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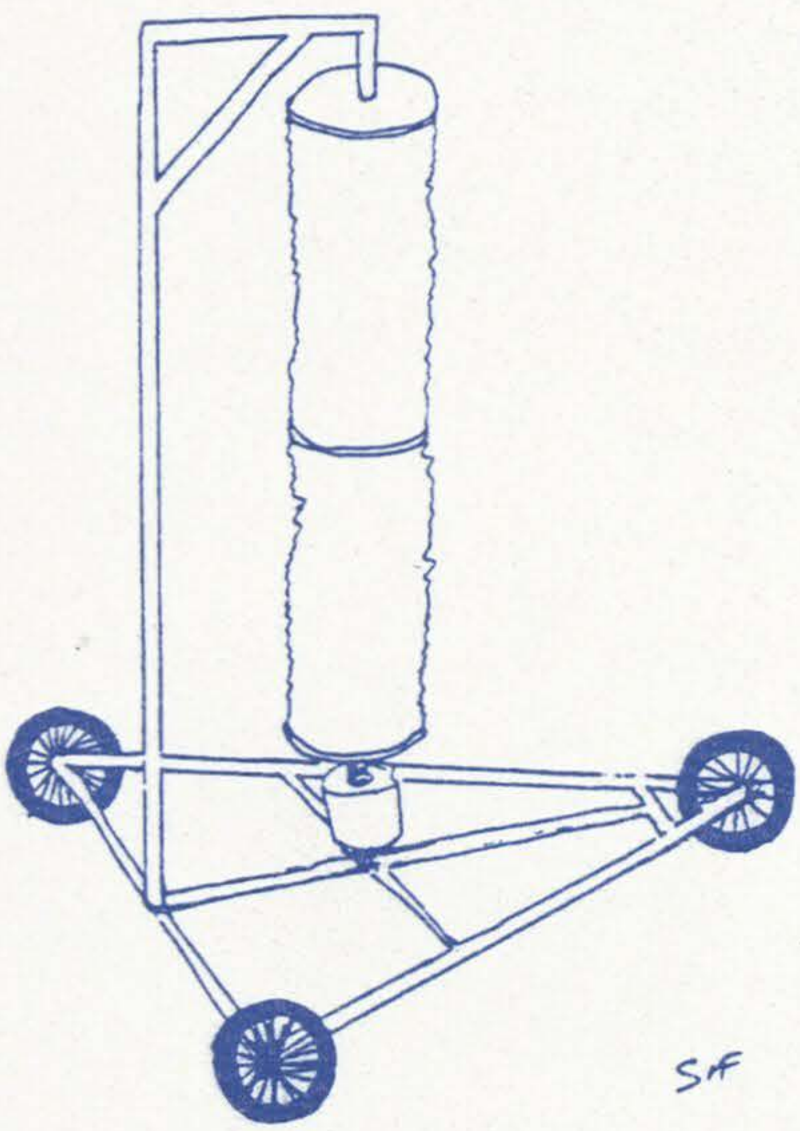
Rotors and Steering - Members Papers 1998



Edited by S Fishwick

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Rotors and Steering - Members Papers 1998

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Submissions Guide

Contributions for future AYRS publications and newsletters should be submitted on 3.5 inch IBM/DOS-compatible floppy disk, in one of the following formats: DOS/ASCII text, Microsoft RTF (Rich Text Format), Microsoft Word/Word for Windows, Word Perfect 5.0/5.1, Windows Write. We hope to accept Adobe Acrobat some time in the future. Diagrams/photos should NOT be embedded, but sent as separate files, using Microsoft Draw V1.0, Micrographx Draw/Designer v3.x, Corel Draw v4, TIFF, GIF, JPEG, PIC, PCX, AutoCAD, or Draw Perfect. Charts from Excel and Lotus 1-2-3 are also acceptable. Note: it is a condition of submission that the right to publish, in any form, the material submitted shall be granted to AYRS.

Material may also typed in black ink, double spaced, with wide margins, on one side of A4/legal paper. Diagrams should be drawn in ink, on separate sheets for preference. We will not reject manuscripts out of hand (unless we cannot read them) but it will take time to get them typed !

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Introduction

Of late, AYRS publications have each had a common theme binding the contents into a coherent whole. However, there are always some papers that do not fit in with the selected themes. Essentially the Editor has two options. The most common choice has been to keep such papers until there are enough to make a themed publication. Although this may be better for our readers, who can look at the title and know what to expect, it hardly fair to authors to keep their material unpublished.

This edition of the AYRS Journal takes the other approach. It contains a number of papers with no common theme, but which are too important to wait on the shelf. It is a return to the original style of AYRS publications, and while themed editions will not disappear (for example, publications on surface-effect craft and on rapid boatbuilding are in preparation), you can expect to see more of these "magazine style" editions from time to time.

This edition can be likened to a three-movement symphony. The first movement is a series of reports by Deiter Schulz on his experiments with Flettner and Thom rotors. This is a magnificent example of the work that can be done by a skilled amateur with a little time and materials to spare. Over a few days Deiter has advanced our knowledge of the behaviour of rotor drives. He has also made a practical investigation into Thom rotors which were heralded in AYRS 120 as a way forward.

We follow this with an intermezzo from Frank Bailey on wind tunnels - an essential tool and one that can be constructed by amateurs.

The main movement though is Henry Gilfillan's Unified Theory of Sailboat Steering. Long-standing members may recall Henry's rudderless boat in AYRS 112. That was but one example of the practical work underlying Henry's theory which he has been developing over some years. The Flyby hull-less craft (to be reported in a future edition) is another.

Finally, we present some variations on a theme - a look forward into the future of yachting in the next century. Whether they are right or not only time will tell, but we can be sure that whatever developments accrue, amateur yacht researchers will be there working on them.

Flettner-Rotor

Dieter Schulz <Sunnyservice@t-online.de>

Date: Thursday, 4 June 1998

While waiting for some documentation from AYRS dealing with the Hows and Whys of a Flettner-Rotor, I took two days time out and built one. The cylinder is 2.5m high and has a diameter of 0.61 metres - determined by the material I found in my little company. Construction: To have the smallest moments of inertia and an easy building-method I took a 48 x 1.4 mm aircraft-tube (alloy) and three circular sections of plywood. One was fixed at the top, one in the middle and one near the other end of the tube. Then I pulled a fabric-cylinder over that construction and fixed it with staples. This looked very good and the weight was about 6 kg. Then I wanted to make it perfect and tried to shrink the fabric - a laminate - to get an absolutely "stiff" cylinder. Result: The fabric became "wavy". If you want to try this, more circle sections are needed. I should have known that from our aeroplanes.

The drive was made from an old battery-screwdriver/drill, which turns at 600 rpm. Connection was made by a little (rubber) friction-disk between the tube and drill head, so the tube was direct driven. The other end of the tube has a little ball bearing and the whole cylinder is hinged in something like a thin steel gallows, which is mounted on a three wheel chassis. The drill is connected to a battery-charger, which gives a constant voltage. Balancing the cylinder was easy when horizontal using small pieces of lead.

Some power measurements:

Drill only:	600 RPM, 14 Volts, 2 Amps = 28 Watt
Drill with tube in gallows	595 RPM, 14 Volts, 2,2 Amps = 30,8 Watt
Drill with tube and sections (without fabric)	580 RPM, 14 Volts, 2,2 Amps = 30,8 Watt
Complete cylinder	500 RPM, 14 Volts, 7,4 Amps = 103,6 Watt.

About 75 Watts are consumed by the cylinder at a constant speed of about 500 RPM. 75 Watts can be produced by a cyclist, if he is in training and drives the cylinder by a little gear, but I have some doubts that a Savonius-rotor driven by the wind will do that, although theory seems to make that possible. A very simple calculation: if forces vary with the cube of the cylinder proportions and with rotational speed, we can use the volume of the cylinder to calculate the power consumption. With my cylinder (0.75 m^3) we need about 100 Watt to rotate a volume of 1 m^3. The "Buckau" Flettner-Rotor had a volume of 96 m^3 and should need 96x100 Watt = 9.6 kW. But it was driven by a 7.5 kW engine - my cylinder is rough and a bit wavy and of another aspect ratio, maybe that causes the error of about 20 percent.

Having added endplates of 1 m diameter to my cylinder now everything is ready for a test on the wheel-construction. What can I expect?

The rotational speed of the cylinder-fabric is 16.36 m/sec at 500 rpm. So a wind of 5 m/sec - Beaufort F3 - gives a speed ratio of 3.27. That is OK and wind-tunnel data tells me that I can expect an overall Lift coefficient for the cylinder of 7.0. The projected area of the cylinders is 1.55 m² and so I could get a total lift of 0.6125 x C_l x Vo^2 x length x diameter = 163 Newton. A simple sail with an overall lift coefficient of 0.9 should have 11.8 m², to generate the same lift. But I'm living in a calm region of Germany and so I have to wait for the wind on our airfield. (The wind is always strong and gusty if we want to demonstrate our aeroplanes to a client. So, perhaps, I need a new client to get first results from my 2-days work?)

First result for me now: It is not too difficult and expensive to build a little test-rotor, which could drive a little boat - perhaps. With a bit more experience this little cylinder could be offered for the same price than a spar with sail and so on. But first we should see what the wind will say to this construction. I will soon tell.

Date: Sunday, 7 June 1998

Having built a 2.5 x 0.61 m Flettner-Rotor, yesterday evening I had my first experience. A little thunderstorm 10 km away brought a gusty wind with 3 - 5 m/sec. I put the rotor out on the airfield on its three-wheel undercarriage - and it moved forwards. The handhold force was - estimated - about 40 Newtons. Then the old battery-drive quit with a smell of burning insulation. I installed a 220V speed-controlled drill motor instead and now I could speed up the column to 700 rpm - quite enough due to some vibrations. Due to the (lack of) length of the 50m cable, I had now to test in front of my little factory, where the wind was more gusty. Once holding the three-wheel-gallows with the fast running rotor I could set my feet on it and it began to run away until the sideforce tried to bring us out of the vertical position. Then the wind went and it was dark.

Experience: Although one is a bit astonished that there are suddenly some forces generated by a fast running column, it feels like standing on a sail-board. To be sure, theory is predicting something like this, but it is another thing to see the theory at work. The forces I felt on my three-wheeler were comparable with those I had in other times, testing a ground-fixed Moth-sail. I hope that the next time the wind will come in daylight-conditions, so that I can make some measurements of the forces - 2 or 3 people are necessary to do this.

If someone wants to build a Flettner-rotor: make it as light, and with the mass as concentrated in the middle, as possible. It can be built like a wing with circular-sections, and it will be worthwhile to discuss this with one of the organisations for homebuilt aeroplanes, if no other experience is available. A rotor-weight with a minimum of rotational inertia, and of the dimensions given earlier, should not exceed 4 kg and will be comparable in power with a 10 m^2 Sail - in theory. Direct drive of the middle spar is a very simple solution, but all tools with gearboxes - drills etc - will not resist the bending of a cantilevered shaft for longer than a few minutes. The gallows, though, is heavy and should be avoided.

So the best would be to make the rotor with a very stiff centre-axis - designed like a simple wing with circular-sections and to use ball bearings at the very bottom of the reinforced free shaft and under the column a reasonable distance away. A three ball-bearing outside - Inline-roller-skate-wheels could be possible - could do this. Spar diameter must not exceed 50 mm, because most forces in the rotor area are taken by the stiff fabric, glued and stitched to the circle-sections. My next rotor in a few weeks will be designed in this way.

From my very first experience: make everything as simple and changeable as possible, because there will surely be changes. Try the whole thing first on wheels, because this is much easier and forces and other things can be observed in a very simple manner. 100 Watts output will be enough to make the rotor rotate at the necessary rpm - given the above dimensions of 2.5 x 0.61 m. The engine should be geared-down, because a slow running engine struggling against the moments of inertia will overheat. In the construction described a very light toothed belt reduction will work fine, if the motor-shaft is held in 2 additional high-speed ball-bearings.

Date: Sunday, 7 June 1998

This afternoon I could test my fabric-covered Flettner-rotor again. Wind was about 2 to 4 m/sec - changing very often. The best force I could measure with that wind was a total force about 130 Newtons. I could only measure forces acting in the direction the wheels can move, but there was no tendency to tilt my three-wheeler to the side (1.6 meter distance between the two main-wheels). 130 Newtons in wheel (or keel) direction is not so bad.

Experience: There is only a very small region of rpm which generates the required forces. Playing with the speed of rotation has the same effect as playing with the angle of incidence (moving the boom) of a sail. But using a sail you can see what you are doing and every sailor will have a feeling for the right angle, or he will watch the windvane at the top of the spar - or tell-tales on his sail. Standing beside a rotor you don't see a thing - you just hear the speed and the "noise", if the fabric is stretched by the forces it generates by itself. (Fabric must be glued onto more sections than I have installed!)

Some little strips of fabric on little tubes 1.5 m distance to the rotor showed that a too high rotational speed bends the invisible streamlines more than 120 degrees, and the maximum force occurs only if the bending is about 90 degrees - a logical thing.

predicted by theory. But this means also, that a rotor running too fast for a given windspeed on a boat can make the ship go backwards - although the main direction is OK. Changing windspeeds and directions could make a man on a light rotor-boat pull out his hair from his head. The boat will go and stop, will be banked and turned and so on.

Conclusion: Four things should be fulfilled before sailing with the rotor:

- A more-or-less steady wind-direction, in order to have a rough guideline for the boathandling
- A more-or-less steady windforce, in order not to over-bend the streamlines
- A quick reacting rotorspeed, though under-bending (increasing windspeed) is not critical.
- A device near the rotor, which shows you the resulting bending of the apparent wind around the rotor, resulting from natural wind and boat speed.

Steady wind-directions we can have more often at the coast or offshore than on the land. Steady wind-force - no rapid reductions - will also be much better at the coast than on my airfield, with hills and trees and other things around to cause turbulation. (More wind means less bending for a given rotorspeed and does not change the desired force direction.) Quick-reacting rotorspeed is a derivative of low moment of inertia as possible. A streamline bending indicator can easily be "invented" using a lever freely rotating around the same centre as the rotor as a kind of "weather-cock". Under those circumstances the rotor could give a boat a nice and well directed push, because 130 Newton total force by a 2.5 x 0.61 m rotor in a wind of 4 m/sec is a fine thing.

Last but not least: The tests I made here on the airfield are very simple and you could say that the theory predicts all the things which occurred. OK; but there is always a big gap between theory and practice, which has to be filled by human trials in order to be able to handle the theory. I have no doubts that there will be some people, who tried a very fine rotor on a boat, and couldn't handle this expensive thing, so missing some basic and simple experiences. And that is also the reason why I took a drilling machine to rotate my column and not an automatic windspeed correcting Savonius-rotor. One little cheap step after the other - the fine and golden things we can show later.

Date: Wednesday, 10 June 1998

This afternoon the weather changed from sunny to rainy and I got a little wind of about Beaufort F2 to F3 - unsteady, naturally. The three-wheeler was fitted in the meantime with a new battery-driven drill-head, which works successfully up to 400 rpm, and a light motorcycle-battery could replace the 220 Volts cable for the bigger drill motor. So I was now independent of the power supply from my factory.

Our runway is about 400 m long, asphalt, and the wind was across its direction. Fine! I started the little motor and then installed myself on the three-wheeler in front of the rotor. The maximum speed in this light wind was about 8 km/h and there was no problem of heeling, because the centre of pressure of the Cylinder was at the height of my shoulders. So I could stand right up without any difficulties. Testing the rotorspeed needed I found that there are 2 speeds which give a bigger force. One was high - about 350 rpm - the other was very low - about 70 rpm. The last one I found when cutting the power and was standing beside the rotor when suddenly it "sounded" and the three-wheeler ran away. Not too fast though that I could not catch it easily!

I tested that three times - whenever the rotorspeed was very low suddenly the whole thing moved again. Windtunnel data says nothing about this phenomenon, and I believe that this is an effect due to my wavy and rough cylinder-surface. Also astonishing is another fact: as you know, my cylinder skin is a fabric. When not turning this fabric is not affected by the wind - it is not pushed in at the pressure side. When you make the cylinder turn at the very low rpm, the fabric begins to "sound" like a flag of that material, and standing about three meters behind the chocked three-wheeler I could see that the fabric was pushed in on the pressure side. The suction side stays normal and cannot be sucked out due to the fixing of the fabric at the circular sections. At higher rpm this effect stops and then, at maximum rpm, which gave a rotational speed about 3.5 times the windspeed, the pushing in occurs again and the cylinder "sounds".

This is new, because all experiments I have heard and read about were made with very stiff cylinders, so that a pushing of skin on the pressure side at 2 speeds could not be observed. Maybe there are several speeds a rough cylinder can work. The first is, when a certain amount of air is rotating, the second when a bigger amount of air is forced and so on. It is not too unusual that things change by steps dealing with air and rough things. And I believe, that the roughness and waviness of my cylinder provokes the effects described.

Then I wanted to know how fast the three-wheeler would run without my weight (about 90 kg). I measured the force - about 8 kg in wheel direction - and then I let it run away. It "speeded up" to about 12 km/h I guess, because I waited at the starting point like a little boy to see what would happen. After about 60 meters the three-wheeler ran into the grass, turned, and now the force of the running cylinder could tilt the whole thing nice and slowly. Bang! The bottom Cylinder-section broke, the upper bearing broke out - finished. Why must grown up man be so childish? OK, this "experiment" was not too professional, but I wanted to see how fast ...

Conclusion: My cylinder developed a maximum of about 15 kg force in the direction of the wheels - in wind about a good Beaufort F3, across and a bit from behind. It feels like a invisible sail. It is very difficult to have the right cylinder-speed in a first trial. You don't really see what you do, and what the wind is doing, because of the circular airstream within one meter distance of the cylinder. Fabric should be fixed to more sections than I used. Weight for a 2.5 x 0.61 m cylinder can be reduced to 4kg. And last but not least: IT REALLY WORKS.

What's next? If I have a little bit time I will build a better Cylinder of the same dimensions - less weight, without the gallows, with a stiff fabric covering and smoother. I think about a simple steel-platform, which should make it possible to install the whole thing also on a not-too-twitchy boat - a catamaran would be fine. And then - you can believe me - I will test the next time somewhere where I have more and steadier wind and not the light gusts turning from here and there and everywhere that we have on the tree-shielded airfield here. These conditions make it nearly impossible to make good measurements of windspeed, rotor-speed, and force within a short period.

Last but not least: The force shown at very low rpm by my cylinder tells us that there is no doubt that a pedal-driven cylinder will work on a little boat. But handling the right speed of the column and the optimal direction of the boat will be another thing. But maybe, once on the water and having the old sailor-feeling again, things could turn out much easier than expected.

This will be continued in a few weeks, when a new cylinder is ready. Greetings to everyone who could not believe that a running cylinder will really work!

COMMENT FROM: DAVE CULP

Date: Thursday, 11 June 1998

I'm amazed at your experiences and your enthusiasm! Unless I'm mistaken, it's been a scant two weeks since you first posited some questions about Flettner rotors, and here you've now got more hours under rotor sail than all but 2-3 living humans! My hat's off to you!

