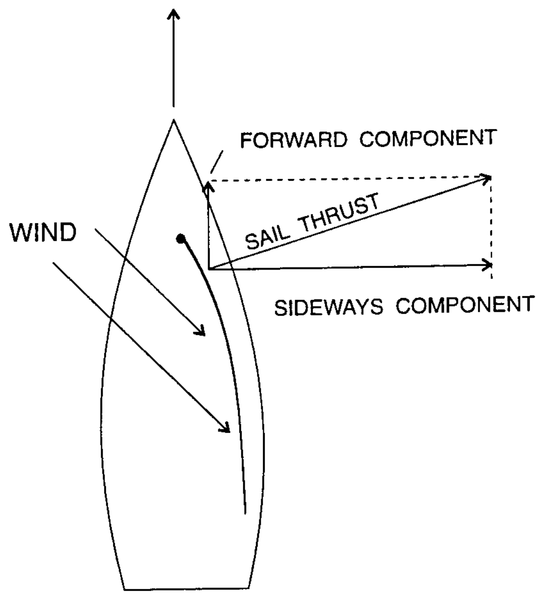

Figure 8. Force components of the sail thrust when going into the wind. The large sideways component must be countered by an underwater arrangement.

The point is that the force preventing the craft from sliding sideways is *not* the drag of the fin moving sideways in the water, but the *lift* produced by its forward motion at a slight angle to its plane of symmetry. This fin functions as a vertical hydrofoil in the water, just as the sail does as a vertical airfoil in the air. It is a pity that the longitudinal and transverse forces on these foils, both horizontal in this case, have to be called drag and lift, the price sailors have to pay for being slower than the flyers in recognising the operative forces on their respective craft.

Air- and hydrofoils

Of the many many factors determining the quality of an air- or hydrofoil, for present purposes I shall mention only three: symmetry, shape (cross section), and aspect ratio (length/width). Birds and most airplanes have wings whose tops can never be mistaken for their undersides. Birds, apparently, do not need to fly upside down, and airliners have people walking around in them. But aerobatic planes must be able to fly upside down as happily as right side up, and their wings can be symmetrical and still almost as effective. The angle of attack is now the inclination of the symmetrically streamlined object to the direction of the fluid flow. For boats it is clear that the wind can hit the sail from one side or the other, and the underwater fin should be just as effective in preventing drift to the right as to the left. Fins fixed to the hull or lowered in the centre are invariably symmetrical, but leeboards can be made different, as there is one for each side. I learned only recently that the Dutch boats have such mirror image leeboards, which must be more effective than symmetric sections. It is clear that a sail, if it is fabric and hence two-dimensional, can curve one way just as well as the other. The price one pays for this flexibility, however, is its inferior efficiency as compared to a properly shaped three-dimensional airfoil, and the tendency as mentioned earlier, to flog itself to shreds, or you to death, if left up all the time. As for aspect ratio, aeronautics taught us that long and thin is better, and that is why the tall triangular or so-called Bermudan sails one sees on modern yachts replaced the quadrilateral ones on older types.

The absolute measure of quality of a foil is its finesse, which is the dimensionless ratio of the transverse to the longitudinal force generated at the optimum angle of attack, usually a few degrees. Another name is the gliding angle or the lift/drag ratio in aeronautics, shown in Figure 9, which also indicates that a curved surface, like a sail, is not as good as an honest solid airfoil. If you are piloting a single-engine plane, it also tells you how many kilometres you have to find a landing spot if you are one kilometre up in still air when your engine dies on you. For a sailboat there will be one such angle associated with the airfoil performance of the above surface part of the craft, and another angle quantifying the hydrofoil performance of the underwater portion of the hull and fin. It is reasonable to presume that these two together determine the way the craft will sail. As I said before, wing theory was developed in the early part of this century, and one of the geniuses in this game was an Englishman called Lanchester, who was an amateur mathematician and had independently worked out the circulation theory of airfoils. It was he who first understood and explained induced drag in real wings, connecting it with the shedding of vortices from the wing tips. He built the first automobile in England and had a company which manufactured fast cars. But apart from all this, the reason I hold him in the highest esteem is for writing down in a few lines, long before anyone else understood it, the essential theory of sailing vessels.

Here are the original words of F. W. Lanchester, written in 1907:

> The problem of sailing yacht mechanics resolves itself into an aerofoil combination in which the aerofoil acting in the air (a sail spread) and that acting under water (the keel, fin, or dagger plate) mutually supply each other's reaction. The result of this supposition is evidently that the minimum angle at which the boat can shape its course relatively to the wind is the sum of the under and above water gliding angles.

Lanchester's brilliant course theorem is illustrated in Figure 10 and makes immediately comprehensible the performance of a sailing craft as expressed by one number, the angle β. A plot of this angle for sailing vessels through the ages is shown in the following Figure 11. The exceptional performance of the ice yachts is very simply due to the gliding angle for the runners on the ice being effectively zero, and only the sail and windage of the yachtsman determining β. Land yachts too have a very small β because they are on wheels, which also have an extremely high ratio of lateral to forward resistance. One such craft is shown in Figure 12.

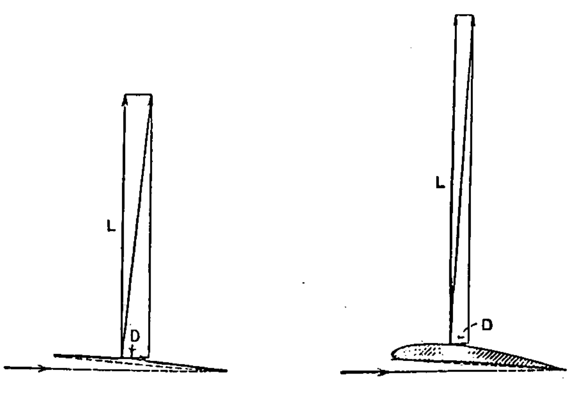

Figure 9. Lift and drag on curved plate (left) and airfoil (right) at an angle to the wind of under 4 degrees. Both have the same aspect ratio of 6.

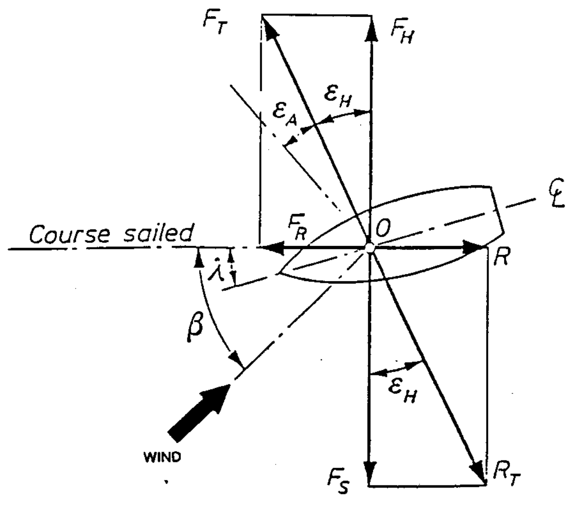

Figure 10. Lanchester's Course Theorem. The closest angle β to the wind that a craft can sail is the sum of the under and above water gliding angles.

Really sailing

Returning to water craft, it is thus clear that the ideal sailing machine will be one which is nothing more than one foil up in the air and one down in the water and which can skim over the surface. The closest approximation is, as is well known, the windsurfer or sail board, which is the most widespread variety of sailing craft today; there are certainly hundreds of thousands, and probably millions, all over the world. Ingenious, portable, affordable, and thrilling to sail, they have brought within reach of millions a sport once considered as only for millionaires. But if, like me, you are not young and fit, and don't like to fall into icy water, it can be more fun to sit and watch someone else learning to sail a board for the first time.

Having seen that a boat can sail at any angle to the wind that is greater than β, we can now look a little more closely at the apparent wind, which (in a steady state condition) is the only operative force governing the speed of the boat. We have already seen that it will be less than the true wind when the craft is running before it. But it can also be greater than the true wind on other points of sailing as evident from Figure 13. Speed sailing will therefore require maximizing the apparent wind to maximize the boat speed. But the bigger you make the apparent wind, the closer it gets to the nose. What is the limit? Clearly it is β, the closest angle to the wind at which the craft can sail. There are a number of other surprises that follow from this one, that the maximum speed is attained when the apparent wind is farthest forward!

Sailboarders and ice-yachtsmen, among others who do not suffer from a hull speed limitation, know all about this, and use it to tack *downwind*. Starting with the wind on the beam and gradually bearing away as they pick up speed, they can end up close hauled even though the true wind is from behind, as shown in Figure 14. If the wind is blowing from A to B, they can start from A, change tack halfway, and get to B *well ahead of the piece of wind that started with them.* There is a very important message here that I would like you not to miss. A small sail acting as an airfoil and producing lift can get a craft to a downwind destination *faster* than the wind. A spinnaker or other drag device can at best approach the wind speed and would then need to be absurdly large to drive the hull with the near zero apparent wind. Another message is that faster craft will generally be sailing with a much larger angle between tacks because of the larger difference between true and apparent winds. Catamarans and similar craft

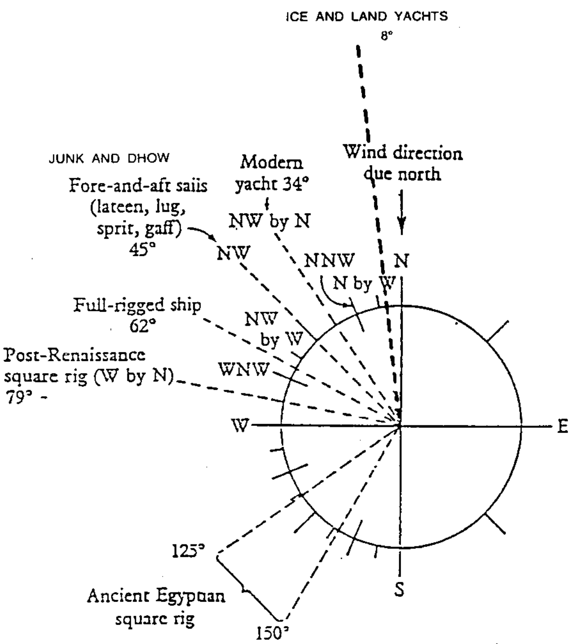

Figure 11. The closest angle to the wind, β, for sailing vessels through the ages. Ice and land yachts can sail very close to the apparent wind because they have a very high ratio of lateral to forward resistance.

Figure 12. A land yacht on three bicycle wheels. The front two are used for steering and the sail is that of a windsurfer.

are often mistakenly thought to be poor windward performers by slower boats which make a smaller angle between tacks. The angle between tacks can be as small as twice β only for craft whose speed is negligible compared to the true wind speed.