OK, some numbers here. Wind "2-3 Beaufort;" perhaps 12 kph? Craft speed 8 kph, giving apparent wind (assuming a square reach--course 90 degrees true) of perhaps 14.5 kph, or 4 m/s. Your rotor of 0.61m dia, yields a circumference of 1.92m. Spinning at 70 rpm (1.17 rps) gives us a rotational speed ratio of the rotor's surface proportionate to apparent wind of $(1.92 \times 1.17)/4 = 0.56$. *(Norwood calls this ratio "alpha.") This is far too slow "it says here" to gain much useful lift at all. Both Flettner and Norwood suggest such a rotational alpha might yield lift coefficients around 0.2--0.3, and a drag coefficient perhaps twice that. And yet you gain useful lift! This is very interesting. Also very puzzling. At 350 rpm (5.83 rps, or 11.2 m/s* *speed at the rotor's surface) gives us an alpha of $^{11.2}/_4$ or 2.8, which should be well up on the lift charts (I see you've given this alpha figure as 3.5 later. You do cite the cart as being blocked at that time, not moving, so the wind at that time is 12, not 14 kph). For a rotor with aspect ratio of 4 and alpha of 2.8 Norwood says we should see a lift coefficient near 3.5 and drag coefficient of perhaps 2.0 - a dismal Lift/Drag (L/D), but as you can see, very high lift.*

Norwood's graphs are inconclusive whether, at this fairly low aspect ratio, "fencing" the cylinder with end plates will yield additional lift or efficiency. He shows conclusive evidence in favor of end fences at higher aspect ratios however. Logic suggests even larger gains are available here. Both Flettner and Norwood indicate that rotational alphas can be increased up to about 5-6, yielding lift coefficients of the order of 4-4.5, with a drag coefficient leveling off around 2.7-3.0 for this aspect ratio rotor. (Flettner's "Buckau" had two cylinders 9 feet dia by 60 ft high, with end plates 11 ft diameter, to give some reference numbers. Aspect ratio = 60/9 = 6.6. They were driven as fast as 700 rpm, yielding maximum rotor surface speed of about 100 m/s. Typically though, they were driven at $^1/_4$ of this speed or less.)

Higher lift coefficients may be had from higher aspect ratio rotors, particularly with end plates, or "fences." Norwood shows a rotor of AR = 12, with end plates of diameter = 3x rotor diameter yielding a coefficient of 10, at alpha = 6. Drag coefficient actually drops a bit, between alpha = 2 and alpha = 4, then steadily rises. <u>Much</u> higher lift coefficients -- as high as 20-25, with a significant decrease in drag coefficient -- yielding L/D's as high as 30-35 -- may be had with the addition of intermediary fences along the rotor's length, and spinning the rotor at alphas of 7, or even higher. Scottish engineer Thom showed that adding 3x diameter fences, every $^3/_4$ diameter, all along the rotor's length, apparently allows the entrained vortices to generate very high pressure differentials, yielding these very high lift coefficients. Thom did his work in the early '30s, and, through a mis-calculation of the power needed to spin the rotor, dropped all his investigations on the cusp of real discovery. Norwood found Thom's error, very recently, and offered his proof in "21st Century Sailing Multihulls." (AYRS #120). Norwood built a small Thom rotor, 150 cm dia by 1 meter long, which suggested to him his proof was accurate.

*Norwood offers math and sketches showing a pedal-proa with a 3 ft diameter, 9 ft tall Thom rotor (Thoms are relatively insensitive to aspect ratio, due to the fencing), which might sail at velocities equal to or a bit above the windspeed (12-18 kts worth) under human power alone, and that a very large, light ocean-going proa (120 ft long, 18,000 lbs disp), might use a 26' tall, 6' diameter Thom rotor to cruise at 25-40 kts around the world's oceans. Diesel power to spin her rotor (Thom's take a *lot* more power than Flettner rotors) might yield about 28 miles per gallon. at 25 kts boatspeed. Poetic license and environmental concerns might leave us desiring* *solar, wind or something even more esoteric for rotor power, but the numbers overwhelmingly favor a modern lightweight turbo-diesel. This sounds a bit disheartening, but it equates to about 80 gallons of fuel to cross the Atlantic--or that 8-900 gals of tankage--say 5000 lbs of fuel--would give one non-stop round-the-world capability).*

Norwood also sketches a 50' cruising cat, displacing a stately 24,000 lbs, able to make 12.5 kts under 10 kts wind, at just under 40 miles/gallon. Such a voyaging craft might carry 100-200 gals of fuel, for a 4000-8000 mile range. Top speed under rotor sail might be 25 kts (Norwood says the math yields a maximum possible of 32, due to the very low center of effort of the rotor, but let's be conservative, eh?).

<u>Nobody</u> has yet built a full-size Thom rotor.

Your finding of two peaks in the drive vs. rpm curve puzzles me a good bit. The higher speed is plausible; as alpha passes (approx.) 2.0, the two stagnation points of the rotating cylinder's airflow join into a single one, and begin to move away from the cylinder's surface (see Flettner, Norwood, Marchaj, Abbot and von Doenhoff, and surely others for information on rotating cylinders' airflow and Magnus lift). I could believe that this occurrence might create localized high pressure areas on the cylinder, with corresponding deformation of the cloth. All the data I have suggest, however, that there is no sudden change in lift at this point, but only a gradual increase. And yet, from your posts, it is evidently at this point that the rotor "lights up" and generates significant increase in lift. The similar phenomena at low speed completely baffles me. At this rotational speed, the cylinder ought to exhibit a slight overall decrease in total drag, and nothing else.

Not too many people have written about surface roughness in Flettner rotors, except to note that absolute smoothness isn't critical, as it is the bound vorticity, after all, which leads to lift generation (the air at the rotor's surface is moving at substantially the same speed as the rotor's surface). Your rotor's surface isn't just "rough," however, but distinctly "wavy." Very likely "wavy" enough to extend some way out into the (presumably) slowing airflow (Presumably because the rotor's surface is spinning at far greater speed than the free air--surely there is a decreasing airspeed gradient as one moves away from the rotor's surface). I wonder if this is having some effect? The only one I'd predict is a greater requirement for power to turn the rotor..

Let's see if the math checks out:

Aerodynamic force = the dynamic pressure of the wind, times the projected area of the cylinder, times the lift coefficient.

Dynamic pressure = $\frac{1}{2}\rho$ (mass density of air) times velocity squared.

At a local airspeed of 20 ft/sec (6 m/s), cylinder a projected area of 17 sq ft (1.525 sq m), and lift coefficient of 3.5: Dynamic pressure should be about 0.48 lbs/sq ft, and total aerodynamic force should be about 29 lbs, or 13 kg. – Only about 14% from the measurement. Dead-on agreement, in my view!

In the past I have given much thought to lightweight, robust small rotor construction. I concluded that an inflated airtight fabric cylinder offers the best compromise (easy to stow, too). The shape would be assisted by the end plates, which would be simply a single layer of fabric, cut into a large disk and hemmed along its edge. Into this hem is inserted a small diameter fiberglass rod (modern kite spar material), forming a round hoop. Centripetal force generated by this hoop while spinning will hold the fabric disk very taut, and should maintain the round, flat-ended shape of the cylinder as well. (Remember that the plate is three times the diameter of the cylinder; thus its perimeter velocity is also three times that of the cylinder. Dieter's little 0.61 meter dia cylinder will need 1.8 meter disks. These, spinning at 350 rpm, will yield a rim speed of about 35 m/s--plenty of centripetal force. To get a Thom rotor, a number of short fabric cylinders will be joined to intermediate fabric disks + hoops, and the whole made airtight. The very light weight, plus careful manufacture (especially in the fences), should allow these cylinders to be made to balance fairly easily. The Thom version should be less prone to wobble, too, as each fence forms a "rigid" plate, in effect. If built as a Thom rotor, it will need (and be capable of utilising) higher rotational speeds than as a Flettner. Norwood suggests a rather large diameter cylinder, spinning at an alpha of 2.5 for the pedal proa (you'll have to read his book to understand why he spins it this slowly--it has to do with sustainable force generated, limited by human power), and 7 for the big diesel proa. Alpha's around 6-7 produce the highest L/D (remember that Dieter's cylinder's alpha is around 2.5--3.5, and at very low windspeeds.)

I once calculated, that, at 30-35 kts apparent wind, the big ocean going proa's fence rims' might exceed Mach 1--a likely upper limit (though Norwood disagrees). Fence diameter = 3 x rotor diameter; rotor surface speed target = 7 x apparent windspeed, for the big proa. Thus fence rim speed = 21 times apparent windspeed = 630 kts, at 30 kts apparent; nearly 740 kts at 35. Mach 1 is, what, 650 kts, at sea level? Likely, of course, even this big boat won't be pushing for maximum drive at this apparent windspeed, and will have "capped" her rotational speed somewhat lower. Racers might test this limit though – YP Endeavour. for example, at 46 kts boatspeed (her best), sees better than 42 kts apparent wind, in 17 kts true. She's "fully powered-up" under this condition, and calling for all the force her rig can provide. Far larger ocean racers are sailing at this, or even higher apparent winds, while maintaining maximum drive in their rigs. I wonder what an on-going sonic boom, 6 ft above one's head, sounds like?

Date: Friday, 12 June 1998

There's another real astonishing thing with my cylinder: Lift is not nearly constant, if the rotation speed exceeds three times the windspeed. Windtunnel data say it should, but I found another behaviour and the only reason I could imagine is: A rough and wavy rotating cylinder which is fixed generates a bending of the streamlines, which can result in a closed circular airstream, which does not show the Kutta-Joukowski airflow-conditions generated by a foil section. Said with simpler words: the possible lift is then acting in all 360° directions, tending to make the air column just fatter, not moving it.

I believe in that reason, because I could see that only at very definite rotation speeds the fabric was pushed in the cylinder. In my third letter above I said on the pressure-side. But this was not correct: I meant on the wind side! There, where the wind could deform the fabric of a not rotating cylinder by pressure. Sorry for that mistake with the words. But this point of pushing in is not located about 180° to the estimated and forcing low-pressure region. We have only about 90°. From a top view. Wind coming from the left, cylinder is rotating clockwise, low pressure region is "at" 12 o'clock, high pressure region at 6 o'clock. But with my cylinder the high pressure-region was at 9 o'clock, if the pushed in fabric showed us the location of high pressure.

And that means, that a rough and wavy cylinder can make the high pressure region travel more and more to the region of low-pressure - with a collapse if speeding up the rough surface more and more. Impossible with a smooth metal tube or something else, but probably possible with a wavy, rough and "floating" cylinder-covering.

Date: Monday, 15 June 1998

Yesterday evening - coming home from Munich - I found some little books from the AYRS in my post box. Now I know what a Thom-rotor looks like and how it is described by Norwood.

Thom wanted to avoid axial-flow by adding fences on a Flettner rotor. This is correct and many aeroplanes have wings with fences to reduce an axial flow - some showed end-plates which increased the effective span. And Thom (Norwood also) believed that the astonishing data of a multi-fenced rotor are the effect of reducing axial flow - following the first thoughts about endplates. But is this correct?

A Flettner rotor will speed up the air by friction due to its skin. Increasing the friction or increasing the area by a given rpm can - not must - result in a region of air around the cylinder, which much more speeded up. The first cause of speeding up the air is the friction.

A Flettner rotor, which is 12 m high and has 1 m diameter has a friction-area of 37.7sqm. Adding fences - circular ring sections - at every 0.75 diameter with three times the diameter of the cylinder has a very special result. Each of these fences presents a rotating friction-area of about 6.25sqm. But we have two sides, which cause friction - the upper and the lower -, so that one fence produces 12.5sqm friction area. On the typical Thom-rotor, which is here 12 m high, we have 16 of those fences. So adding those fences to a rotor we have added 201sqm rotating friction-area. The rotor itself has 37.7sqm friction-area, the fences have 201sqm friction-area and both together have 238.7sqm! About 6.33 times more than the rotor without fences.

There is no doubt that fences at the end of a rotor will avoid axial flow. But when adding so many fences we have to leave this common picture and look to another one. The Thom-rotor is not a super fenced Flettner-rotor – it is the most practicable way to speed up a column of air by friction, using a very large friction area with compact dimensions. I think it is not the usual fence-effect, it is the increased friction area which results in the given data: which show very high lift coefficients and a wonderful L/D. That's my point of view – ready to be discussed.

But why do we have such a wonderful L/D and why can Norwood suggest that the aspect ratio of a Thom-rotor is not of great interest? This seems to be against all verified practice with wings, sails etc., where the aspect ratio is a big influence. The most sensible explanation, I think, is this one:

Did you ever row your boat back to the harbour and did you have a look at the oar? You will often see a column of air just like a tornado in the water. This "tornado" is the effect of a circulation due to different pressure areas which are rolling in - as behind a wing tip. Dealing with a Thom-rotor it produces a very strong vertical vortex of air due to its large friction-area. We will find an area of fast circular running air beside it. But this area cannot be thought isolated from the surrounding atmosphere - there must be an interaction. And I bet that we will find, above the Thom-rotor, a tornado-like rotation going nearly vertically and then bending to give a "tube" of air which is much more higher than the mechanical rotor itself. This, naturally, increases the effective length of a Thom-rotor to an aspect-ratio which is much more better than the geometrical dimensions can show us. And then, under those circumstances, it is not a "wonder" that wonderful L/Ds will result. We are not handling a 12 m rotor, but a mostly invisible rotor which could have a height of 36 m and more!

The problem, I think, is that all measurements with the Thom-rotor were made with a fixed one and within a low-speed-airstream. (A closed wind tunnel could be expected to "avoid" creating the "tornado" and better AR). But what will happen if this rotor moves - moves very fast say at 25 knots? Most possibly the virtual-air-rotor bends more and more down due to the forces it generates by itself. And then we have the picture of a low-aspect-ratio-wing, producing high-lift and being balanced by two vortexes right behind it. (A Thom rotor has only one vortex due to the adjacent ground/water giving an "endplate effect.") Under those conditions, the virtual effective span of the rotor will decrease, the L/D will decrease and probably the "wonder" is gone.

I do not know this and I cannot and will not calculate it, but I think, perhaps, I'm not too far away from the truth.

So, what about a Thom-rotor which is of aspect-ratio = 1? With a high alpha (rotating speed/airspeed) it should have a remarkable strong and long top vortex increasing the effective aspect ratio. But on the other side: the higher the rotation speed, the less the pressure (?) in the vortex and the more slender the vortex that will result - formed to a thin tube by the normal pressure of the atmosphere (like a propeller-stream, which has just a percentage of the diameter of the propeller). I guess, the best test will be to build a Thom, set my little company office on fire, and move the running Thom through the smoke, or to wait until we have a thick fog laying on the airfield. Then the rotating column of air above the Thom should become visible. OK, fog maybe *is* the better solution!

Last remark:

I do not believe that the Thom needs a very remarkably stronger power source than a rough Flettner of the same dimensions. The air between the "slots" of the fences will rotate like the fences after a short while - forced out by the centrifugal forces but held in by a necessarily generated "vacuum", if no air comes from the centre of the rotor into the "slots". So the most part of the friction under constant running conditions will be the friction of a rotating column of air – a bit broader, but much higher than the Thom-rotor itself. (Do not forget, also, that the pressure distribution of a Flettner must be balanced by energy-eating vortexes, which cannot be avoided by endplates)

And I think, also, that a Thom-rotor does not need an inner Flettner-rotor. A simple tube should do the mechanical work and many circular sections with unknown slot-dimensions could do the aerodynamic friction work - not as fences, but as friction-areas.

Last but not least: These are only suppositions. Don't be too disillusioned about the possibilities of a Thom-rotor. You are invited to discuss those suppositions, not necessarily to believe them.

(The pictures in the book of Norwood tell me that there is a travelling of the stagnation-points, which can explain some of my observations - the pushing of the fabric at 90° degrees. But I believe, that things are much more complicated and maybe we could find a counter-rotating column of air beside the cylinder under certain circumstances. I will build a Thom rotor of 1 m height and 1.2 m diameter with a lot of fences. A centre tube will show circular sections of foam and between the foam I can glue bigger circular "fences" of thin corrugated board. This should be light and not too complicated for a trial. My three-wheeler gallows must be cut and we should hope that the upper part of the gallows will not disturb the "tornado", which can be made visible with some foam packing bits thrown in this area.)

Date: Wednesday, 17 June 1998

In my last comments I supposed the Thom-rotor to be a "friction-machine" and I had a picture in front of my eyes, showing a Thom with many fences every 0.25 diameter of the inner Flettner. So it is interesting to see if this speculation was right, and so I built such a thing.

Dimensions:

Diameter of the inner Flettner:	0,4 m
Height:	1,2 m
Projected area:	0,48 sqm
Aspect Ratio	3
Fences diameter:	1,2 m
Distance from fence to fence:	0,1 m = 0,25 x diameter Flettner

Construction:

The Flettner-rotor was built up around a centre tube with circular sections of foam, wire-cut out of sheets and glued together. Between those foam-sections I glued the bigger fences, which were made from corrugated board and cut out by a saw, turning the board around a nail. The weight was about 12 kg, although I used very light material. (The Flettner weight was nearly half of the total.) The whole thing looked like an old rectifier, but interesting. Direct-drive was similar to the Flettner experience, with two different motors - one after the other in the experiment. I used my trike with the gallows, which was cut down and welded together again.

For comparison: the Flettner is: Diameter 0.61 m, height about 2.5 m with two bigger endplates.

At first I installed for the Thom the same motor I used for the Flettner, in order to have the possibility to compare the Watts. But this was not possible, because my Ammeter range stopped at 15 Amperes and 12 Volts - the lines became hot. To avoid the big initial moment of accelerating the higher mass of the Thom, I wound a rope around the centre-tube projecting above the drill, then pulled very hard and constantly, and having reached about 50 rpm I connected the driver to the battery.

Now the Thom came up to 205 rpm, but still drawing more than 15 Amperes, so a guessed minimum of 250 Watts were needed, to give a constant speed of about 200 rpm. The Thom ran without remarkable vibrations. The surface speed (on the diameter of the inner Flettner) was about 4 m/sec. Almost nothing.

But I put the Thom outside, where we had a little wind of about 2 m/sec. Nothing happened, the trike stood there with the running "rectifier" and me beside it. The next stage was to install a 220 Volts drill motor with reduction gearing. This could speed up the Thom to about 400 - 420 rpm - but I could hear and smell that it seemed to be hard work. Outside again with the Thom and the wire in the wind - virtually nothing happened, although now a $V_{rotorsurface}/V_{wind}$ ratio of about 4 was available. Just a very light movement of the trike with a unmeasurable total force. Having installed "paper fences" I now could cut out very exactly all the fences until I had a rotor proposed by Norwood with a fence every 0.75 diameter of the inner Flettner. This "new" Thom could be speeded up with the heavy drill to 650 rpm - 13.6 m/sec. Outside again – now the trike moves and I guess the total force is about 1 kg. My spiral-balance is a bit inaccurate in the lower region. Then I remembered that I had supposed a "tornado" above the running rotor and I smashed little pieces of foam above the rotor. They were blown away horizontally - there was no "tornado" visible increasing the effective span. I was a bit disappointed with the whole experiment, which had no great cost but gave me glue-covered fingers and trousers, and took about 14 hours to build the Thom-rotor.

My supposition about a friction-machine was right, but I was wrong with the supposition that more friction could have a good effect - a fast running column of air generating better forces. Maybe the projected area was a bit too small - 0.48 sqm. But also in a bit fresher wind, about 3-4 m/sec, I could not feel a total force more than just 1 to 1.5 kg, although I stood beside the rotor and noted in all the trials that there was a certain circulation of air around the fenced cylinder. I expected a Lift Coefficient of about 10 and more and this should have given me about 2.7 kg at the balance or more.

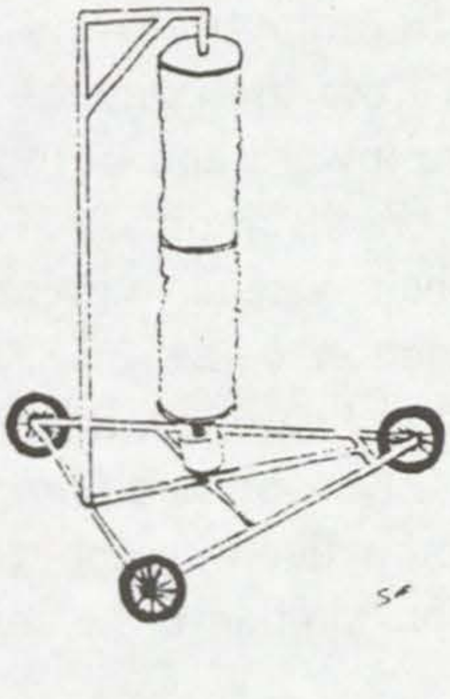
Being so disappointed after the trials, I went for a coffee and decided to repair the older broken Flettner and to re-weld the gallows. This was done within 3 hours and this afternoon I could test the Flettner again - the bottom endplate was missing due to breakage and the lower parts of the fabric were a bit more wavy after my quick repair.