Speed sailing

If speed sailing is your thing, the angle β also tells you how much faster than the wind you can sail and the direction in which you must sail to achieve this maximum as shown in Figure 15. Cosec β is the maximum possible ratio of boat speed to wind speed and this can be achieved when the true wind is β degrees abaft the beam. The apparent wind will then be just β degrees off the bow. The small β of land yachts racing across the dry lakes of California allows them to reach 90 knots, and for the same reason ice yachts have exceeded 100 knots on glare ice in Wisconsin. For floating craft, the ideal place for speed attempts would be a stretch of water with the wind blowing roughly at right angles to the course and with no waves to slow the craft down.

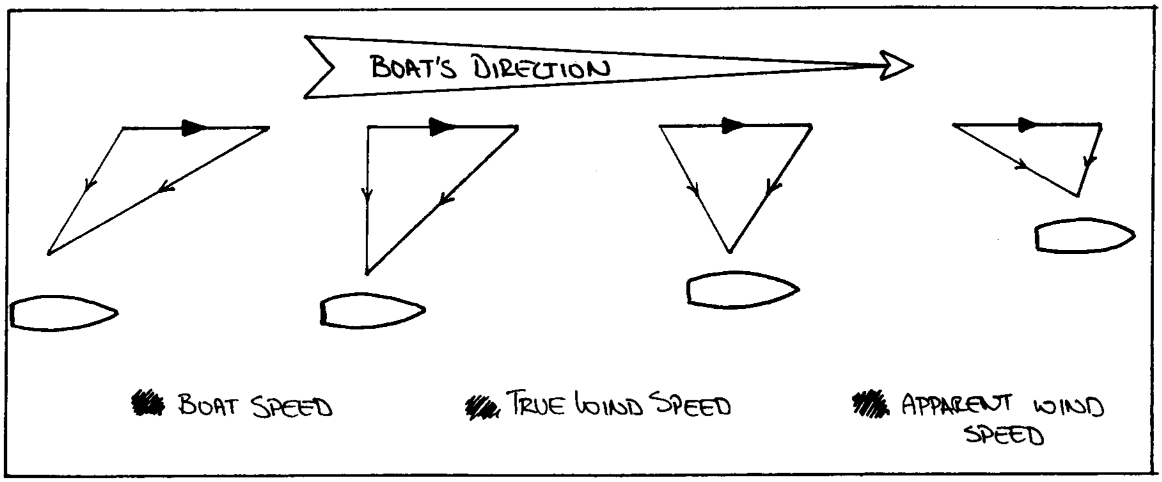

Figure 13. True and apparent winds. The apparent wind can be less than, equal to, or greater than the true wind depending on the point of sailing. The boat speed has been kept constant in all cases in this illustration.

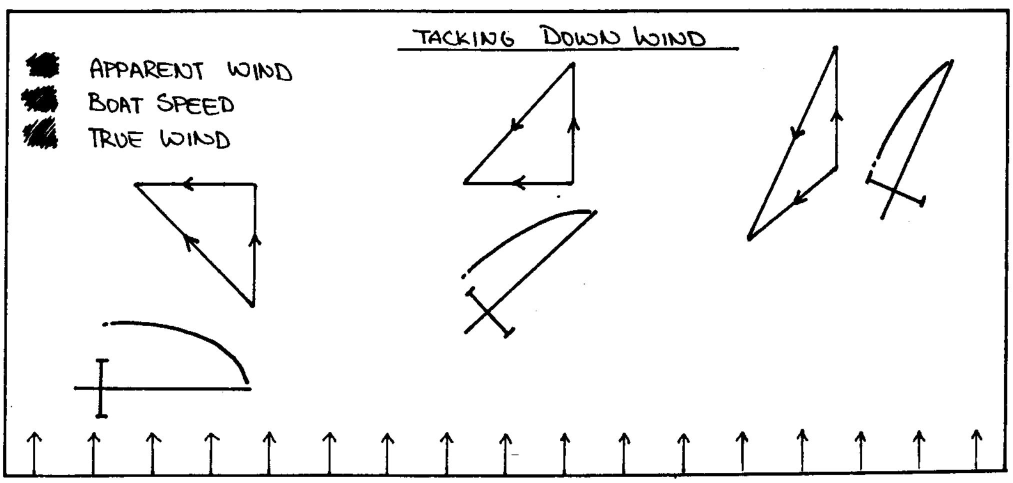

Figure 14. Illustrating how an ice yacht would tack downwind, starting as in the left of the figure with the wind at right angles to the direction of travel. The direction can gradually be changed anticlockwise to the middle configuration and eventually to that in the right of the figure, when the apparent wind is as close as it can get. The yacht speed is almost double that of the true wind, which is now almost from behind.