The wind was about 3 m/s and the Flettner, although twice as high and having 0.2 m more diameter than the Thom, ran up much more easily - also due to being half of the weight. The battery and the little motor could give about 300 rpm - about 9.4 m/sec. And again happened, as I described in my previous comments. As it reached only 50 - 70 rpm (about 4 m/sec surface speed) coming up to speed the fabric began to "sound" the first time and to be pushed in a bit. Cutting the power at about 100 rpm, I could let the trike run - me beside with wide eyes to avoid another crash - and we both reached about 7- 9 km/h as the rotor slowed down. Not so bad. Running at full rpm it was no problem in the light wind to stand on the trike which reached then about 10km/h, so that I could roll up and down our runway - sometimes a bit faster, often slowed to about 3 km/h due to the unstable wind-conditions we have here. A steerable trike would be better and changing the rotation direction by reconnecting the wires to the battery is not a problem - it's simple.

When the battery finally ran down, one could hear that the rotor lost speed in the little gusts - quite normal.

Conclusion: I would never say, that a Thom rotor will not work. Maybe my one was a bit too small with 1.2 x 0.4m projected Flettner area, and maybe there is a minimum necessary dimension of the inner Flettner, due to an unknown Reynolds effect related to rotating cylinders. But it is evident, that the Thom consumes much more energy and that the energy needed by a bigger Thom would increase as a cubic. But maybe other experimenters who can spend about $100 on their trials will have better or other results with other dimensions - I hope so, because it would be a fine thing. For me the Fl ettner with 1.5 sqm projected area seemed to be the better solution - at the current moment. Installed on a boat I guess I would have the same feeling as on my Moth-boats of 20 years ago. Remarkable is that my rough and wavy Flettner produces such a high total force in very light winds with very, very, low rpm. This could be a solution for a pedal-driven little proa or catamaran, which will not run 20 knots, but could be a nice toy for fun.

My thoughts now, due to the simpler construction of the fabric-covered Flettner, are to build a better one with a smoother surface, interchangeable with one with a rough surface - both fabric. Dimensions should stay as I have now, in order to be able to compare the results. But this cannot be done tomorrow, because the two weeks time I foresaw for the first, quick-and-dirty, tests are over — and I'm still waiting for a good idea!



Wind Tunnels: A Retrospective & Quantitative Approach

Frank Bailey, Grove City, Pa. USA

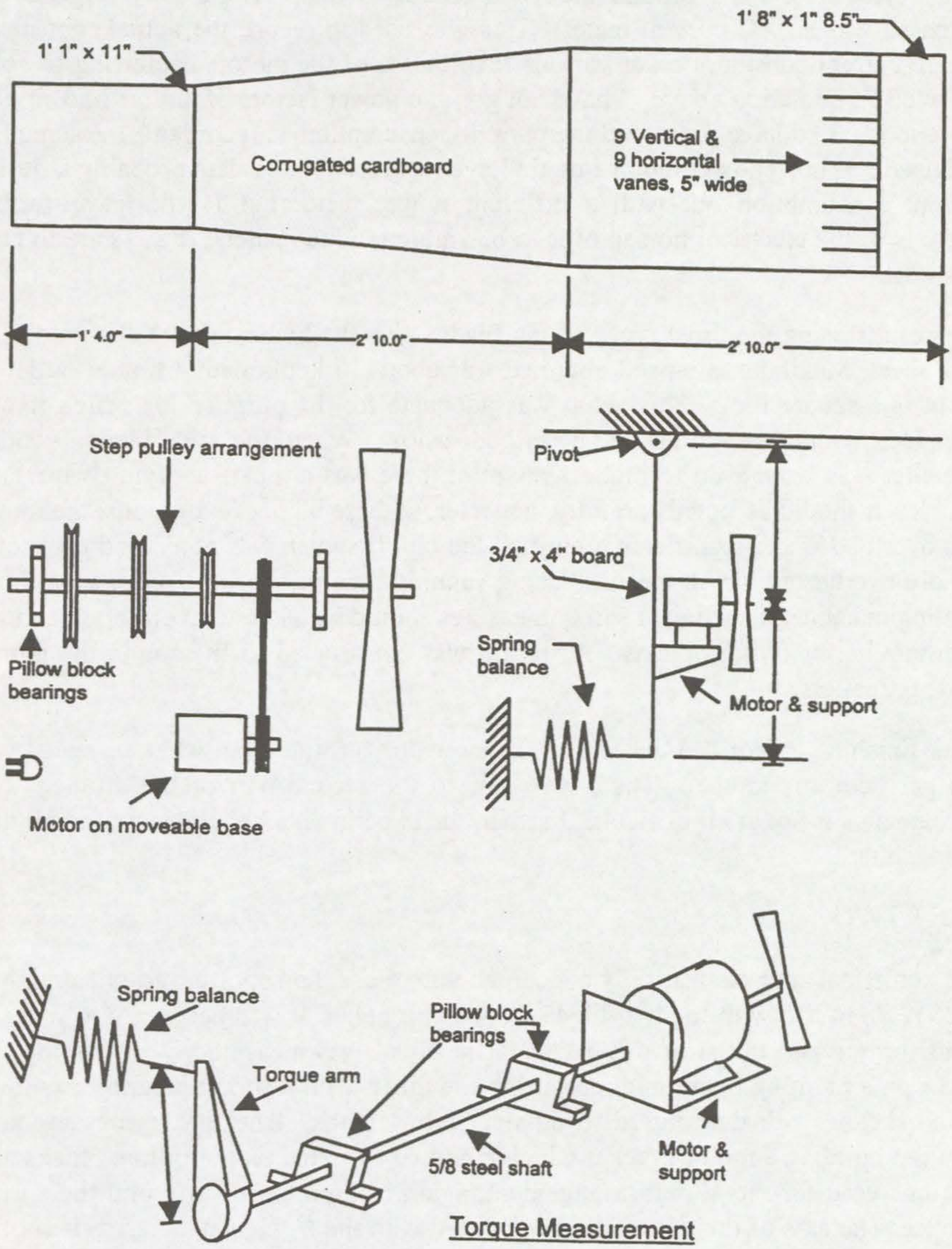
"*Throughout the whole history of the A.Y.R.S. we have run against people who cannot understand what we are doing, which is not surprising as we barely know what we are doing ourselves, and certainly don't know what we are going to do next.*" John Morwood A.Y.R.S. No. 52, 1964.

INTRODUCTION:

There are, in my opinion, two main tools for yacht research: Test Tanks & Wind Tunnels. At first thought, a test tank might appear to be the larger challenge of the two, considering that one must have, for decent results, something like a space 24 ft. long and manage between one and two tons of water. On the other hand, a wind tunnel perhaps requires a smaller space and the handling of air only, a seemingly simple task. As we shall see, this is not the case. This article is divided into three parts. The first part is the nuts and bolts of a small tunnel recently constructed and the second part consists of some useful formulas and data for those who wish to pursue a wind tunnel project themselves. The third part is a review of previous articles on wind tunnels in the AYRS journals.

PART ONE

The Wind Tunnel: Having need of a small tunnel to do some calibration work, I had no idea of what airspeed I might achieve nor how to figure it out and I did not want to spend a whole lot of time on the project. Charging blindly ahead, I constructed a small tunnel as shown in the sketches, using corrugated box cardboard stiffened with wooden battens. I used a small commercial house fan initially. Its motor might be in the neighborhood of $^1/_8$ horsepower with a 5-blade plastic fan 20 inches in diameter. As this did not create enough airspeed, I next carved a two-blade wooden propeller 20 inches in diameter as described in AYRS Journal No. 109 by Phillip Thiel. The pitch was chosen and computed from the tip inwards. I mention this because some propeller pitches are determined from the point of maximum blade width and the other angles computed from there inward and outward. (A convention is to figure the pitch at the $^2/_3$ or $^3/_4$ mark on the radius.) I applied this propeller to a $^1/_3$ horsepower motor, pulley and V belt system giving me four different revolutions per minute, the highest speed of rotation being one to one with the motor. I also constructed out of $^1/_4$ inch plywood two other flat blade propellers as described on the data sheet. The blade angle of the four blade propeller was about 50 degrees and the blade angle for the 5-blade propeller was about 30 degrees, these angles being measured from the plane of rotation, similar to the angle of attack. Most items for



Wind Tunnel Components

this project were lying around the Toad Hill Boat Shop so the only large dollar purchase was an AC current meter. This was used to record the actual root mean square current consumption at various revolutions of the motor. Referring to John Morwood's quotation above, I have not got into power factors of motors and similar esoteric ideas so have presented the current consumption as recorded. I assume if I had used a ½ horsepower motor I might have recorded similar data probably at lesser current consumption but with a different power factor but I will leave further analysis of the electrical horsepower to our more erudite readers, if any care to read this stuff.

The results using the three types of fan blades plus the house fan are shown on the data sheet. Maximum airspeed obtained was about 16 knots with a tunnel outlet of about one square foot. This setup was adequate for the purpose for which it was intended, with reservations as described below. When the two blade wooden propeller was wound up to highest rev/min. there was a most satisfying whirr and rumble. It should be noted carefully, however, at these higher revolutions, the motor was overloaded and significant arcing on the on/off switch was noted and the motor rapidly overheated which meant keeping running time very brief. Also, as with all rotating machinery, sufficient safety measures should be taken to avoid body contact with moving or flying objects. A shroud was constructed to fit around the home-made propellers.

After finishing this drill, I asked myself: How do you figure out what air speed you can get with any motor? Thus, we come to the second part of the article. The mathematics is not at all difficult. Further, the experimental results were not all that good, either.

PART TWO

The numerical analysis was only concerned with the $^1/_3$ horsepower motor running at 1725 rev/min and with the two-blade wooden propeller. It was necessary to find the motor torque and thrust at this RPM. The thrust was measured by mounting the motor on a pivoting board and measuring the thrust with a spring balance as shown in the sketch, with due regard to moment arm lengths. The torque measurement required building a motor bracket which could be mounted on the pillow blocks and bearings used for the V belt arrangement, again using a torque arm and the spring balance. The axis of the motor shaft coincided with the $^5/_8$ inch steel shaft. It should be stated here that all calculated results are merely order of magnitude results, since the spring balance available had too much capacity for the forces developed. Maximum scale load for the spring balance was 400 lbs. and forces developed were no more than 2 lbs.

Computed data for 2-blade Wooden Propellor using 1/3 nominal horsepower motor @ 1725 rev/min

Equation 1 : Thrust $T = A.V^2.\rho$

Equation 2 : Power $P = ½. A. V^3.\rho/Eff$

Equation 3 : Horsepower $= 2.\pi.Q.N/550$

Thrust Coefficient $Ct = T/\rho.N^2.D^4$ $Ct = 0.14$

Torque Coefficient $Cq = Q/\rho.N^2.D^5$ $Cq = 0.01$

Power Coefficient $Cp = P/\rho.N^3.D^5$ $Cp = 0.24$

Where:

A = Outlet area = 1.0 sqft at outlet
Eff = Efficiency (a decimal between 0 and 1.0)
V = Air speed = 26.2 ft/sec at outlet. $V^2 = 692$ $V^3 = 18122$
1 horsepower = 550 ft.lb/sec
T = Thrust = about 2.3lbs actual. (1.7 from Eqn 1. Direct driven)
Q = Torque = 0.365 ft.lbs actual. Mounted on vertical pivoted board
ρ = mass density of air = 0.0025 lb.sec/ft^4 from physical tables
N = 1725 rev/min = 28.75 rev/sec $N^2 = 828$ $N^3 = 23764$
D = prop dia = 1.67 ft $D^4 = 7.78$ $D^5 = 13.0$
P = power = 1/3 horsepower (electric motor) = 183 ft.lb/sec

From Eqn 3: Horsepower $= 2.\pi.Q.N/550 = 2 \times 3.14 \times 0.365 \times 28.75 / 550 = 0.12$

From Eqn 2: P @ 100% Efficiency = 22.5 ft.lb/sec or 0.04 hp

@ 50%	45	0.08
@ 12½ %	181.2	0.33 i.e. about 1/3 hp

Computed Data for 2-Blade Wooden Propellor using $^1/_3$ nominal horsepower motor at 1725 rev/min.

From most any hydraulics text or handbook, equations 1 and 2, and the coefficient equations can be obtained. Equation 3 is actually a "mechanical engineering" formula but useful here also. The sheet showing the computed data should list all items entering into the calculations for the two blade propeller. I have tried to identify, for clarity, each item, their "units" and actual experimental measurements. I will walk the reader through each formula and its results.

Thrust: The measured thrust was about 2.3 lbs. It is assumed thrust at the inlet equals thrust at the outlet, as in the calculation the outlet area and airspeed were used. Plugging values into Eqn. 1, I got 1.7 lbs. of thrust, which was at least in the ball park.

Power: The power calculation using Equation 2 is a bit trickier because there is an unknown efficiency involved in the answer. I assumed efficiencies of 100%, 50%, and 12½%. The 12½% was chosen because it gave a result of about $^1/_3$ horsepower. One assumption here is that the motor actually was developing something in the neighbourhood of $^1/_3$ horsepower. Here again we must repeat John Morwood's quote above and continue. Referring to a handbook or text book again, if one looks at a graph or chart showing dimensionless performance characteristics of a typical airplane propeller, you will note where the thrust coefficient is maximum, the efficiency is zero where the speed of advance dimensionless ratio is also zero. In other words, our propeller's speed of advance is also near zero so its efficiency is also near zero. However, at this point, we do not wish to get into propeller design. Note also that the efficiency figure includes all losses of the propeller and motor and anything else.

Using Eqn. 3, and the experimental measurement of the torque, we calculate about 0.12 horsepower, which is at least not off by a factor of 10. It is to be noted that this horsepower is calculated from a measured torque value while the Eqn. 2 results are derived from a measurement of air speed. Interesting.

The Coefficients: The thrust and torque coefficients were calculated using the experimental data and $^1/_3$ horsepower was used for the power coefficient calculation. Note that these two coefficients drop to zero on a dimensionless plot as the speed of advance approaches and goes beyond 1.0. In other words, they change.

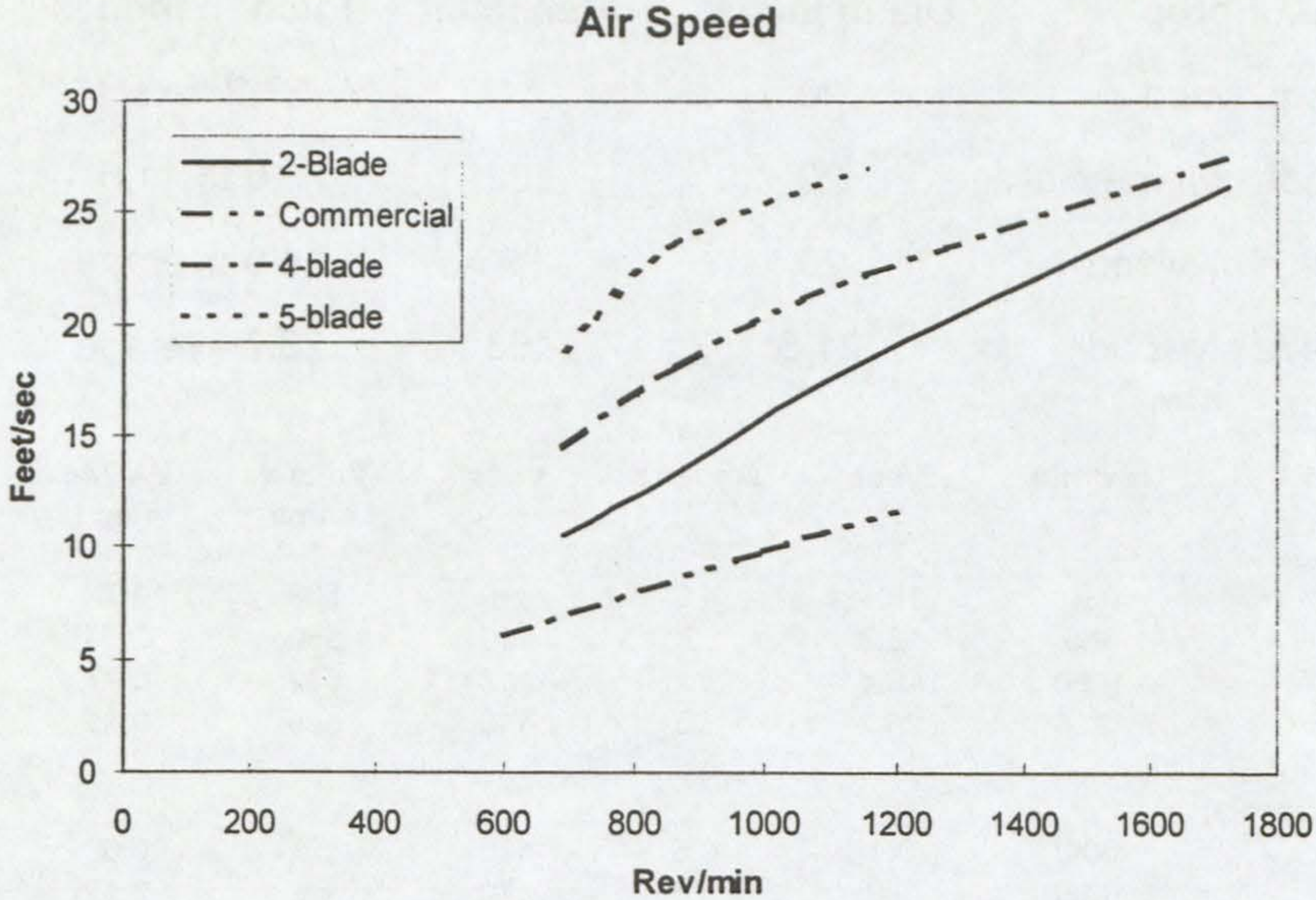
Conclusion to Part Two: We may now see how we might design a small wind tunnel from some known experimental data. We know our two blade wooden propeller develops a known thrust at no speed of advance and a known airspeed. Re-arranging the thrust coefficient equation, we can solve for T. Using the same geometry on a propeller of a different diameter and/or rev/min, and using the thrust coefficient, a new thrust can be obtained and from Eqn. 1, the airspeed can be calculated. From the new air speed, the power can be calculated. It could also be calculated from the power coefficient equation.

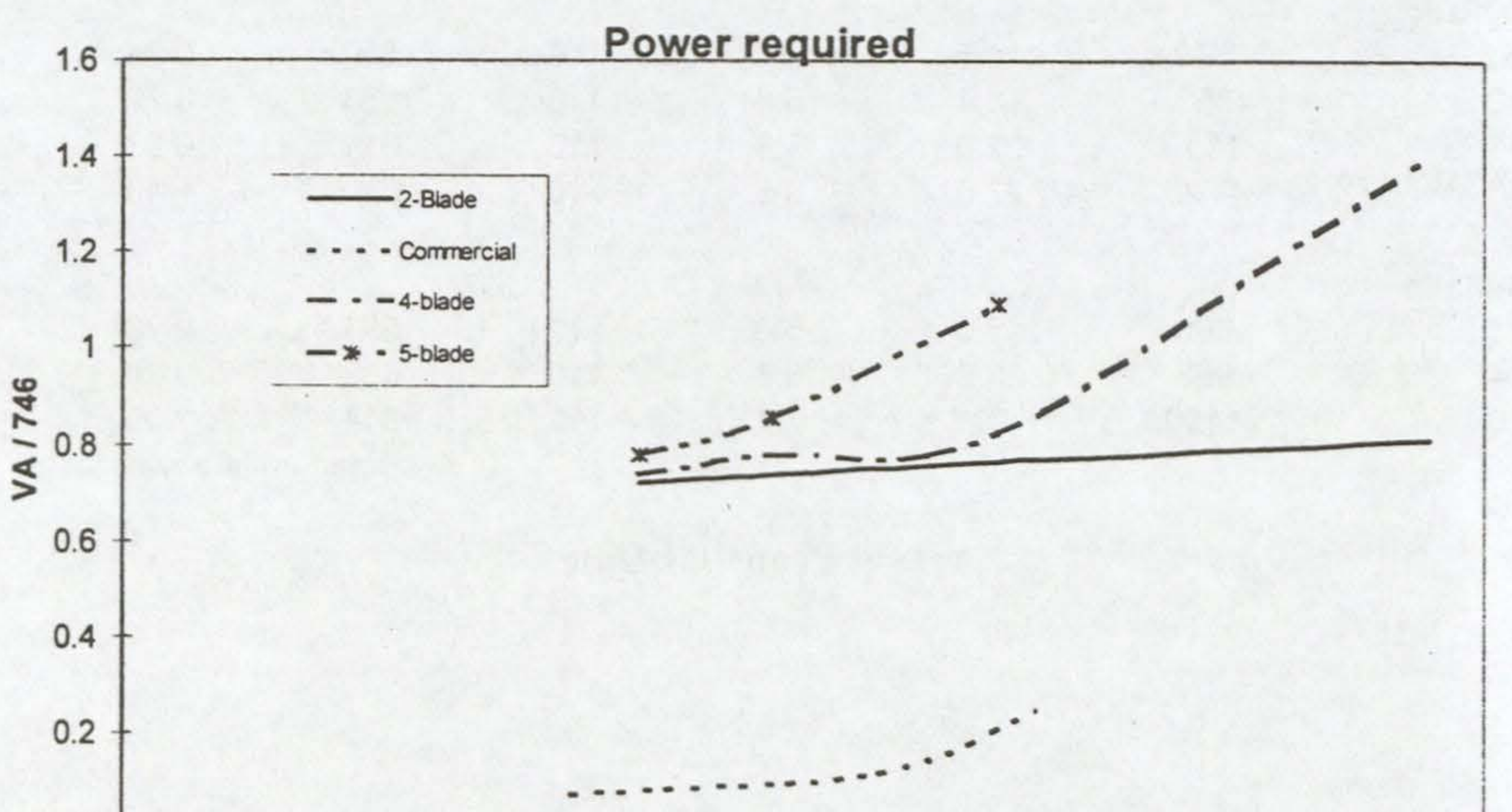
Type of prop	Dia in inches	Area in in^2	Pitch in inches
2 blade wood	20	41	27.2 exact
5 blade commercial	20	132	9.6 to 11.5
4 blade plywood	20	99	44.0 average
5 blade plywood	21.5	168	23.7 average

knots	rev/min	ft/sec	amperes	Volts	Volts x Amps	VA/746 = hp *
2-Blade						
6.2	690	10.5	4.9	110	539	0.72
7.87	863	13.3	5	110	550	0.74
10.9	1150	18.4	5.2	110	572	0.77
15.53	1725	26.2	5.5	110	605	0.81
Commercial						
3.67	600	6.1	0.5	110	55	0.07
5.83	1000	9.8	0.8	110	88	0.12
6.9	1200	11.6	1.7	110	187	0.25
4-blade						
8.6	690	14.5	5	110	550	0.74
10.7	863	18.1	5.3	110	583	0.78
13.3	1150	22.3	5.6	110	616	0.83
16.3	1725	27.5	9.5	110	1045	1.40
5-blade						
11.2	690	18.9	5.3	110	583	0.78
14	863	23.6	5.8	110	638	0.86
16	1150	27	7.4	110	814	1.09

* Assumes unity power factor

Actual Propellor Data





Data for Propellors

PART THREE

The following is a collection of primarily numerical data from past AYRS. journals. It is not complete. At the end of this section I will point out certain pitfalls and difficulties associated with wind tunnels. It will show you why a wind tunnel presents much more difficult problems to handle than those associated with a test tank. Each item below refers to the journal number and the author or person associated with the article and the year published. Where no author is shown, substitute "AYRS."

12- Brabazon/Fairy 1957: Lord Brabazon's motor was ½ horsepower and his model masts in the region of 2 ft. high. Sir Richard Fairy's tunnel was 17 ft. high and used a 10 horsepower motor. It is suggested that an AYRS. wind tunnel would need 100 sq.ft. outlet area and an 8 horsepower motor.

18- Lord Brabazon 1958: This issue describes some experiments by Lord Brabazon with his wind tunnel. The model masts are 2 ft. high. The motor is ½ horsepower giving an air speed of 29 ft./sec. which is remarkable! He used a floating model. Instrumentation had to be damped.

24 - Fairy 1959: The Hayes wind tunnel "was 15 ft. high of a square cross section 12 ft. by 12 ft. and an air speed of 7 to 10 miles per hour." (about 10 to 15 ft./sec.) About 7 horsepower for every 100 sq. ft. of outlet area is recommended. The AYRS tunnel would need 729 sq.ft. and 50 horsepower for a 10 mile per hour air speed. Propeller tip speeds should be kept below 500 ft./sec. This journal, titled Yacht Wind Tunnels, is, of course, filled with miscellaneous design information. (My tip speed was about 162 ft./sec.)

30- H. C. Adams 1960: The model should not be more than 75% of the height. This issue contains a drawing of a large wind tunnel capable of containing a 12 ft. dinghy. It is of the pull through type with a 13 ft. 6 inch 3 bladed Firefly airscrew set to a 7 ft. 6 inch pitch (perhaps). A 30 horsepower 1400 rpm motor is used with a 3:1 reduction. Air speed is 10 ft./sec. in the working section.

36,37- R. J. Harrington & Hudson 1961 : Mr. Hudson's propeller was made of four flat blades 24 inches in diameter. The outlet area was 3 ft. x 3 ft. The air speed was 6 ft./sec. It was 9 ft. long. of the pull through type. Instrumentation required measuring forces of .01 oz. Apparently, useful data was obtained on a Dragon model with an .835 sq. ft. main and a .492 sq. ft. genoa. From this sail area can be obtained the boat model scale and thus the Reynolds number at which it is being tested. These two articles by Mr. Harrington are very worthwhile.

40- 1962: This issue contains a description of the AYRS wind tunnel inauguration and the purpose and program for it. It took 18 months of part time work and £100 to construct. It was intended to use hot wire anemometers for measurement of air speed. John Morwood describes also the Severn Bridge wind tunnel and vertical velocity distribution aspects.

52- John Hogg 1964: The AYRS wind tunnel. Air speed is measured with a cup anemometer timed over 30 second intervals. A propeller anemometer is also used. Air speeds were measured at 4.7 and 5.3 ft./sec.

111- Peter Schenzle 1993: Referring to testing a rig for larger sail craft: "The sail models were made from sheet metal, with a 15 cm. (6 inch) chord. Rigid models were used to achieve a Reynolds number of 4×10^5.

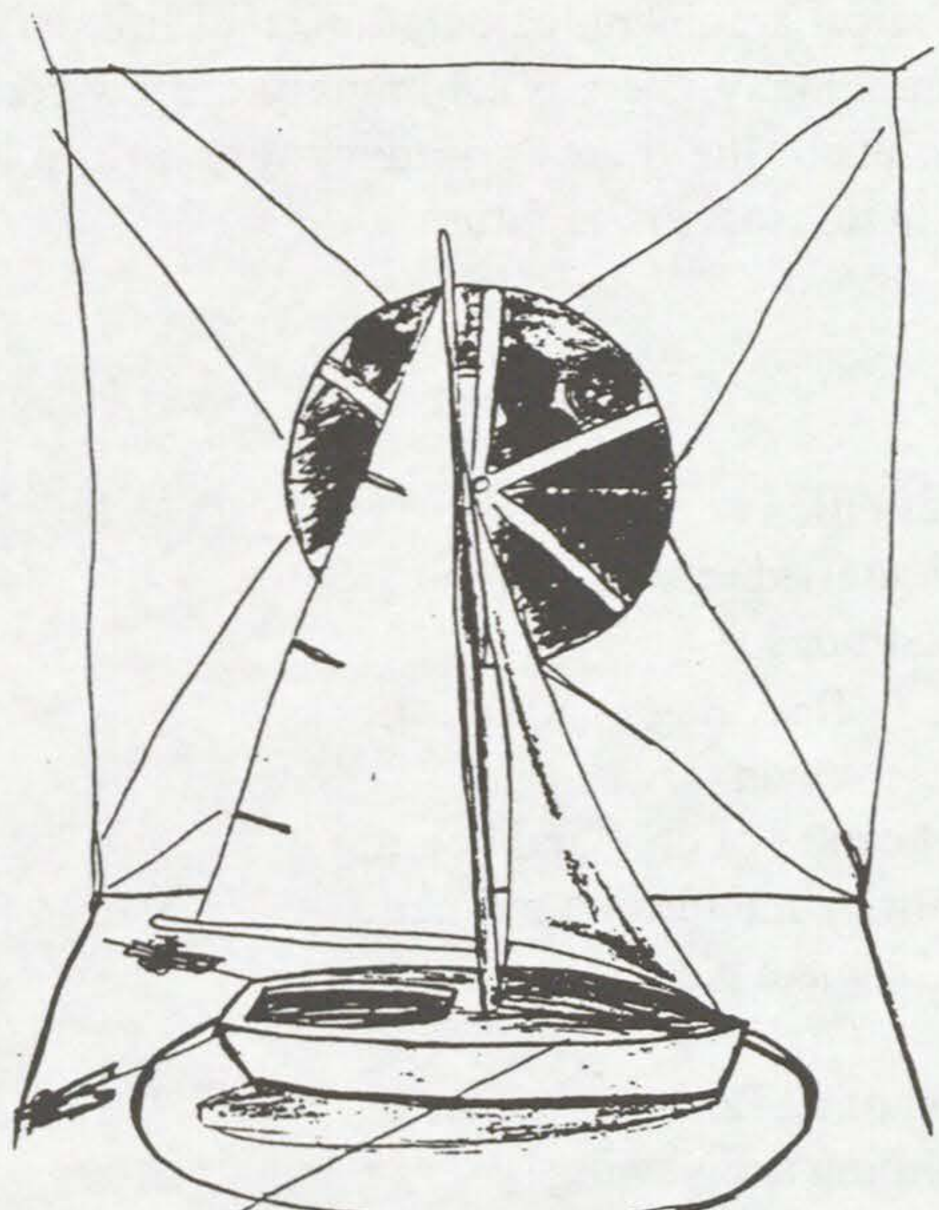
Conclusion to Part Three: The above is not an exhaustive summary. Mentioned in the above journals are many aspects of tunnel design. Here a few of the more important ones.

There are three types of tunnels: blowing, sucking and closed. The sucking types probably give a more stable air flow. The closed types, requiring much more duct work, are probably the most efficient as the air passing the fan blades is already moving with some speed. Thus, there is a blade speed of advance. Water test tanks require the use of the Froude number whereas wind tunnels require the use of the Reynolds number, which is greatly more restrictive in relation to model size. Mounting of the model in the tunnel and its associated instrumentation is more complex than in a test tank. The design of the tunnels no doubt requires a knowledge of what will or will not work considering eddy problems, fan shrouds, straightening vanes, smoothing screens and convergent/divergent angles and the like.

CONCLUSION:

From a listing of the journals in Part Three, it appears that the majority of wind tunnel testing by AYRS amateurs was done in the seven years following 1957. Also, somewhere along the line, the AYRS wind tunnel was dismantled. Where does this leave the amateur for future tunnel research? There are only two possible alternatives. One: All future research will be done by the larger colleges and universities or at some large facility which will result in a publication such as AYRS journal 111, Rig Efficiency. Conceivably, some arrangement might be made with an institution so that a person could use the large facilities. Second: Some amateur researcher will get the urge to construct a small closed tunnel. That person will have the space and time to build it with a sufficiently sized horsepower motor. The tunnel will supply a sufficient constant speed amount of air with minimum eddy currents across the test area. A range of air speeds should be available. Instrumentation will be developed to measure very small forces. The testing of the tunnel itself should be undertaken in regards to horsepower requirements at different rev./min. of the propeller. Thrust, torque, and power measurements should be taken with the view to establishing better coefficients. Most importantly, Extensive testing of standard objects in the air stream will be undertaken and results compared with handbook values. The drag of discs and spheres would be a good place to start. Next, a standard airfoil section (e.g. Clark Y) could be examined for lift and drag and compared to table in Abbott & von Doernhoff. What is the effect of different Reynolds numbers on the results? Is it a significant percentage difference?

This testing should once and for all determine if a small wind tunnel is actually worth the time and effort. Perhaps this has already been done. Surely, this has been done by some enterprising student in some university since 1957. I would suggest at least a two year program is a minimum for a project such as this. Two years is 730 days at, say, 1 hour per day gives you 730 hours project time. Second most importantly, assuming the preliminary testing and the instrumentation is a success, what program should be developed for the use of this piece of equipment? Many suggestions are scattered throughout the AYRS journals. Presumably, some of these unknowns have been determined since 1957. This cannot have been the end of amateur research, can it?



Unified Theory of Sailboat Steering

Henry W. Gilfillan

ABSTRACT

A general theory is developed which, the author believes, provides better understanding and insights into the complicated interaction between the many aerodynamic, hydrodynamic and inertial forces (and their spatial relationships to each other) which generate or modify the turning moments crucial to the steering of sailboats. Some unexpected conclusions are drawn, especially those relating to the surprisingly large migrations of the center of aerodynamic effort (CE) and the hydrodynamic center of lateral resistance (CLR) with respect to each other and the consequent profound effects on the magnitude and direction of turning and heeling moments.

Rather than to offer practical advice, it is intended to present a "unified theory" of sailboat turning moments which explains what has been observed over the millennia and to predict some effects that may not yet have been noticed or exploited.

The plan of presentation is to state the underlying premises, followed by an attempt to validate them by logical argument, calculation, real life personal experience, and data from the literature. Finally, there is a summary of new conclusions to be drawn and some speculation about the theory's implications in the hope they may prove useful to imaginative innovators in the future.

CONTENTS

Optimum rudder size
Rudderless steering
Alternate concepts and approaches (CLR? Who needs it?)
Some conclusions and speculations

INTRODUCTION

The writing of this paper was motivated by the author's need to clarify his own understanding of the nature and role of the center of lateral resistance (CLR) in the successful performance of sailboats, especially as it relates to steering and maneuvering. His previous perceptions had become unsettled somewhat by his own work in developing a boat with an unorthodox steering system, a rudderless craft which depends solely on the relative positions of the CLR and the center of effort (CE) of the sails to impose turning moments for directional control.

The deeper the nuances of CLR were explored, the more new questions arose which required answers, and the author became fascinated with the pas de deux executed by CLR and CE as they ceaselessly pursue and elude each other. Gradually, a "unified theory" evolved which seems to explain what has been experienced and observed over the millennia in attempts to improve sailboat steering. The theory also predicts effects not yet observed, measured or exploited. It is hoped that some of these speculations will lead toward truly imaginative new concepts and practical design solutions.

As is the rule when discussing sailboats, the lines between observation, deduction, hopefulness and prejudice are often blurred, and to this rule the author may not be the exception. The reasoning and conclusions expounded below probably add little that is actually new, but perhaps offer a fresh viewpoint and expanded scope. Review of standard published references has thus far revealed no serious contradictions, but only gaps in scope and comprehension, some of which the author hopefully has spanned.

Because C.J. Marchaj has such a large and loyal following, his symbols are adhered to herein and many of the drawings are based on Fig. 224 taken from his indispensable classic "Sailing Theory and Practice" (redrawn here as Fig 1).

In order to preserve consistency and clarity it was felt necessary to define some terms more strictly than is usual. The reader is urged to refer back frequently to the definitions of symbols and terms to avoid misinterpretation and confusion. (For example, "aerodynamic center of effort" must not be considered to be the same as the center of pressure of the sails.)

SYMBOLS AND DEFINITIONS

Course sailed: The horizontal direction of motion with respect to the water

Heading: The direction of the hull centerline

Lateral: In a horizontal direction perpendicular to the course sailed

Turning: Changing the course sailed

Yawing: Changing the heading

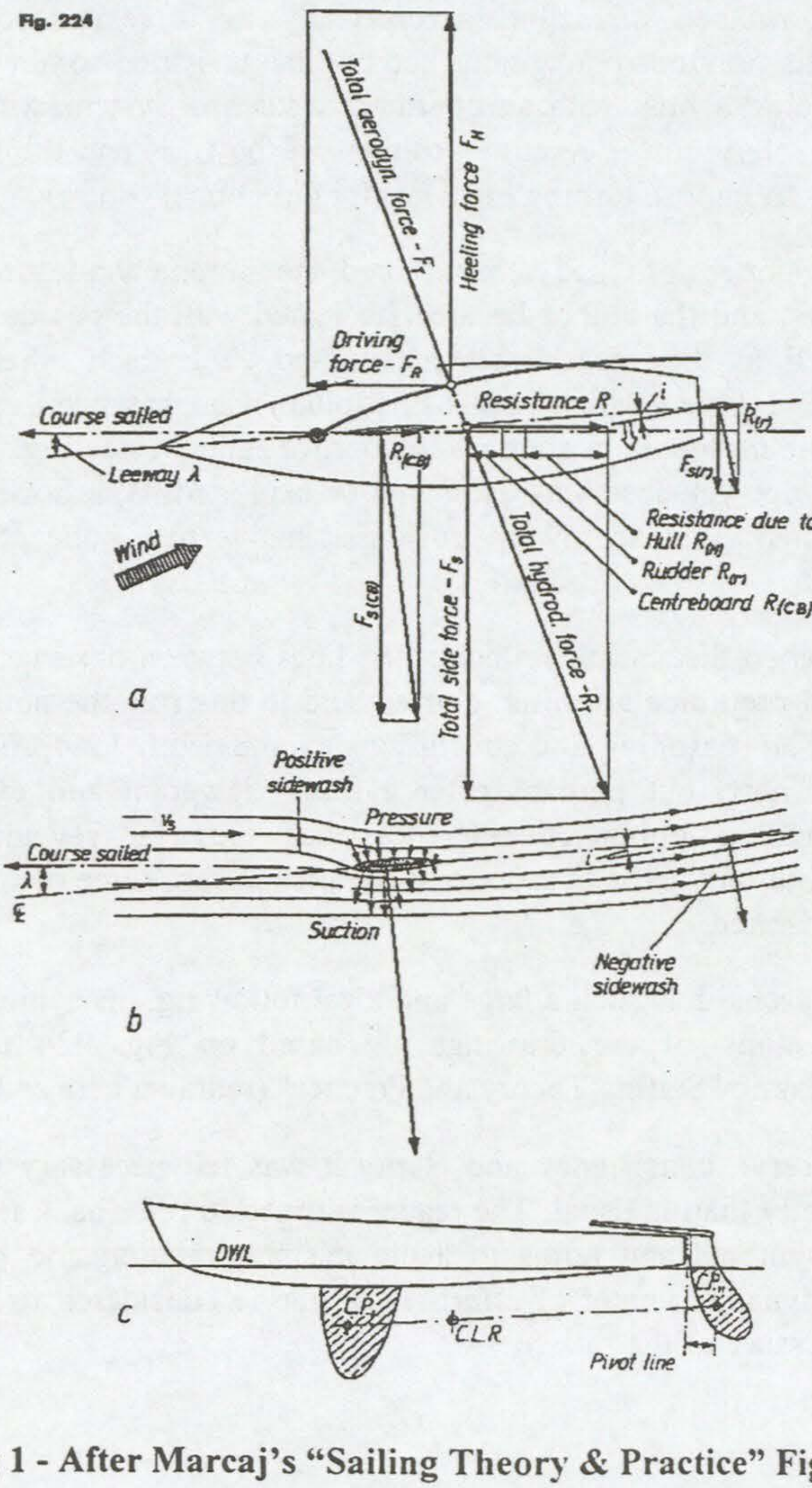


Fig 1 - After Marcaj's "Sailing Theory & Practice" Fig 224

a	Unbalance arm.
AR	Aspect ratio.
CD	Hydrodynamic center of drag.
CE	Aerodynamic center of effort
CG	Center of gravity
CLR	Hydrodynamic center of lateral resistance
CPi	Center of lateral pressure on the hull/centerboard combination
CPii	Center of lateral pressure on the rudder
Ft	Resultant of all aerodynamic forces applied to boat
Fh	Lateral aerodynamic heeling force
Fr	Aerodynamic driving force parallel to course sailed
Fs<cb>	Lateral side force of centerboard (or keel)
Fs<r>	Lateral force of rudder
Fs<h>	Hydrodynamic lateral force of all but rudder [= Fs - Fs(r)]
Fs	Resultant of all hydrodynamic lateral forces applied to boat
Ip	Polar moment of inertia about yaw axis
ι	angle of incidence of the rudder
ℓ	Angle of leeway
LOA	Length over all
LWL	Load water line
Mt	Turning moment
R	Total hydrodynamic resistance parallel to course sailed
Rt	Total hydrodynamic force applied to boat
Vs	Boat speed through water

EXPANDED DEFINITIONS

CD Center of drag: the center of total hydrodynamic resistance along the course sailed of all submerged portions of the boat including the rudder. Its position is unique to individual hull designs.