Such a place is Weymouth in England where as seen in Figure 16, a strip of beach separates the ocean from the harbour stopping the waves but allowing the wind to blow across. Every year in October when the wind is often very strong, people with strange contraptions come from all over the world to try and sail as fast as possible. This Speedweek, as it is called, is run by the Amateur Yacht Research Society, an extraordinary organization that has pioneered the support of every type of innovation in sailing including the development of multihulls over the last forty years against enormous prejudices and pressures. I was introduced to the AYRS

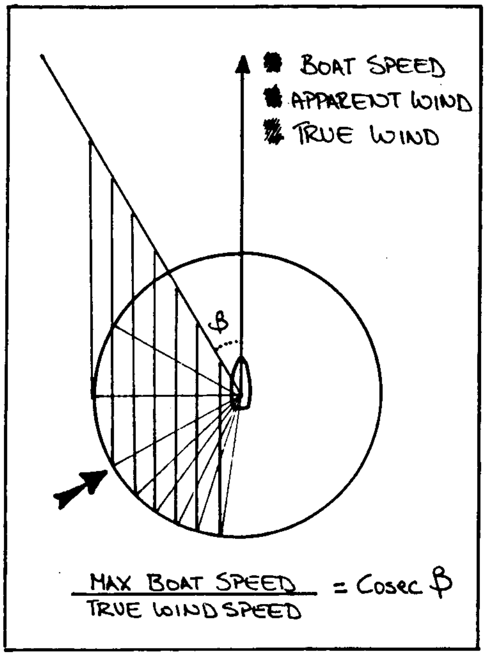

Figure 15. Speed sailing. The maximum possible ratio of boat speed to wind speed is Cosec β, and this can be achieved by starting with the true wind β degrees abaft the beam and building up speed till the apparent wind is just β degrees off the bow.

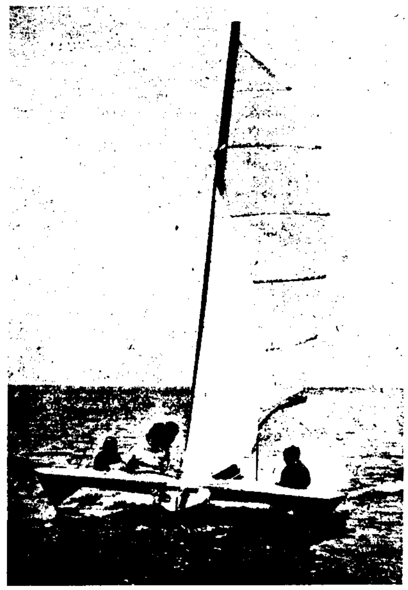

Figure 17. Martin Ryle, in the back on the left, trying out the hydrofoil trimaran designed and built by him in the very early sixties.

Figure 16. Weymouth. Portland harbour on the right is separated from the English Channel on the left by the strip of beach which stops the waves but lets the wind blow across. Speed trials for sailing craft are conducted here every year in the autumn when the winds are very strong and roughly at right angles to the course.

Figure 18. AYRS publications, over 120 since 1955, have covered almost every topic of interest related to sailing, both theoretical and practical.

by Martin Ryle, a name well known in astronomy, who was also a keen sailor and innovator who built the first hydrofoil trimaran in England. Figure 17 reproduced from an early issue of the journal shows him with his family, trying his craft out. A sample of the range of topics on which the Society has brought out publications of inestimable value to the open-minded sailor is seen in Figure 18.

I was at the Speedweek in October 1995 and intend to go again this year. Just to give you a flavour of what it is like, I would like to show you a few scenes from two years ago. Sailboards (Figure 19) dominated as they have done for a long time now, and the men's winner did over 50 km an hour in a 30 km-an-hour wind. Of course they were the only *monohulls* there, if you can call them that. All other craft had either two or three hulls of various kinds. Coming to innovations now, Figure 20 shows two sailboards with a bridge across, the idea being to provide the righting moment by this arrangement, and not the weight of the person,

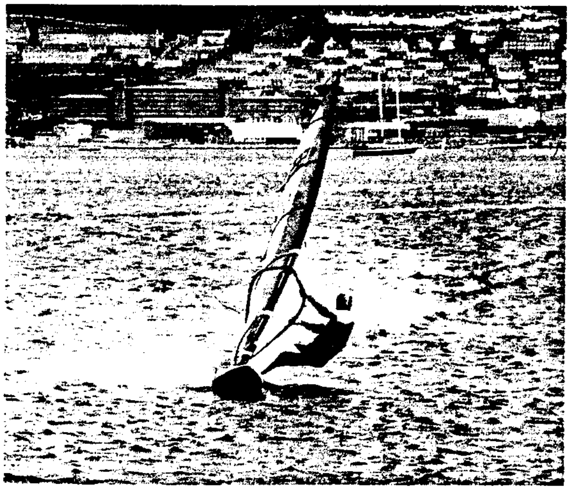

Figure 19. Sailboards dominated the scene at the Speedweek in Weymouth. Maximum speed recorded was over 50 km/hour in a 30 km/hour wind.

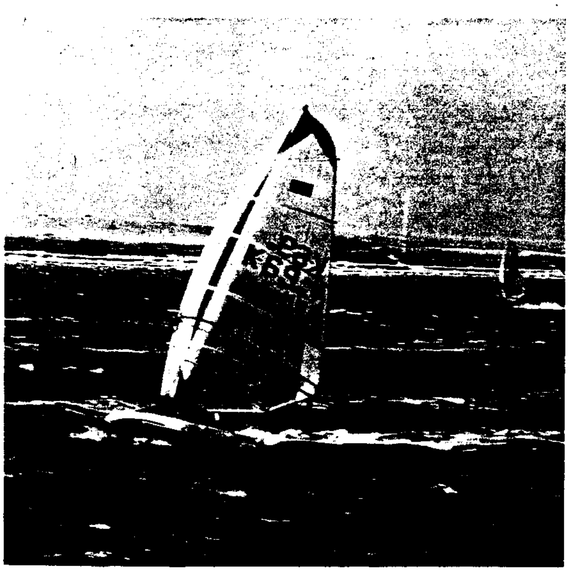

Figure 20. A double sailboard for greater stability.