CE Aerodynamic center of effort: as viewed from above, the intersection of the resultant of all horizontal aerodynamic forces applied to the boat (Ft) with a line drawn through the center of hydrodynamic drag (CD) parallel to the course sailed.

CLR	Center of lateral resistance: as viewed from above, the intersection of the resultant all lateral hydrodynamic forces (Fs) with a line drawn through the center of hydrodynamic drag (CD) parallel to the course sailed.

NOTE: Under steady conditions CLR and CE are coincident as viewed from above.

Lateral:	Horizontal in a direction perpendicular to the course sailed.

Lee helm:	The tendency of a sailboat to fall off when the tiller is released.

Weather helm:	The tendency of a sailboat to luff up when the tiller is released.

PREMISES OF THE UNIFIED THEORY OF SAILBOAT STEERING

The unified theory is based upon the following premises, which are to be proven.

1. A sailboat is steered by the application of turning moments to the hull, the moments being in a horizontal plane. Windward moments cause the boat to round up, leeward moments to fall off, zero moments to move in a straight line.

2. Turning moments are generated when an unbalance arm exists between externally applied lateral forces and the center of lateral resistance, CLR. These forces include:
    a. The lateral component of the resultant of all aerodynamic forces on all air immersed surfaces of the vessel, principally the sails.
    b. Centrifugal force applied at the center of gravity of the vessel.
    c. Inertial force through the center of gravity due to lateral acceleration.

3. Additional turning moments are generated when an unbalance arm exists between the center of drag, CD, and inertial forces through the center of gravity due to acceleration of the vessel in the direction of the course sailed.

4. The center of effort, CE, as defined, normally can migrate between its position with sails close hauled and infinity aft when sheets are slackened.

5. The center of lateral resistance, CLR, as defined, can migrate through all points along the line of the course sailed from infinity forward to infinity aft. CLR can also move vertically upward and downward to infinity.

6. The center of drag, CD, as defined, can migrate laterally to a limited extent as a result of heeling.

7. CE, CLR and CD can migrate throughout their respective ranges independently of each other.

8. Heading and course sailed differ by the leeway angle, which can vary from zero to 90 degrees.

STEADY STATE CONDITIONS (CONSTANT COURSE SAILED, WIND, WAVES, CURRENT, TRIM, BALLAST, ETC.)

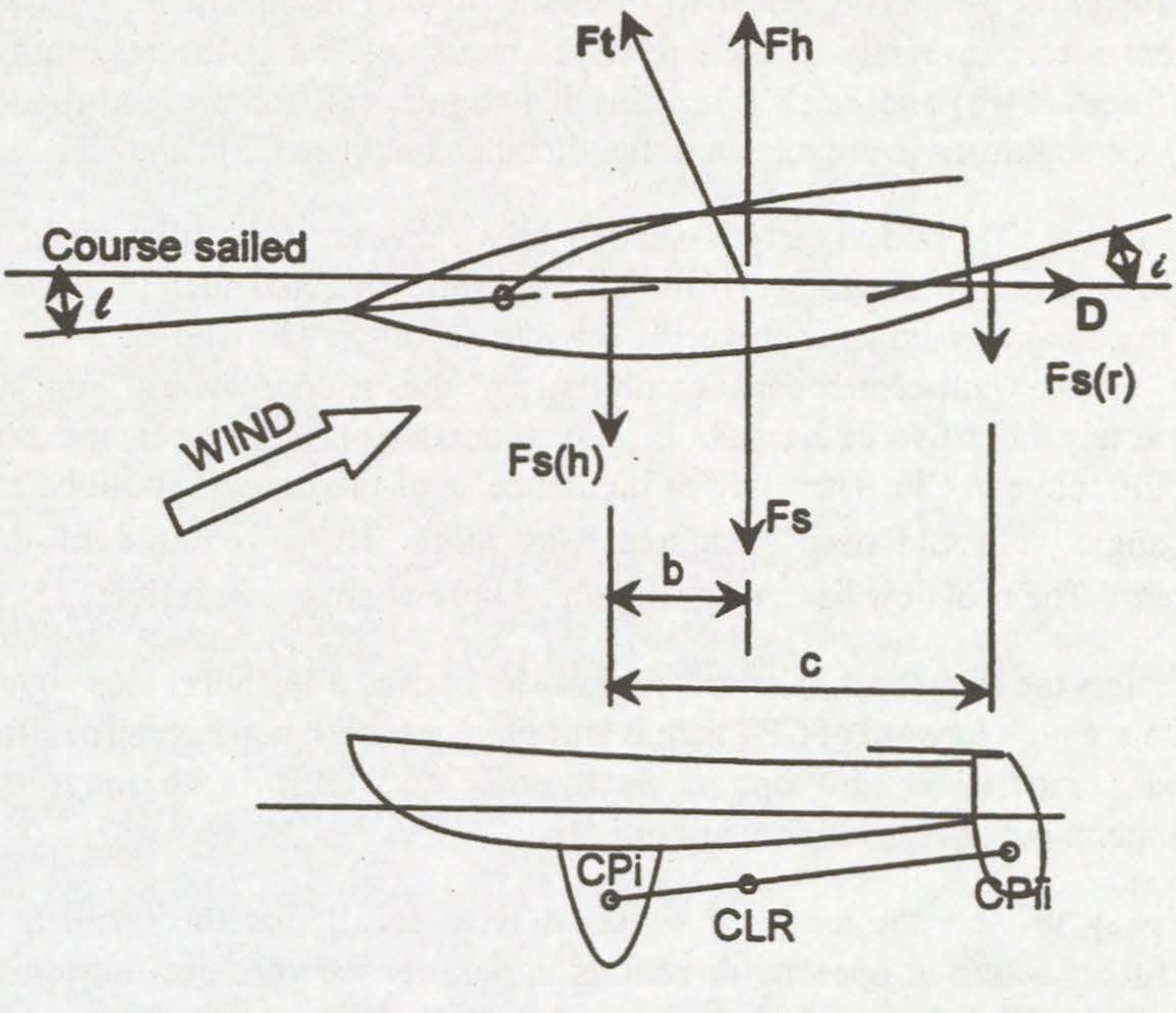


Fig 2: Weather Helm

POINTING:

Marchaj's Fig. 224 shows a simple cat rigged dinghy sailing upright close hauled and with its rudder contributing a share of the total side force, Fs. Fig. 2 is drawn from Fig. 224, but altered somewhat to facilitate analysis, and for clarity, vectors representing pure hydrodynamic drag in the direction of the course sailed are omitted.

As is evident, Fs must be equal and opposite to Fh. Also Fs = Fs(h) + Fs(r). The distance C between CPi and CPii, as projected on the course sailed, is very nearly a constant.

Taking moments about CLR:

$$Fs(h) \times b = Fs(r) \times (c-b)$$

Solving: $b = c \times Fs(r)/Fs$

From this we conclude that the fore and aft location of CLR depends directly upon how much of the hydrodynamic side force is generated by the rudder.

Another way to reach the same conclusion is to recall that the resultant of two parallel forces is parallel to, equal to the sum of, and divides a line between the component forces inversely as their relative intensities. Fs is the resultant of two parallel forces, Fs(h) and Fs(r). From this it is again evident that the rudder must generate a lateral force in proportion to the distance between CLR and CPi.

The boat of Fig. 2 is said to carry a weather helm, that is, if the tiller were released she would tend to turn to weather. If its sail plan were changed such that, when close hauled, the total aerodynamic force, Ft, passed through CPi, the center of lateral pressure of the hull-centerboard combination, the rudder would not need to contribute any lateral force because b, and hence Fs(r), would become zero, and CLR would move to CPi. The angle of incidence, ι, of the rudder would be zero, but leeway angle, ℓ, would need to increase as more lift is required of the hull-centerboard. The boat now has a neutral helm. These changes are reflected in Fig. 3.

Fig. 4 depicts the same boat balanced so that she carries a lee helm close hauled. As Fh and Fs are now forward of CPi, then b and Fs(r) are both negative. The lifts of the centerboard and rudder now oppose each other and CLR is no longer situated between them, but has moved forward of CPi.

Another way to view the lee helm situation is to recall that the resultant of two parallel forces acting in opposite directions is parallel to both, lies outside both on the side and in the direction of the larger and is equal to their difference, and that of any two parallel forces and their resultant each is proportional to the distance between the other two.

Note that the rudder angle of incidence, ι, is now negative, while leeway angle, ℓ, remains positive but larger, as it must be in order to generate a lift force now greater than the total side force, Fs. It is assumed that the centerboard and rudder are adequate to produce their required lifts. The author found that, in mild conditions, he could sail close to the wind in his 20 ft. sloop (Cal-20) under working jib alone, a condition of severe lee helm. The lateral planes must have been operating near max lift, as occasionally one or the other (the author knows not which) would stall, with the result that the craft would suddenly fall off to a broad reach and would need to be rounded up again.

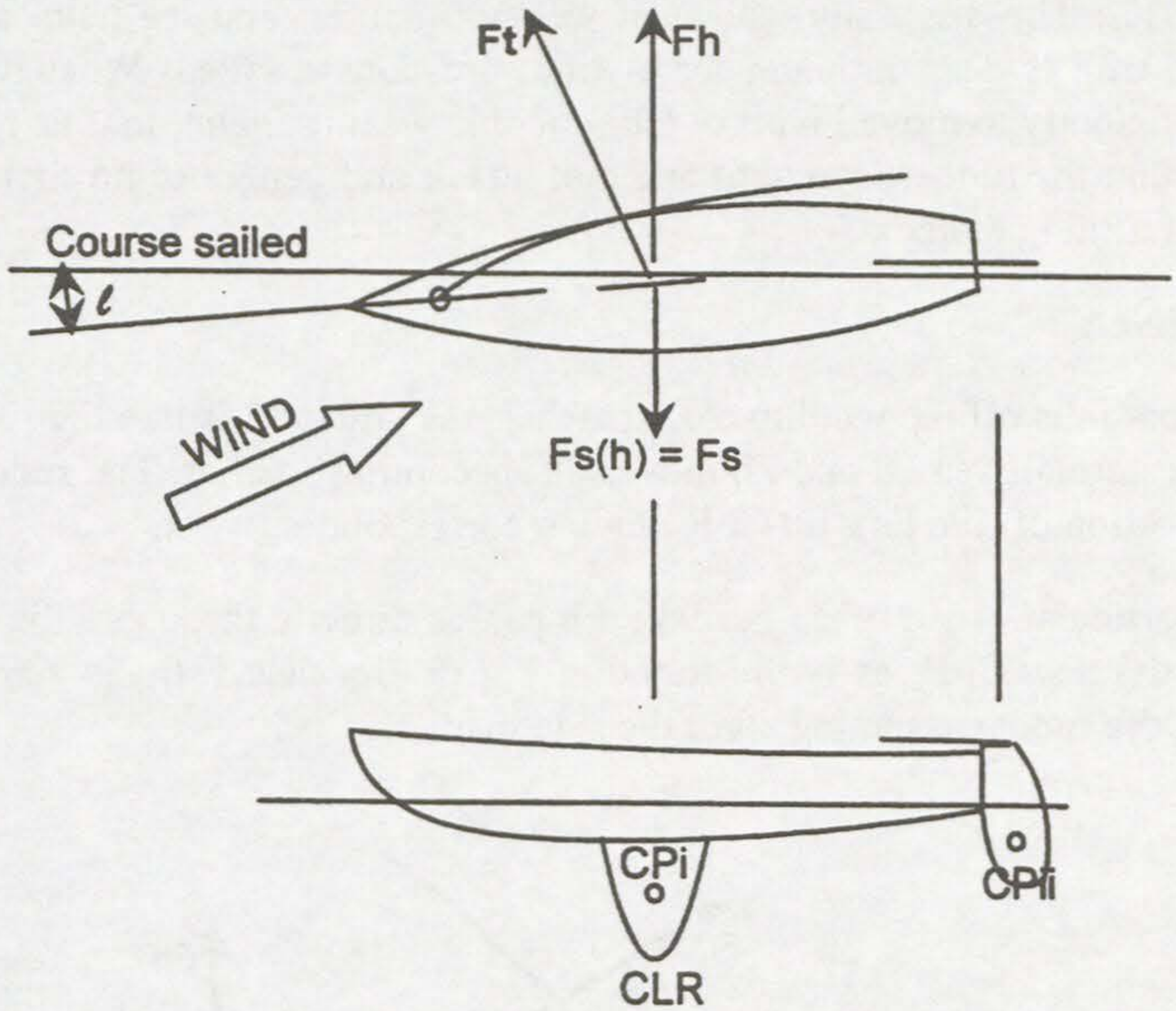


Fig 3: Neutral helm

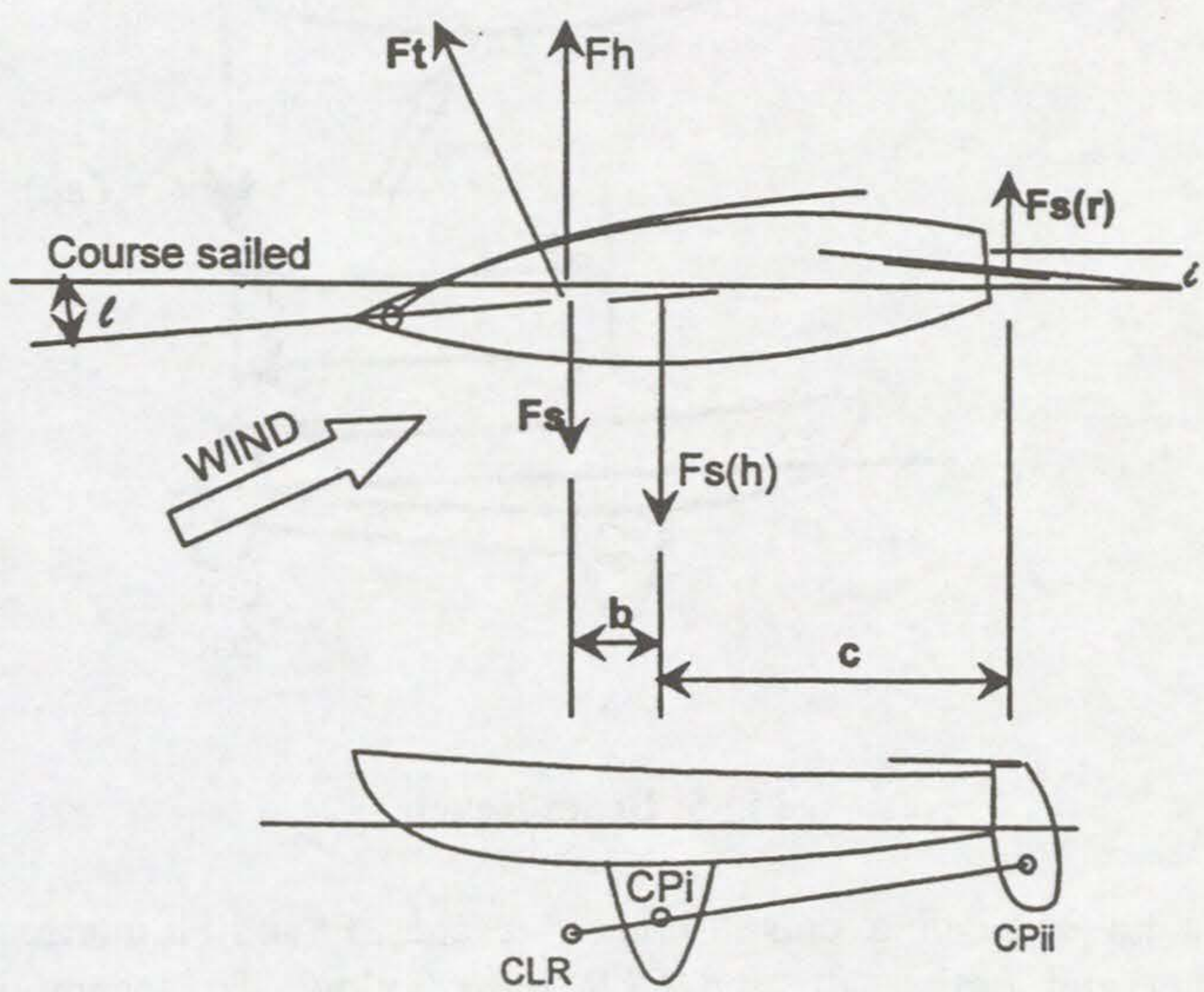


Fig 4: Lee Helm

NOTE: The discussion above of weather, neutral and lee helm applies only when sail trim is near optimum for a windward course sailed. Whenever sails are eased sufficiently to move Fh aft of CPi, there is weather helm, that is, releasing the tiller (so that the rudder is at zero angle of attack and generates no lift) results in a windward turning moment.

REACHING:

As the boat falls off the wind to close reaches, the situation is like Fig. 2 except that sheets are normally eased and Fh moves aft, becoming smaller. The rudder assumes a larger portion of side Fs with CLR moving correspondingly aft.

On one particular broad reach heading, Fh passes directly through CPii, which now becomes the new CLR, as is illustrated in Fig. 5. Because Fs(h) is zero, leeway is also zero, the rudder assuming all of the side load.

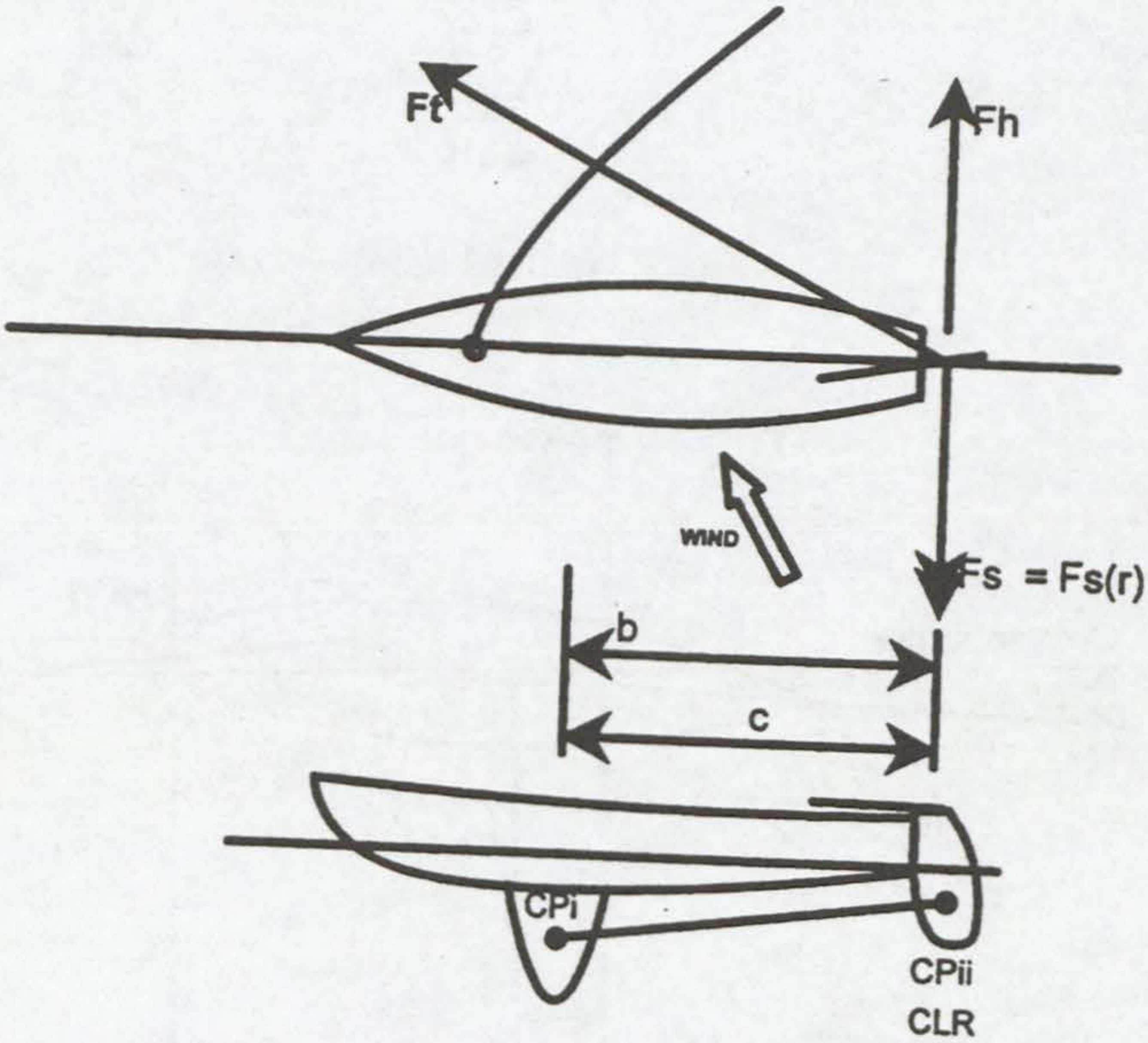


Fig 5: Beam Reach

Beyond this unique heading, on still broader reaches, Ft and Fh intersect the course sailed further and further aft, and CLR must follow. To accomplish this the centerboard and rudder must be in opposition, the rudder exerting side force larger than that of the centerboard in order that their resultant, Fs, will lie aft of the rudder in exact opposition to the heeling force, Fh, as depicted in Fig. 6. Note that hull leeway is now negative. CLR now lies aft of the boat's own dimensional envelope, and as the course becomes more downwind CLR will move to great distances aft. For example, when the angle between Ft and the course sailed is less than one degree CLR may fall hundreds of feet, and perhaps many miles, behind.

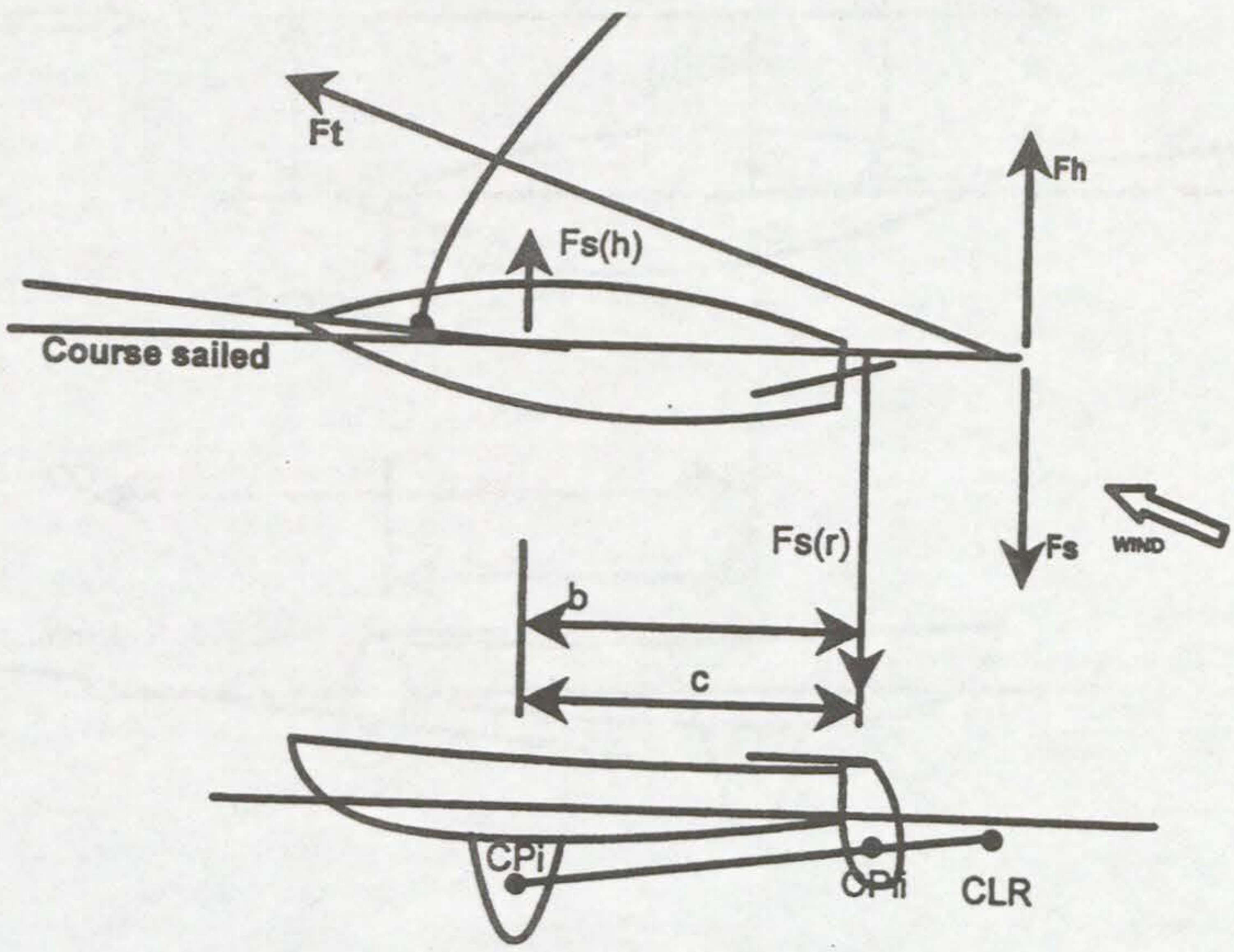


Fig 6: Broad Reach

It should be emphasized that on broad reaches both aerodynamic and hydrodynamic side forces are small and of little practical consequence under steady state conditions.

RUNNING:

A truly unique circumstance exists on a dead run, (or very broad reaches) when sail trim can be such that Ft is parallel to the course sailed. As illustrated in Fig. 7, Ft can intersect the course sailed only at infinity, Fh and Fs fall to zero and b becomes infinite. Fs(h) and Fs(r) are equal but in opposite directions, forming a couple (which has no resultant) while Ft and the total hydrodynamic resistance (drag) of the hull, R, spaced apart by lateral distance d between CE and CD, comprise another equal but opposite couple. One result of the foregoing is that CLR must be located, either fore or aft, at infinity!

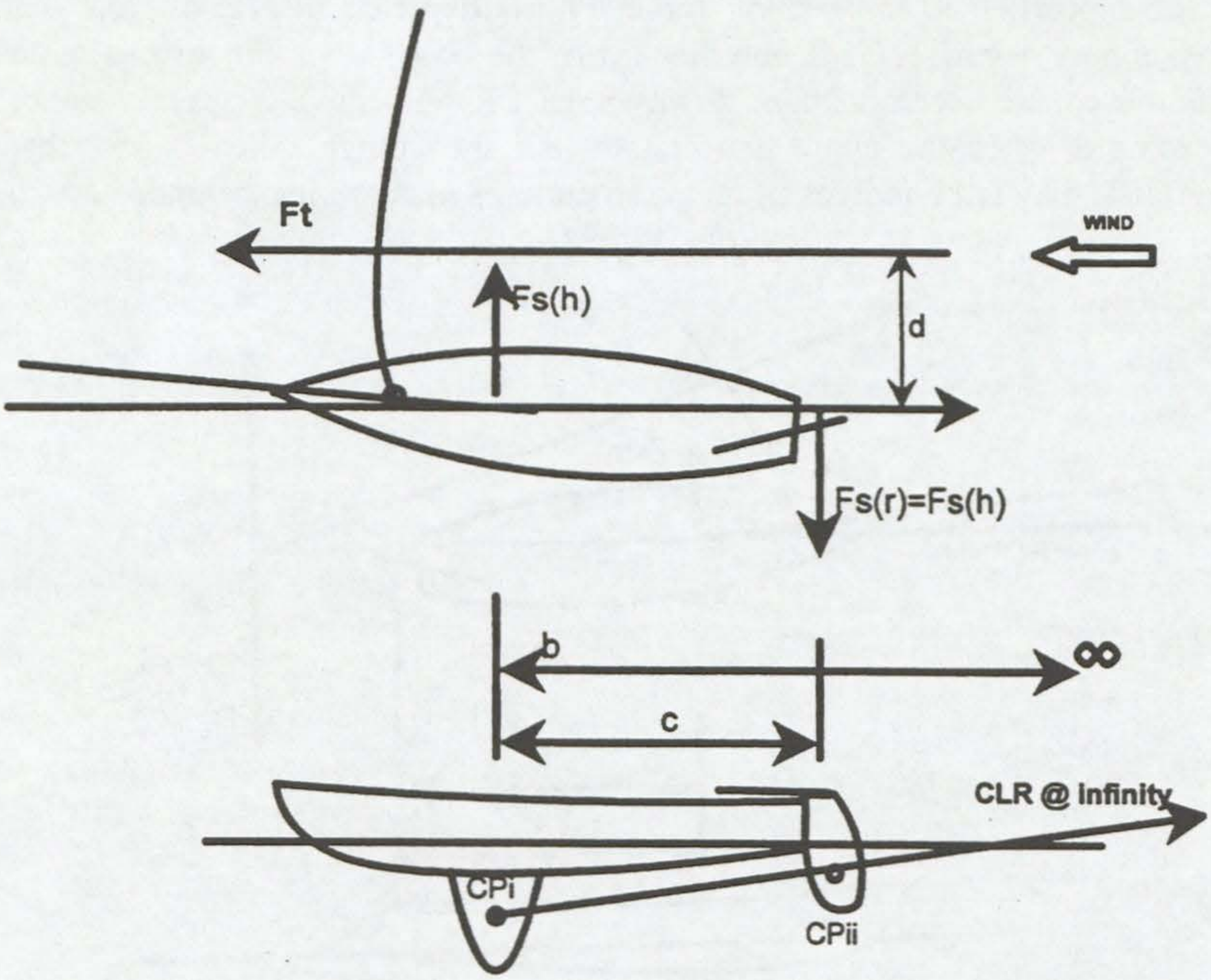


Fig 7: Running

If by some means (such as by deployment of additional sails, like jibs and/or spinnaker) Ft is made to pass through CD (center of drag) then Ft and Fr cancel, producing no moment, while Fs(h) and Fs(r) become zero, as do leeway angle, *ℓ*, and rudder incidence, *ι*.

GRAPHICAL REPRESENTATION

Fig. 8 summarizes the fore and aft movement of CLR by graphing the previously derived general equation

$$b = c \times Fs(r) / Fs$$

where b is the distance of CLR from the center of pressure of the hull/centerboard, CPi, projected along the course sailed. At the origin where b is zero, CLR and CPi coincide, which by definition is the condition of neutral helm, as illustrated in Fig. 3. A (+) value for b indicates that CLR is aft of CPi, generating weather helm, and a (-) value of b is associated with lee helm. The value of b is plotted in units of c, the substantially constant distance between CPi and the center of pressure of the rudder, CPii, as projected along the course sailed.

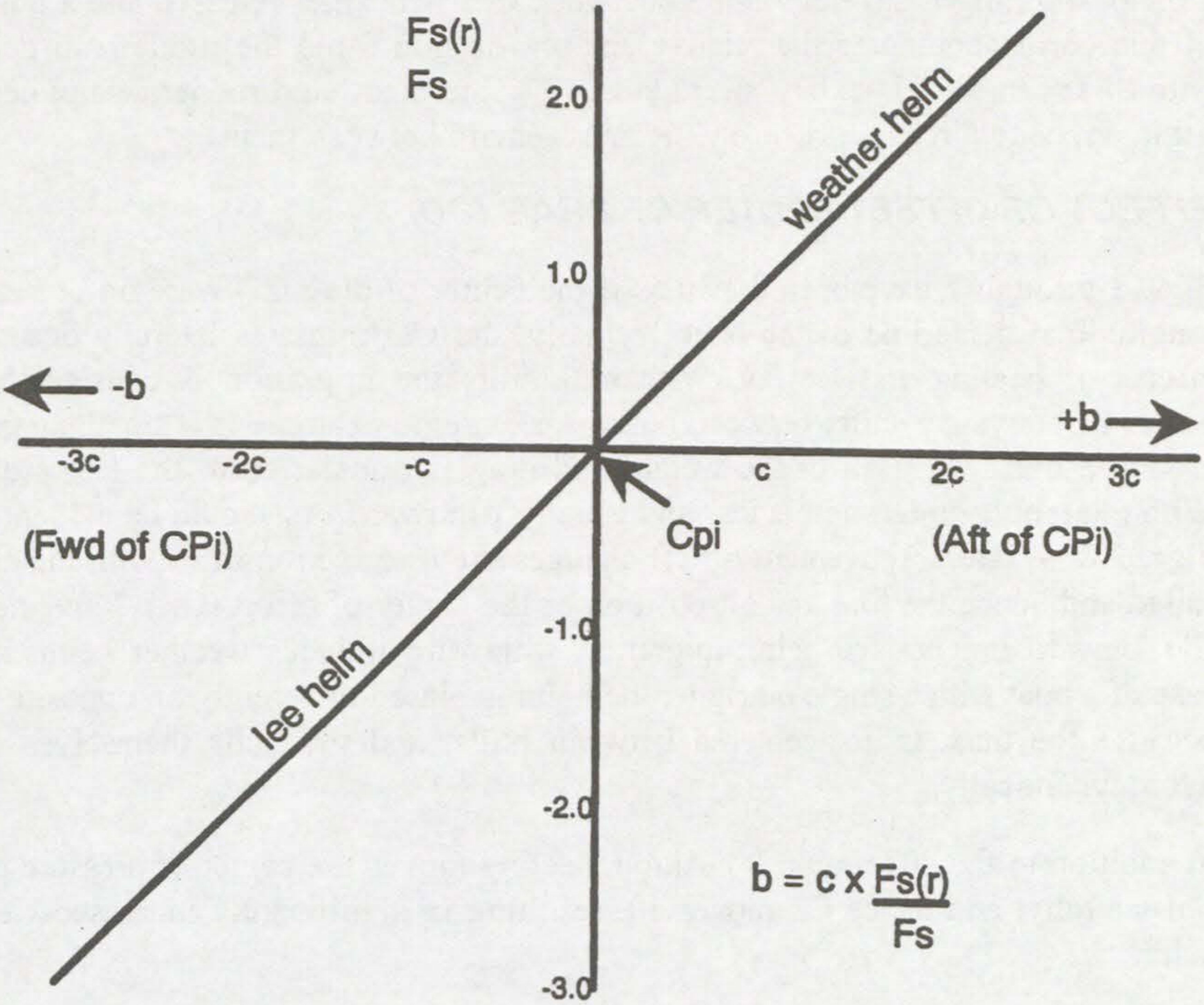


Fig 8: b = c × Fs(r) / F(s)

Typically, on courses between pointing and broad reaching, b is positive and less than c. In this range the lifts of hull/centerboard and rudder share in resisting the aero heeling force Fh, their respective angles of incidence being on the same side. When b is greater than c, their angles of incidence and respective lifts are in opposition, and CLR migrates to their resultant Fs, which is now aft of the rudder. When b is negative, Fs(h) and Fs(r) are again in opposition and CLR is positioned at their resultant, now forward of CPi.

Note that as the equation is a straight line there is no limit on the value of b and hence CLR may move to infinity, both fore and aft. At large values of b, rudder lift must be many times larger than total side force Fs. This is physically possible because heeling force Fh diminishes and vanishes when falling off to a dead run or in putting about.

A unique situation is when forward speed is very low, or zero, and both blades stall when sails are sheeted tightly, perhaps in an attempt to get out of irons. Possible CLR positioning is severely limited between CPi with tiller released and a point aft of this corresponding to the relative amount of side force the rudder can develop with tiller centered. Lacking "steerage way," centerboard and rudder cannot develop lift in opposite directions, hence CLR must remain between them.

EFFECT OF OFFSET CENTER OF DRAG (CD)

Figs. 2 through 7 have been drawn as if the center of drag CD were on or near the longitudinal centerline of the boat. Actually, the CD migrates laterally due to the effects of heeling and leeway. With multihulls the migration is considerable as center of buoyancy shifts between hulls. An extreme example is a small catamaran "flying a hull" when all of the weight and drag is transferred to the leeward hull. With monohulls, migration is less and usually windward. As should be evident from Figs. 2 & 9, lateral movement of CD changes the intersection of Ft with the course sailed and hence the fore and aft position of the center of effort (CE). Movement of CD leeward induces lee helm; migration windward induces weather helm. In the case of a boat with a single outrigger the helm is biased differently on opposite tacks because the mast is not centered between hulls, and the hulls themselves differ hydrodynamically.

In addition to the effect on CD position, heeling moves the center of pressure of the sail laterally, and hence CE moves aft, resulting in significantly increased weather helm.

TRANSIENT CONDITIONS AND TURNING MOMENTS

Thus far this discussion ha been confined to steady state conditions. In reality, conditions at the interface of air and water are virtually never constant, nor even regularly repetitive, not to mention predictable (except perhaps statistically). The concept of an aerodynamic heeling force (Fh) in balance with an equal and opposite hydrodynamic side force is useful, but the forces and moments applied to the craft by ceaselessly undulating water and turbulent, backing, veering, vortexing wind reduce it to only a random occurrence. Newton's laws are not thereby violated because other transient forces and moments associated with mass, acceleration and friction preserve the overall balance of the system. It must be emphasized that whenever there is change, or rate of change, there are usually evanescent disturbances that complicate analysis.

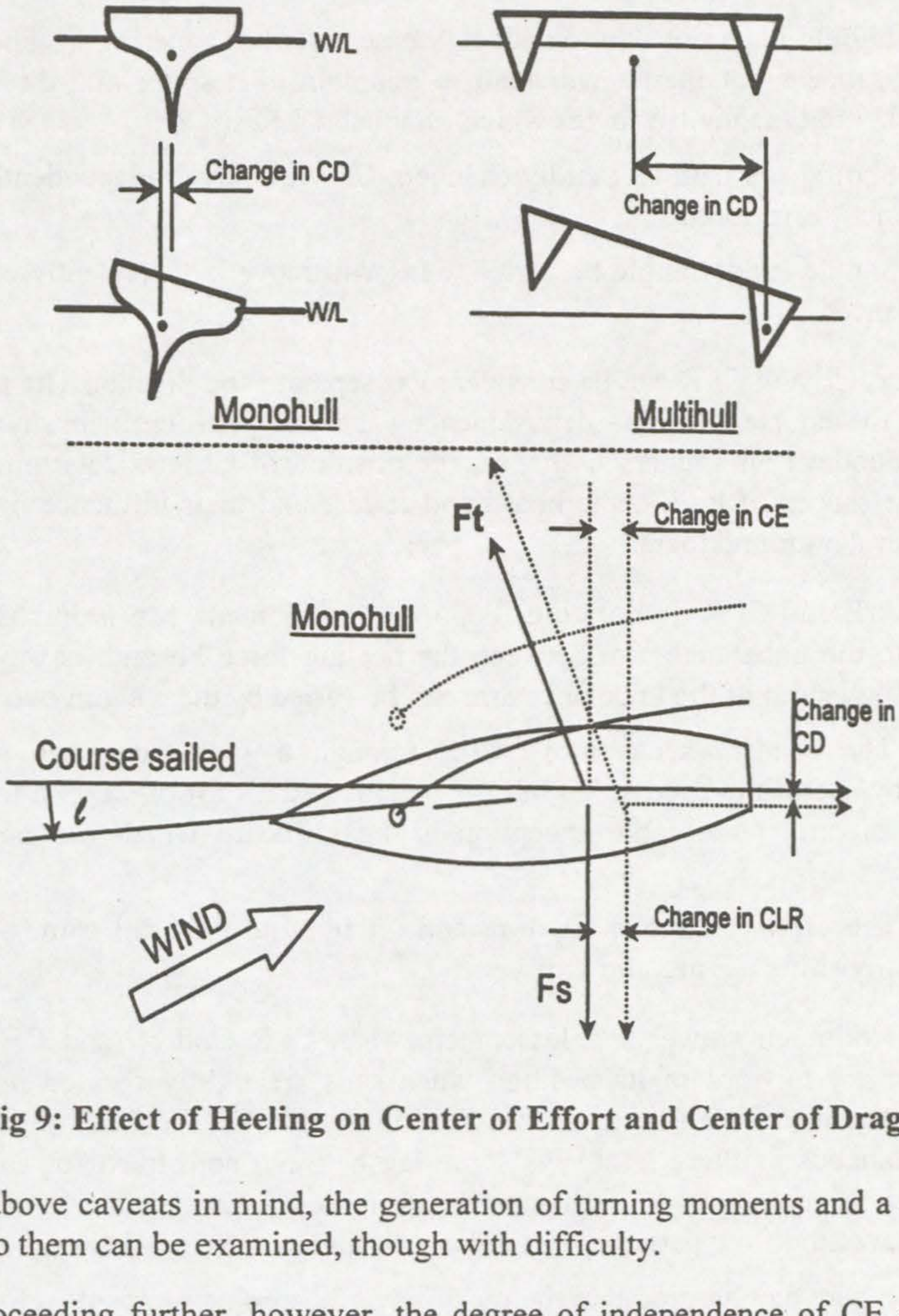


Fig 9: Effect of Heeling on Center of Effort and Center of Drag

With the above caveats in mind, the generation of turning moments and a sailboat's response to them can be examined, though with difficulty.