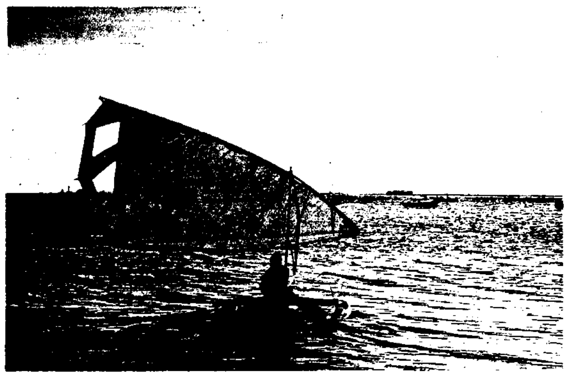

Figure 21. A planing trimaran with a Polynesian sail of high efficiency.

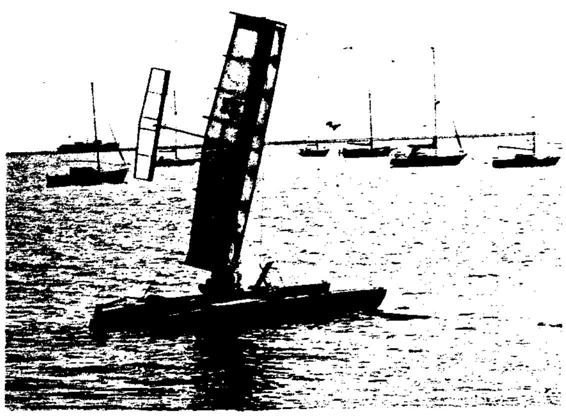

Figure 22. A catamaran with a true wingsail. It is an asymmetric one, and so has to be flipped over the top to sail on the other tack. The white tail at the back functions like an airplane elevator, and is set to control the angle to the wind of the main wing.

as in the previous picture. The next one (Figure 21) is a trimaran with a sail of Polynesian origin. The boards are meant to plane, and the fins sticking out under them to provide the sideways resistance, as I have discussed at length. The last craft shown (Figure 22) has a real three dimensional asymmetric wing with an arrangement for the top of the wing to become the bottom when sailing on the other tack. I have talked about airfoils all through, but this is the first craft I have shown you a picture of with a real one. The tiny white tail in the back functions exactly like the elevator of an airplane, which can be set at different angles and which then automatically keeps the main wing at the desired angle to the apparent wind. This is the principle on which most or all wingsail boats work, as we shall soon see.

I mentioned that the sailboards were the fastest craft at the 1995 Speedweek and had been the fastest in the world for some twenty years or so. But in the last few years sailing craft are coming back, and some years ago a wingsail trimaran hydrofoil called Yellow Pages Endeavour did 46.52 knots in 18 to 20 knots of wind. Staggering as is the achievement of such speed, you might feel that such highly experimental one-off designs may need real wing sections, but yachts built for sale could not possibly work with such devices, and conventional sails will surely continue for a long time to be the only practical and, more importantly, safe ones, whether for harbour sailing or ocean cruising. If you do feel this way, then, in my opinion, you could not be more wrong, and I shall try now to persuade you of that.

Plane sailing

One of the distinguished members of the Amateur Yacht Research Society and one of the most dedicated pioneers of the wing sail concept is John Walker, who built a boat over twenty five years ago with four wings, as you see in the picture (Figure 23) taken from an AYRS publication of that time. Some twenty years and a lot of research later, he built a better one with two wings in a biplane sort of rig which you see to the left in the next picture (Figure 24). This boat was sailed across the Atlantic and back and went safely through a severe hurricane in the process. Downwind of the main bearing, and just barely visible behind the portside wingsail, is the tail whose angle to the two main wings is adjusted by computer; the wind does the rest.

On the right is seen his latest and most beautiful creation which has now evolved, as airplanes did, to a monoplane configuration. The smaller wing downstream is again the tail whose angle is set to match the wind direction to the course desired, again by a computer powered by solar cells which get their energy from the sun, as does the wind itself. They can be seen in front of the wingsail in the view from above (Figure 25). The symmetry problem has been solved by a movable flap at the leading edge, similar to those you see coming out just before landing on airliner wings. In this case the flap can be moved either to the one or the other side and provides an enormous increase in thrust. Figure 26 shows the flap in operation, and all the pictures reproduced here are courtesy of Dick Ogilvie, and John Walker, who kindly made them available to me for this lecture.

The whole airplane part is completely free to rotate on a bearing seen clearly in the same figure, and the little motor for setting the angle of the tail is also supplied with power from the same solar cells. Of course there is a back-up, and even a manual control if it should ever be needed. Everything is controlled by a processor, and there is a lever for forward and backward movement seen to the left of the wheel in the picture (Figure 27) of the cockpit, which now looks like that of an airplane. It goes without saying that like any respectable multihull, she also sails upright, and not on her side when going into the wind. The monoplane version is now in full series production in Plymouth in the UK.

One of the important implications of using airplane type wings on boats is that it makes no more sense to take them down after use than demounting the wings from an airplane after you have landed. If free to rotate and align itself with the wind, a wingsail presents less windage than a bare mast and rigging on any boat, and doesn't rattle when it blows. And wings are happy in the wind, as the speeds at which even light airplanes cruise are way beyond the Beaufort scale for storms and hurricanes.