Before proceeding further, however, the degree of independence of CE and CLR from each other should be mentioned. It is customary to think of them as inseparable, the heeling force Fh acting through the center of effort CE establishing an equal and opposing side force Fs acting through a center of lateral resistance CLR directly in line with CE.

Recalling that the definitions of CE and CLR make no reference to each other, some examples of their non-coincidence and how one can exist in the complete absence of the other may be in order. Consider a sailboat on a steady windward course with both centerboard and rudder generating lift:

(1) Should apparent wind suddenly cease, as when entering a wind shadow, CE will disappear but inertia will tend to maintain boat speed and direction, and hence the hydrodynamic lift forces which establish CLR.

(2) Should sail trim be rapidly changed, CE will move independently of CLR until "balance" is restored.

(3) Should rudder angle be varied, CLR will move independently of CE until again "balanced."

In summary, CE and CLR can be considered as separate and distinct. The position of CE along the course sailed is determined by the sail plan and trim and the flow pattern around all air immersed shapes; the position of CLR is determined by the underwater shapes of hull, centerboard and rudder and their influence on the flow pattern of water around them.

Whenever CE and CLR do not coincide, a turning moment, Mt, is imposed on the boat due to the unbalance arm between the heeling force Fh and leeway resisting force Fs. The length of the unbalance arm can be varied by the crew in two ways:

(1) The helmsman can move CLR through a wide range and with great precision by use of the rudder. To fall off he moves CLR aft of CE and to head up, moves it forward. (A notable exception is the sailboard which has no movable rudder.)

(2) The crew can move CE fore and aft by adjusting sail trim. Slackening sheets usually shifts CE aft, and vice versa.

CE control is much slower and less precise than CLR control, and CE does not normally move forward of its position when sails are tightly sheeted in, whereas CLR can be moved from infinity forward to infinity aft. CE and CLR migrations are not instantaneous as there is always some lag between adjustment of sails and/or rudder and the corresponding change in lift forces, because time is required to establish new fluid flow patterns, particularly around submerged shapes.

It should be here emphasized that the most powerful turning moments are generated when the angles of attack of rudder and centerboard are opposite to each other. When rounding up, this opposition is easily and quickly brought about by simply turning the rudder to reverse its angle of attack. When falling off, the angle of attack of the centerboard must instead be reversed by swinging the entire craft, which is quite time consuming by comparison. This is one of the reasons why most sailboats are more responsive to the helm when rounding up than when falling off. Additional reasons will be examined in a later section dealing with inertially induced turning moments.

CENTRIFUGAL HEELING AND TURNING MOMENTS

Whenever a boat is turning, centrifugal force acts upon it through its center of gravity perpendicular to the instantaneous course sailed, producing additional heeling and turning moments.

The centrifugal turning moment is centrifugal force times the horizontal unbalance arm between it and CLR, and during a windward turn when CLR is normally forward of CG, it adds to the aero turning moment, accelerating the turn. By contrast, during a leeward turn when CLR is normally aft of CG but centrifugal force is reversed, the centrifugal turning moment is still windward, subtracting from the leeward aero moment and retarding the turn.

NOTE: for completeness and accuracy, it should be here mentioned that when a turning moment is first applied but before there is any yawing, angular acceleration is maximum, angular velocity is zero and yawing is about the center of gravity. During the interval that angular velocity increases to a steady value, angular acceleration falls to zero while the yaw axis moves to CLR. Conversely, as the turn is checked yaw axis returns to CG.

The centrifugal heeling moment is the product of centrifugal force times the vertical distance between CG and CLR. Assuming that CG lies above CLR, during a windward turn it adds to the aero heeling moment thus increasing the angle of heel and, for a monohull, moving CE aft to further increase the windward turning moment. For a multihull, the windward turning moment is decreased, as discussed in an earlier section dealing with the effect of off-set center of drag.

Centrifugal forces can be considerable and may be estimated by the formula:

$$F = Wt(Vs)^2/15r$$

where F = centrifugal force (lbs), Wt = weight of boat (lbs), Vs = boat speed (mph), r = turning radius (ft).

For example, consider an 33ft daysailer carrying 450 sq ft of sail, weighing 3600 lbs and travelling at 5 mph on a 30 ft turning radius, then:

$$F = 3,600 \times 25 / 15 \times 30 = 200 \text{ lbs}$$

which is equivalent to more than 200 sq ft extra of sail in a 20 mph wind.

SURGING

Transient inertial turning moments are also generated when there are linear speed changes along the course sailed, as may be due to gusts or waves. The instantaneous value of such moments is the product of the acceleration times the boat's mass times the lateral offset of CG from CD. As these moments are detrimental to yaw stability, they might be minimized by designs which minimize the lateral moment arm between center of gravity and center of drag.

VERTICAL POSITION OF CLR

An additional curiosity is the vertical movement of CLR. If, as indicated in Fig. 2, CLR lies on a line drawn through CPi and CPii (as projected on the course sailed) and if this line is not horizontal due to geometry, trim or pitching, then when b is very large CLR will plunge deep below the surface or rise high in the sky.

As heeling moments are a direct function of CLR vertical position, this effect may become important under some circumstances. For instance, with monohulls, the center pressure of the rudder typically is higher than the center of pressure of the hull/keel and hence CLR sinks lower as it moves forward. During the interval when CLR is well forward, as when rounding up, heeling moments are correspondingly increased, with sometimes undesirable results, as for instance, broaching. It is speculated that if CPii were to be positioned substantially below CPi, then while rounding up sharply CLR would move up rather than down, and perhaps rise high enough to actually reverse the heeling moment to windward!

RESISTANCE TO TURNING AND YAWING

Recalling from the definitions of terms that heading and course sailed differ by the leeway angle, then when a boat has more than sufficient steerage way, leeway angle will not as a rule exceed about 10 degrees. Under these conditions, turning and yawing will occur nearly simultaneously and through about the same angles. Under other conditions when speed may be below steerage way, or even zero or possibly negative, leeway angle may increase to as much as 90 degrees. Course sailed and heading may then have little relationship to each other, and yawing can occur without turning, and vice versa. Examples are as when in irons, hove to, or routinely in the case of rudderless craft to be discussed later. What follows relates to conditions when leeway angle is normally small and applies almost equally to yawing and turning.

The effort required to turn a vessel (and subsequently to check the turn at the desired heading) is a complicated function of its geometry and mass. Treated briefly, the resistance to an applied turning moment, Mt, comprises both inertial and hydrodynamic counter torques which are out of phase with reach other, one being a maximum when the other is zero. The inertial counter torque is proportional to the ship's polar moment of inertia times its angular acceleration. The hydrodynamic component of the counter torque varies as the square of the angular velocity (the speed of the turn) and inversely as the square of the aspect ratio of the lateral planes. This last deserves further comment: if the tiller is released so that the CLR moves to CPi, being the center of pressure of the centerboard, the torque generated by the turning centerboard will vary inversely as the square of its aspect ratio, that is, a centerboard with deep draft and short cord will turn more easily, the lateral area being the same. If the tiller is positioned such that the rudder shares lateral force, the rudder's area projected onto the plane of the centerboard represents a second lateral plane with variable aspect ratio, and the resistance to turning of the combination will vary as the cube of the horizontal distance separating them. A related effect is that angular velocity of a turn changes the relative angles of attack of rudder and centerboard in a way that moves CLR aft during a windward turn, but forward when turning leeward, reducing the turning moment in either case. This effect is greater for wider separation between centerboard and rudder because the lateral component of water velocity impinging on the blades is more altered.

Instantaneous values of inertial and hydro counter torques add as the turn is initiated and subtract as it is checked. At the risk of stating the obvious, the above argues that the most maneuverable hull will be flat bottomed and short with its mass concentrated near a high aspect ratio keel or centerboard and with a closely coupled high aspect ratio rudder.

TACKING

The application of turning moments and a boat's response to them may be illuminated by tracing events while putting about and falling off on a new tack.

Beginning with steady state conditions close hauled on the wind as in Fig. 2, releasing the tiller results in weather helm as CLR moves forward to CPi. Pushing the tiller alee reverses the rudder's angle of attack, moving CLR further forward and increasing the aero turning moment, CE remaining relatively unchanged. As turning begins, centrifugal force adds to the turning moment, Mt. Centrifugal force also adds to the heeling moment (with a monohull), adding further turning moment.

While the course sailed is being altered to windward, yawing is also windward, but is resisted momentarily by polar moment of inertia Ip, the instantaneous resisting yawing moment being equal to Ip times angular acceleration about the yaw axis.

As the heading approaches the eye of the wind and luffing begins, Fh, Fr and CE all disappear, but inertia tends to maintain speed and centrifugal force to maintain turning moment. Meanwhile, the rudder angle is being adjusted to keep CLR well forward. As (now leeward) yawing continues and heading becomes far enough off the wind for sails to fill, Fh reverses, followed by a reversal of leeway angle. As leeway angle approaches zero, CLR disappears into infinity forward at the instant Fs(h) and Fs(r) become equal and opposite, the re-appears from infinity aft as Fs(h) falls below Fs(r). Leeward aero turning moment is thus momentarily large, but is countered by centrifugal turning moment which is now windward. As leeway angle reverses, centerboard lift Fs(h) builds up in the same direction as rudder lift Fs(r) moving CLR forward, shortening unbalance arm, a, and because aero and centrifugal heeling forces continue in opposition, the net turning moment becomes very small, tending to put the boat in irons. But as boat speed drops and turning radius increases, centrifugal force diminishes, and if steerage way has been maintained, the rudder may be able to keep CLR far enough aft for aero heeling force to generate a leeward turning moment sufficient to fall off on the new tack. In this it is assisted by polar moment of inertia which now tends to maintain angular velocity of yaw. As heading becomes further off the wind, sail trim and rudder may be adjusted to re-establish steady state windward balance on the new tack.

From the above, it is seen that during a tack, an excess of turning moment is available for rounding up, but very little for falling off. Larger craft may depend heavily on inertial forces for successful putting about, lighter boats depending more on small hydrodynamic resistance to yawing.

The main problem in putting about appears to be that of yawing the boat sufficiently to allow filling sails on the new tack, the actual change in course sailed being of secondary importance until this is accomplished.

The reader is invited to make for himself the same analysis for multihull tacking and for jibing of both monohull and multihull.

MULTIHULL VIRTUES AND VICES

How multihulls differ from monohulls has been pointed out occasionally above and are summarized below:

1. Heeling tends to move CLR aft. This inhibits rounding up and assists in falling off.

2. Centrifugal turning moments are generally less important because of characteristically lighter weight. An exception is when an attempt is made to round up while flying a hull, in which case CG rises considerably above CLR, inviting capsize.

3. Hull resistance to turning is much greater because the hulls contribute a very large part of the total lateral resistance and have a very low aspect ratio. (Flat bottomed hulls with high aspect ratio centerboards would greatly improve maneuverability, but might be objectionable from some other standpoints.)

The author is a multihull fan and fully appreciates that they have many fine virtues beyond the scope of this discussion, but regrettably maneuverability is not among them.

FORWARD RUDDERS

A rudder positioned forward of the fixed lateral plane would be quite as effective in steering as the conventional aft rudder, and may be analyzed in the same way. However, from at least two standpoints it would be considered undesirable: (1) if it shared any lift on a steady course, the boat would have lee helm with tiller released, which is dangerous, and (2) response to the tiller would be enhanced when falling off, but degraded when rounding up. This last is opposite to the effect on tiller response of a conventionally positioned rudder, as explained in a previous section dealing with transient conditions and turning moments.

It is speculated that a design with two rudders, one fore and one aft, with coordinated control, could enjoy enhanced tiller response both to leeward and windward.

OPTIMUM RUDDER SIZE

Traditionally, rudders are much smaller than their associated keels or centerboards. Conventional wisdom favors this disparity in size because the rudder is situated in the turbulent wake of the keel or centerboard and hence at a degraded lift to drag ratio, which impairs weatherliness, and because an excessively large rudder increases wetted area unnecessarily. There is another reason which may have been overlooked or under appreciated.

Recall that whenever the lift of a rudder is opposite to and greater than the lift of the centerboard, CLR moves aft of the rudder with consequent leeward turning moment. The theory predicts that an overly large rudder might under some circumstances cause the boat to fall off when the helmsman intended to round up. In this curious situation, the hull would yaw into the wind, but the course sailed would turn off the wind (please refer to definitions of terms). To avoid this, the helmsman would need to take care not to turn the rudder so far that Fs(r) exceeded Fs(h). The author has no firsthand experience with this particular anomaly and does not know if the effect would be large enough to be objectionable.

On the other hand, a rudder that is too small cannot move CLR far enough to generate adequate turning moments.

Implications of the theory are that the relative size of rudder and fixed lateral plane is of little consequence as long as (1) both are at max lift to drag ratio when going to weather and (2) response to the helm is satisfactory to the helmsman.

It would be interesting to experiment with a design having equal size rudder and centerboard with adjustable longitudinal spacing between them. Even more interesting would be two rudders connected by a coordinating linkage and no centerboard.

RUDDERLESS STEERING

Certain designs do not have a lateral plane whose angle of incidence can be varied with respect to another fixed plane, as is customary. A familiar example is the sailboard, and the author has developed two other types which are described in other papers. Rudderless boats have the advantage of not needing "steerage way" in order to be steered, but can be yawed to any heading at low, and even zero or negative speeds. Sailboards steer by radically changing CE position with respect to a comparatively fixed CLR. One of the author's rudderless types has a single centerboard which is movable fore and aft in order to vary CLR position. In either case, CLR remains well within the boat's length. As discussed earlier, in order for CLR to move forward of the centerboard's center of pressure, CPi, or aft of the rudder center of pressure, CPii, the centerboard and rudder must have opposite angles of incidence, that is, one of them must be exerting force to starboard at the same time that the other exerts force to port. This is possible because the rudder can be turned about a vertical axis.

In the case of the sailboard, with two fins always in the same plane, the CLR due to them (but excluding any lateral resistance of the board itself) must remain at one of, or between, the fins. In the case of the author's boat with a single, but movable, centerboard, CLR remains closely adjacent to the centerboard's center of pressure. This boat is highly maneuverable at speeds below what is necessary steerage way for conventional boats. It can, in fact, yaw the hull to any heading while at zero, even negative speed, sail and tack upwind stern first, sail directly abeam, and other tricks. But it is less maneuverable at higher forward speeds, because it cannot move CLR over the wide range, and hence develop the large turning moments possible with the conventional arrangement of lateral planes.

By contrast, another of the author's designs maintains both CE and CLR in very nearly fixed positions with no unbalance arm between them, because with this concept there is no dependence on fluid dynamics to generate turning moments. The single rotatable leeway resisting lateral plane, which serves also as the rudder, is easily turned about its vertical axis mechanically by the helmsman, the course sailed being in the plane of the rudder, minus leeway. The omnidirectional circular hull is held weathercocked by the mizzen of a cat-yawl rig and does not turn as course sailed is altered, hence the effects on steering of inertial forces and heeling are negligible. It is perhaps the most maneuverable sailboat yet built, but otherwise performance has been lackluster, though certainly improvable. This craft is described in a 1988 AYRS publication.

Another minor advantage of having only one lateral plane is that its efficiency is not degraded by being situated in the turbulent wake of another.

ALTERNATE CONCEPTS AND APPROACHES (or CLR — WHO NEEDS IT, ANYWAY?)

All of the above discussion has been based on the assumption that such a thing as a "center of lateral resistance" actually exists. It is quite possible (maybe even preferable) to arrive at the same numbers, ratios and most of the same conclusions without any reference to CLR at all. Without going into detail, this may be done by taking moments of aerodynamic, hydrodynamic and inertial forces about any arbitrarily selected axis, for instance the mast. However, if one insists on having a CLR, but objects to its moving about, even jumping ship at times, he can declare the center of pressure of the centerboard/hull combination, CPi, to be the only true and immutable CLR, and then take moments about it. The burden of balancing out any lee or weather helm created by the sails, or anything else, the falls entirely on the rudder. But regardless of approach, if one accepts Sir Isaac's suggestion that sigma F and sigma M be zero, the results will be the same.

SOME CONCLUSIONS AND SPECULATIONS

Some interesting conclusions can now be drawn:

1. With two exceptions, a boat on any steady point of sail makes leeway. The exceptions are (a) on a reach when CLR is at CPii, the center of lateral pressure of the rudder, and (b) when running with sails deployed such that Ft, the total aerodynamic force applied to the ship, passes through CD, the center of hydrodynamic drag of the hull.

2. Although usually thought of as "in balance," CLR and CE seldom coincide, as both are continually changing, but rarely by the same amount at the same rate in the same direction at the same time.

3. Although it exists only because of forces acting on the boat's structure, CLR frequently strays away from its mother ship, often far inland or exploring the surface and interior of the moon (but normally not much below the Earth's surface) and reaching the farthest galaxies. Having no mass, it's OK for it to travel faster than light, and during a jibe disappears into infinity aft and returns from infinity forward, presumably having circumnavigated the universe! Meanwhile, its creator, the ship, plods along at a few miserable knots. Columbus might have felt frustrated and annoyed had he known that the three CLRs of his fleet had reached and explored the Americas well ahead of him without his knowledge and consent.