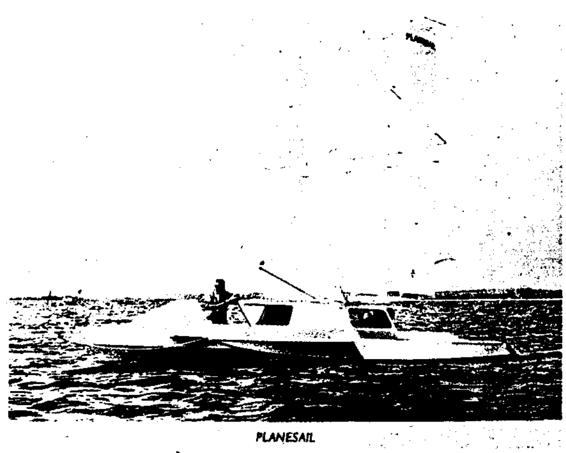

Figure 23. John Walker's first wingsail trimaran built over a quarter century ago had four main wings. The tail controlling their angle to the wind can be seen behind them.

Messing about

As already mentioned several times, yachting is the exercise of extracting energy from the wind and using it to push accommodation from one place to another over the water. In the case of land vehicles like cars or bicycles, the power available is limited by the engine or the strength of a person, and the varying load, due to inclination of the road (or wind), is matched to the

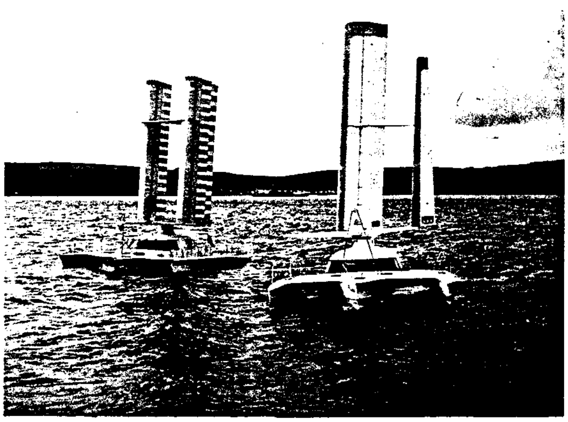

Figure 24. *Blue Nova* to the left was the first wing powered boat to cross the Atlantic and back, and went safely through a severe hurricane in the process. To the right is *Zefyr*, the latest monoplane version of the Walker Wingsail. The tail is clearly seen on this boat but is partly hidden from view in the other.

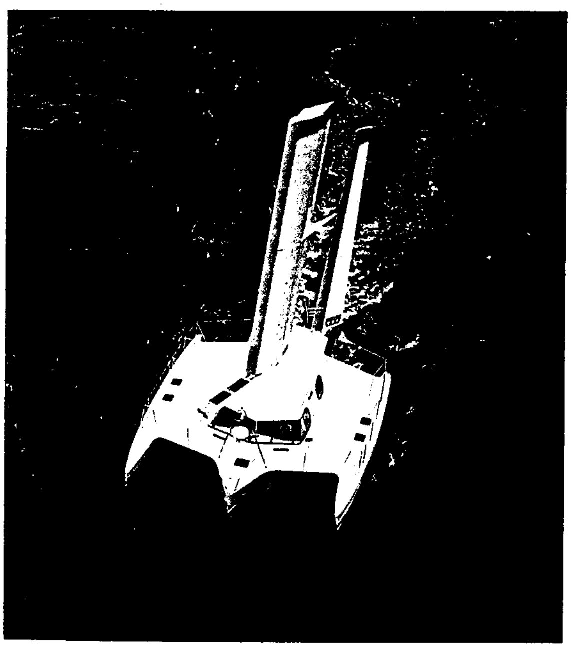

Figure 25. Solar panels can be seen in front of the wing sail in this view from above *Zefyr*. They supply power for the computer and the little motor for setting the angle of the tail.

Figure 26. The bearing on which the whole airplane part is completely free to rotate. The flap on the wingsail is in the operating position.

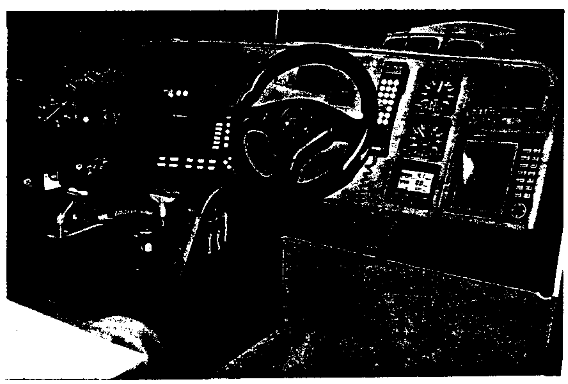

Figure 27. *Zefyr's* cockpit looks like that of an airplane, not without reason. On the left is the thrust lever for forward, neutral and backward, exactly as in a powerboat. A remote control lever which can be operated from anywhere on deck also has sideways movement for docking.

available power by the use of a geartrain. This keeps the source of power running at a speed where it is happy and adjusts the speed of the vehicle to absorb the available power. In the case of sailboats, the available power is proportional to the area intercepting the wind and the third power of the apparent wind speed. By anybody's reckoning, the range of wind speeds encountered at sea is over a factor of ten, so even if we restrict it to this number, the power available for good or evil ranges over a staggering factor of a thousand. If we now try to deal with this range, made worse on a craft suffering from the disease of hull speed limitation, then as already indicated, the effective sail area must be varied by a factor which can be very large. This usually means replacing sails of one size with others larger or smaller.

To be in the right frame of mind to discuss boats, I spent a day sailing on one of the inland seas. I think it is fantastic to be on the water and to be pushed along by the wind, and I feel a deep kinship with others who share this feeling. So I hope I don't offend some of them if I express my view that the business of taking down one sail and putting up another can be compared only with stopping and changing the size of the wheels on your car or bike every time you come to the bottom of a hill, and doing the reverse on reaching the top. Reefing the mainsail when the wind freshens suddenly is a pathetic operation on most yachts, and only roller reefing of the jib is quick enough to excuse comparison with *manual* shifting of gears in a car or a bicycle.

The masts for holding up the sails, the shrouds and spreaders for holding up the mast, the hundreds of meters of rope and wire to pull up the sails, tilt them at the right angle to the wind or bring them down, the pulleys and cleats and turnbuckles and travellers and poles and everything else above deck are all for adjusting two and only two miserable parameters, the area and angle of the sail spread. And the sails are usually mounted with their pivoting points as far as possible from the centre of effort, so you need expensive winches and footballer's muscles to adjust them. Add to this the hundreds of words in the nautical vocabulary you need to know and the dozens of knots you need to tie and the result is a fantastic degree of mental obtuseness which we put up with just to get out on the water and be pushed along by the wind.

You can well imagine how disconcerting it must have been for the establishment with its vested interests to suddenly find that someone is selling an ocean-going sailing machine which has no use for words like hoisting, reefing, or furling, not a single line on deck over which you can trip, and is equipped with a driving element that uses the force of the wind to adjust itself and pushes the craft at twice the usual speed for its length, keeping it level so your drink will not spill, and available or to be dispensed with as instantly as its engine. It is not surprising that the influential British magazine *Yachting World* attacked the claimed performance of this revolutionary trimaran with such malice and hostility that in an unusual victory of right over might, and after an extended libel trial, Walker Wingsail was awarded close to a million and a half pounds of damages by Britain's High Court.

Traditional sailboats are as picturesque as old Dutch windmills, but if you are serious about using wind power safely and efficiently over the water, the same switch must be made as in the case of the modern wind generators that are now found all over the world. Mr Mole in the children's classic *Wind in the Willows* said that there is nothing, absolutely nothing like messing about in boats. I could not agree more, but do feel that the design of most of them provide more than abundant scope for messing about.

Stability, safety and innovation

By now it should be clear that when going to windward, there will be an enormous sideways force generated by the airfoil as shown in the sketch of Figure 8. We have already seen how sideways *drift* due to this force is countered by the action of a hydrofoil below, but their vertical separation leaves a very strong *moment* tending to heel the craft over to leeward. Ways of countering this force start with hanging over the side as shown in Figure 28, considered by many to be both *fun*, as well as an essential and natural aspect of sailing. For bigger boats, the traditional solution in the West was to attach an enormous weight to the bottom of your fin, which doubled as a tombstone should the craft be holed and fill with water. The likelihood of this happening was also increased a little due to the greater draft of the vessel with this attachment. Apart from the safety aspect,

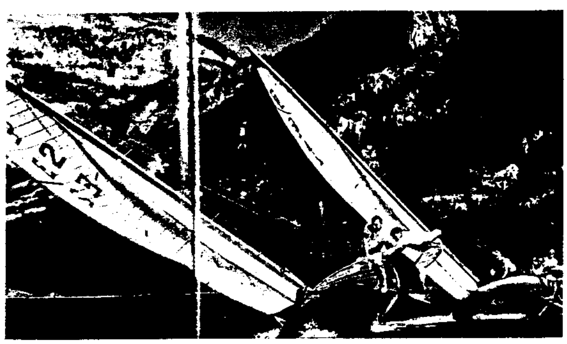

Figure 28. Countering the heeling moment when going to windward with agile human balast. Weekend sailors tend to consider the discomfort associated with this angle of heel a thrilling bonus not to be missed.

the performance would now be definitely limited by the length of the craft as described earlier, and exceeding the hull speed would be like trying to run with a ball and chain attached to your ankle.

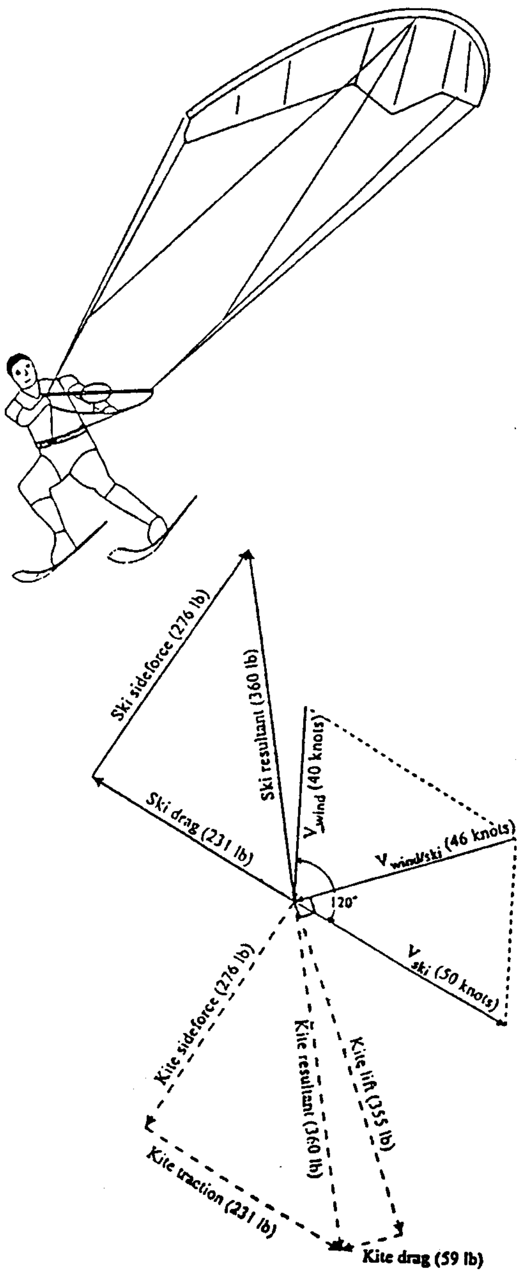

Figure 29. The KITESKI system. The diagram below shows the operational forces at a speed of 50 knots (90 km/h).

But worst of all is that unlike human (or other movable) ballast which can provide a (counter) heeling moment even when the craft is level, the effect of a weight fixed at the bottom comes in only as the sine of the heeling angle. This guarantees an unnatural and highly uncomfortable attitude of the craft when going into the wind, which can be for days or weeks on end in an ocean voyage. On the other hand, the Polynesian and Melanesian craft, both big and small, which used outriggers or double hulls for stability stayed effectively level, and were unsinkable. Voyages over great distances have been made for centuries with such craft, which are the forerunners of the modern multihulls, now gradually and grudgingly being recognised as superior craft in many ways.

An even better way of opposing the heeling moment due to the sail would be to generate such a force with a hydrofoil suitably inclined and displaced from the longitudinal axis of rotation of the craft. Such a balance can be achieved even at zero angle of heel, and can be made to track changes in wind speed which affect both boat speed and heeling moment. Multihulled hydrofoil sailing craft are usually designed this way, which enables them to safely achieve their *fantastic* speeds on an *even keel*!

A point I made at the beginning was that there *should* be a wind so that power can be extracted from the relative motion between air and water. A wind is all that is mandatory, and the form of the sail or the craft, in other words of the over and underwater portions of the device, are totally flexible. A number of extraordinary experiments in futuristic sailing craft have been carried out, mostly by AYRS members, and to end with, I'll say a few words about some of them.

In general, as discussed above, the heeling tendency results from the attachment of the sail to the mast, which is rigidly fixed to the boat. This condition can be relaxed and the sail could be something like a parasail, (a large kite), attached only by lines to the craft at a point not far above the waterline. There is now no mast being pulled to the side and forcing the heel. One such form of sailing involves a person on waterskis holding on to an enormous kite whose position with respect to himself he controls with lines. Such an arrangement is called a kiteski and has a speed in excess of forty knots in a reasonably strong wind. Figure 29 shows the various forces in operation with such a device at a speed of fifty knots!

The link with the water need not even be something on the surface like skis or boats, but could well be a submarine which would suffer no more from wave-drag limitation than dolphins or sharks. The sailor or pilot could be in the submarine. An even more interesting option has the pilot, as we must call him now, in the air hanging from a kite, or in a balloon or similar object, but with an anchor-like device dragging in the water at the end of a line. An old and much respected AYRS member from France, Didier Costes, has several patents on such devices which he calls 'Chien-de-mer,' or Sea Dog. An airplane pilot who has to parachute out of his plane over water could drop such a device on a line before he reaches the surface and remain in the air, using the wind force on his chute to hold him off the water. What is more, as said above, such an *aquaviator* could control both the device above him and the one below to 'sail' in some desired direction to safety.

Every issue of the AYRS journal has any number of such innovations all in the same early stage now that multihulls, hydrofoils and wingsails were a few decades ago, and there is no saying what the future will bring.

Glossary of nautical terms

Abaft the beam	To the rear of the normal to the boat's axis
Angle of attack	Angle of foil to the direction of fluid flow
Bearing away	Turning away from the direction of the wind
Close hauled	Sailing at small angle to direction of wind
Displacement	Displacing its weight of water
Downwind	Going with the wind
Direction of the wind	The direction from which the wind blows
Draft	Depth of water needed to float a vessel
Form drag	Resistance to motion in fluid due to its shape
Furling	Rolling up and binding (a sail)
Heel	Lean over due to pressure of wind
Hoisting	Raising of sail to operating position
Induced drag	Resistance implied by the generation of lift
Jib	Triangular sail in front part of ship
Knot	One nautical mile (1.8 km) per hour
Leeboard	Lowerable plank attached to side of ship
Leeway–lee drift	Sideways drift away from the wind
Leeward	Away from the direction of the wind
Lift	Force on foil perpendicular to fluid flow
Mainsail	Big sail mounted on mast of ship
Multihull	Craft with two or more hulls
Off the bow	Angle to the front end of boat's axis
Reefing	Reducing area of sail
Runners	Long blades on which an ice yacht slides
Spinnaker	Very large sail hoisted in front to go downwind
Tack	To sail at small angle to the direction of the wind
Trimaran	Three-hulled craft
Windage	Area exposed to pressure of wind
Windward	Towards the direction of the wind