4. A sailboat will heel to windward if its CLR is vertically above the center of pressure of the sails.

Paddle Wheels

Theo Schmidt, Steffisburg, Switzerland

Date: Sun, 31 May 1998

Bill Volk writes:
"*I know that props are far more efficient than paddlewheels .... but I was wondering what the efficiency of a paddlewheel is ... as a function of blade size, shape, and diameter (of the wheel).*"

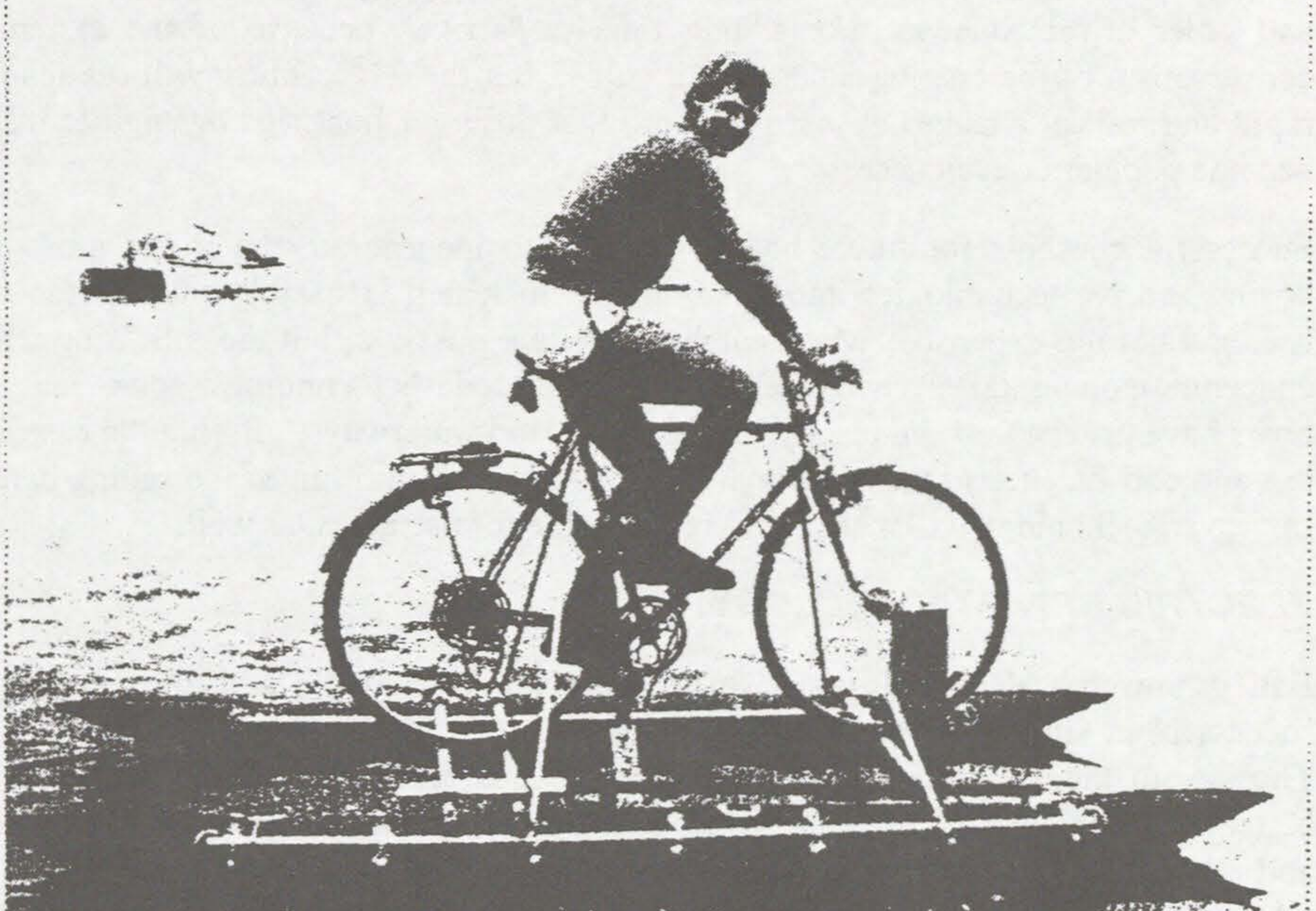
Theory: Paddle-wheels are drag devices and can theoretically approach 100% efficiency if large enough. The equation for efficiency is:

$$\eta = \frac{1}{1 + \sqrt{\dfrac{\text{Area of Hull x } C_d \text{ of Hull}}{\text{Area of Device x } C_d \text{ of Device}}}}$$

In practice most losses come from recycling the surface from the end of a stroke to a new beginning, e.g. lifting the paddle out of the water and putting it in again, which is not covered by the equation above. Even with large, fully feathered paddle-wheels (expensive) there is some splashing, however boats so-equipped do have very good efficiencies and I guess 80% is about right. Small, unfeathered paddle-wheels are much poorer. Very large unfeathered paddle-wheels with small paddles dipped only a little will also be good but have more air resistance.

In order to use the equation above, measure the wetted surface of the hull in square meters (or other unit), and take Cd to be about 0.003 if it is a fine hull like a kayak being used at a speed below which wave-making becomes significant. Now work out the frontal surface of your drag device in square meters (or other unit the same as above) and its associated Cd. A cup shaped paddle could have a Cd of 1.5 but this will cause lots of splashing. A flat plate might have a Cd of about 1 and could be introduced with very little splashing. Most paddle wheels have paddles very slightly cambered in one dimension as a compromise, especially as the usual mechanisms do not feather 100%. A good paddle-wheel will therefore be one which combines a large surface area with a geometry or mechanism minimising splashing, but without increasing air resistance too much or becoming too costly. Getting the best shape is probably more of an art than a science, as it will be difficult to predict things like the vortices formed. Vortices can add a virtual area to our calculation or indeed alter the behaviour radically, as shown by the "clap and fling" mechanism by which insects fly, which doesn't correspond at all to conventional fluid dynamic understanding (remember the old "bees can't fly" stories?).

With screw propellers it is different, as there is no splashing at the power levels we are interested in. Theoretical efficiency is also 100% if the propellor is large enough. In real fluids (including air) with the best foil sections available, 98% is about the limit, according to my program PropSim. With real materials as well, I guess 95% is about the limit. In practice, I guess the best propellers have 92-94%. This is a peak at a single operating point. Cruising propellers for Human Powered Boats will be optimised for 85-90% and be less peaky. Conventional propellers will be as low as 70% and poorly chosen propellers will be around 50%. Keep in mind that the propulsive efficiency of a boat standing still in a headwind is by definition zero, and will still be pretty poor in these conditions when creeping ahead slowly.



Theo Schmidt

Photo by Norman Champ

Boating in the 21st Century

Theo Schmidt

This article and the following one were received in response to Ian Hannay's suggestion, in the AYRS newsletter, for a publication with the above title. Since there was so little interest in the topic these are now reproduced here.

INTRODUCTION

Perhaps the greatest ongoing change in boating is a continuing diversification. The number of materials, hull types, rigs, and engine types continues to grow although really novel boats are vastly outnumbered by standard, industrially made craft. One of the few really new concepts is the solar-electric boat drive and it is likely that this will play a considerable role in the 21st century. A somewhat older but no less novel technology is the kite-rig, which still needs considerable development but will also eventually find its way into mainstream boating, as a jury rig at the very least. These and other novel concepts take a long time to "arrive" because of the extreme conservatism of the boating industry and public, but the 21st century will see many rapid and radical changes on our planet, so that different boat rigs or engines may become popular or even necessary.

Successful concepts for future boats will have to incorporate the right "mix" of available drive technologies into a hybrid system which is useful, reliable, fun to use, and not too expensive. Many combinations are possible, but the following will concentrate on a solar-electric-based concept. With today's technology, solar-electric boats have proven to be eminently suitable on inland waterways, offering the ease of use and convenience of the motorboat and the autonomy and fun of the sailing boat. Improved technology will make such craft suitable for use at sea as well.

ELECTRIC DRIVE TECHNOLOGY

Battery-powered electric drives have been around for a while and are extremely successful in situations where the severe handicap of limited range is acceptable. The key to more widespread use is the continuous replenishment of the storage battery by ambient energy (solar, wind) and by stored chemical energy (oil-based and other fuels, human power). This is a new way of motor-sailing: you "sail" the (electric) motor, feeding it ambient energy from solar cells and/or a wind turbine. If there is not enough of these or if warmth is required, an electricity generator is started, or in the case of small, canoe-based craft, a human-power drive. All these components are described in the following.

THE ELECTRIC MOTOR

Electric motors can be lighter and smaller then other engines for the same power, especially if water-cooled. They can be extremely quiet and efficient, can be over-loaded for specified periods, can easily be reversed in direction, can be extremely reliable and long-lived, and can be cheap, although not all these properties are possible at the same time. Most motors can also act as generators, making power generation possible if under sail. The motors can be encapsulated with waterproof seals, so that even underwater operation is possible. Several motors can be used or carried, either in order to split up the drive for shallower draft and better manoeuvrability or as redundant systems for safety. DC motors with commutator and brushes require occasional maintenance but can be used without electronics, whereas AC motors are maintenance-free but completely dependant on an electronic system.

THE DRIVE

Of the many possible arrangements, only the screw propeller will be described here. (Propulsion by passing electric current through sea-water in the presence of a magnetic field is certainly an elegant future possibility, but has not yet proved practical.) Most boat propellers are compromises and are generally chosen too small on all craft except speed-boats. Such props have peak efficiencies in the range 50-70% but are often below this if not carefully matched. It is however possible to design propellers with peak efficiencies of 80-90%. Such props are larger and more slender than usual. Due to relatively slow turning, the potential danger to people and animals is much reduced. On the debit side, such props are more vulnerable and likely to catch weeds. It is therefore best to have a retraction method for inspection, cleaning and draught reduction on occasion. Besides the classic outboard arrangement, drive units mounted in inboard wells have been shown to be very practical.

THE ACCUMULATOR BATTERY

In contrast to electric land vehicles, the battery problem on boats is very much smaller. The classic lead-acid battery works fine and the only real problem is the limited lifetime of several years. This is a distinct disadvantage for pure electric boats, as the replacement of up to several tons of batteries on even small boats is no light undertaking. Hybrid boats require far less batteries and they tend to last longer. The electrochemical insides of lead batteries are being improved steadily but not dramatically. Modern batteries however feature convenient packaging and handling. Electronic charging and management systems are available which can increase the battery's lifetime several-fold.

THE SOLAR GENERATOR

Solar cells are an extremely elegant energy conversion system which work reliably for several decades without any noise or pollution. They do not require direct sunlight and convert even the weakest midwinter gloom to electricity with an efficiency of between 5 and 20% (poorest to best cell types). The full deck area is sufficient to completely power an efficient hull except in high-latitude winters. Present day solar panels are very sensitive to partial shading so that they do not work together with sail rigs and other items on deck. For practical and hybrid craft, great emphasis must therefore be placed on special wiring systems which reduce this problem, as well as minimal shading layouts and equipment. Present crystalline solar cells must be protected and mounted carefully to avoid breakage and corrosion. They are also still rather expensive (about £5 per Watt, 1994 consumer prices). Research is concentrating on developing cheaper and lighter amorphous cells which could be applied to almost any surface.

THE WIND TURBINE

In contrast to sails, wind generators can provide energy even when moored. A carefully designed wind generator also allows sailing directly upwind, even if the power transmission is electric rather than mechanical. On reaches, present wind-turbine boats often use the rotor like a sail in the so-called autogyro mode without actually deriving any rotational power. Downwind it becomes possible to use the rotor as an efficient propeller and a sail at the same time, permitting travel downwind faster than the wind. With pure wind turbine boats this is only possible in the most efficient of craft; with electric hybrid boats it becomes a practical proposition when additional power can be borrowed from the battery. If this sort of operation is frequently intended, the wind rotor might have either symmetrical wing sections or two sets of blades, as air passes through the rotor in the opposite direction when propelling instead of generating.

Full-sized wind rotors are problematic because of safety, dynamic strength, and in the case of solar boats, shading. Hybrid boats could be equipped with medium size rotors which fold away when not in use.

THE KITE

Kites and especially launching systems are not yet sufficiently developed for practical use as cruising sails but the potential has been proven. They would be particularly good for solar craft because shading would be minimal. Conversely, no masts or rigging would foul the operation of the kite. Wind-borne generator schemes which would tie in with the hybrid boat's electric storage have been proposed but not proven. Maybe something for 22nd Century boats!

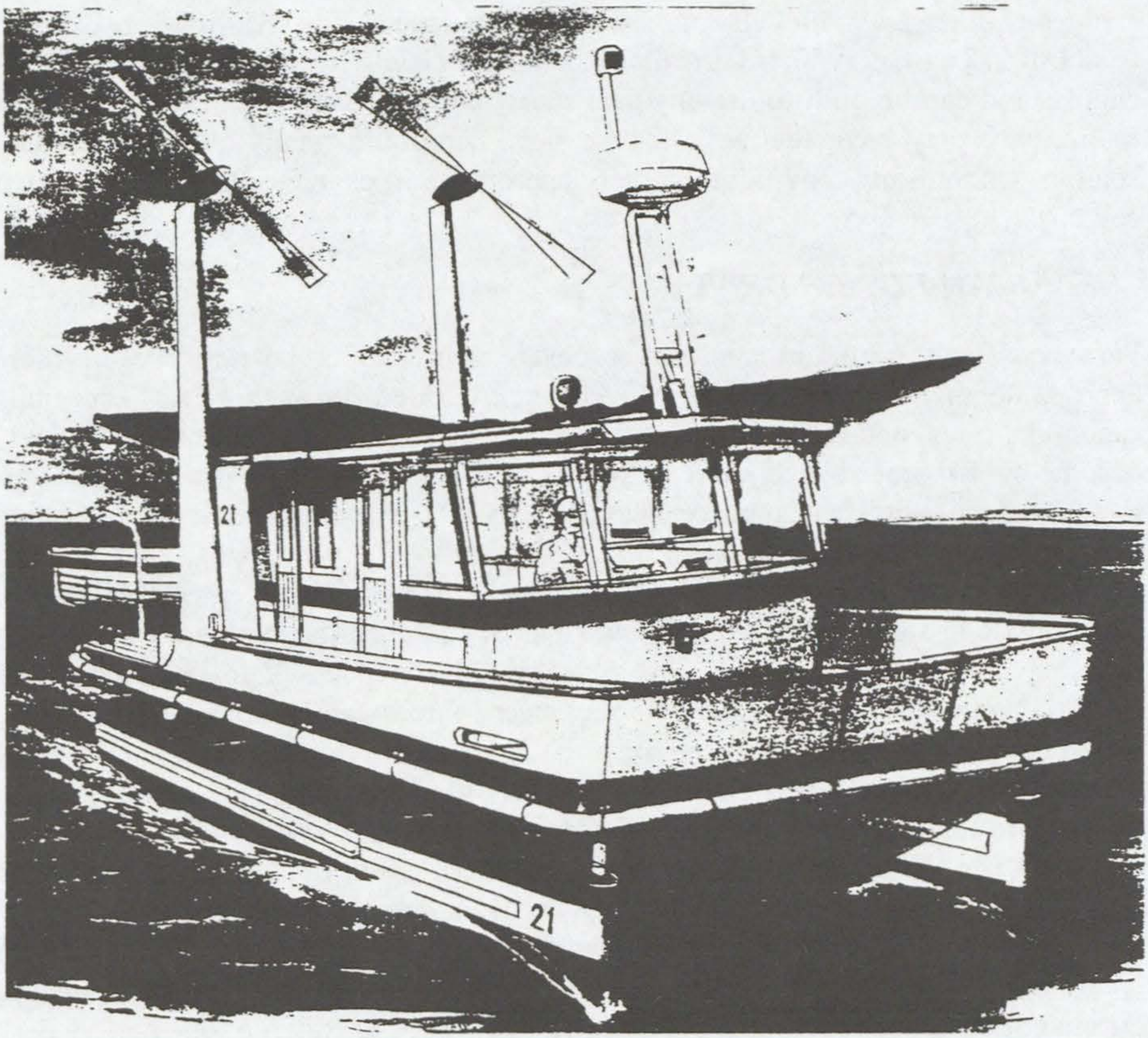
THE CHEMICAL STORAGE ENGINE

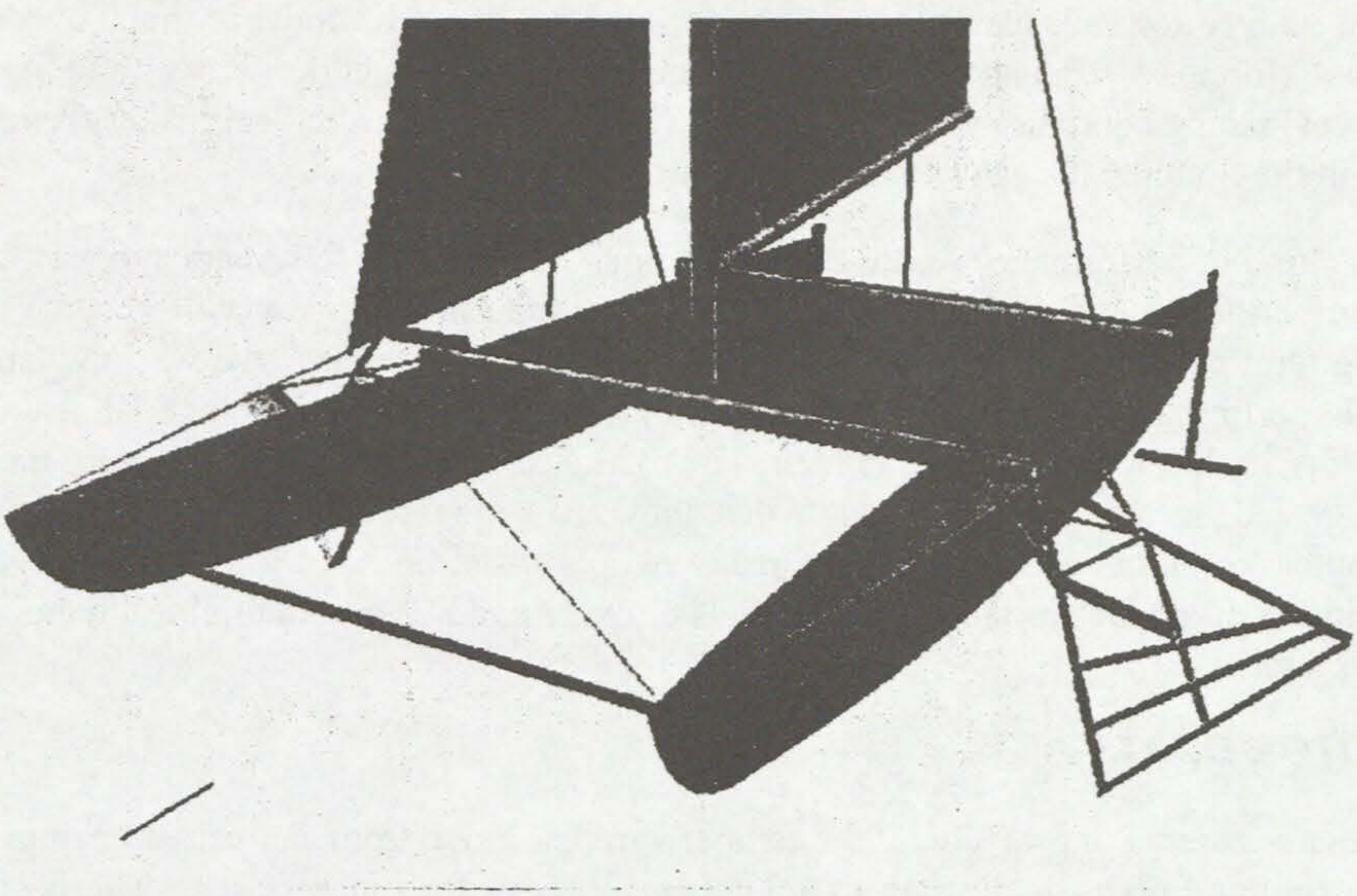
When ambient power sources are lacking, it becomes convenient to draw on highly concentrated chemical energy in the form of diesel or similar fuels. As the conversion process generates heat in any case, this is available for heating and hot water. If an engine is used which is chosen to generate electricity and heat in proportions which can both be used, this is called combined heat and power, or co-generation. Conventional engines produce far more heat than can be used on a boat so that most of this is wasted. A hybrid generator can be very much smaller so that not only can most of the heat be used, but the installation can be smaller and quieter as well. Early 21st Century boats will probably still rely on conventional diesel engines, while later models may well be equipped with Stirling or external combustion engines, which burn fuel much more cleanly than internal combustion engines and can be built to use any heat source and hence any fuel. Further into the future, craft may have fuel cells for the same purpose, a totally quiet and elegant solution without any moving parts, very appropriate in character to the boat's solar cells.

THE HUMAN-POWER DRIVE

For very small craft, an auxiliary or even main human power drive is more appropriate than a heat engine. Movement is limited on such boats, especially canoe-like ones, and as such craft are at least partially open, the crew will quickly become cold if not able to exercise occasionally, except in very warm conditions. Even if warm, exercise also prevents a stiff body and generates a sense of well-being derived from self-produced chemicals. There is also a psychological advantage in that the craft's speed is perceived differently: small (displacement) boats are generally quite slow, but even very few knots of speed can be quite enjoyable when paddling or pedalling, whereas the same speed would be felt to be tedious and boring when under motor alone. If both power sources can be added, so much the better: the boat may not become very much faster due to the rapidly increasing resistance of wave-making, but it will feel very much faster, giving a thrilling and fun ride. In this context, it is not so important what you do with the human power input, but very important how the human power act is felt by the body. Experience shows that the correct "coupling" to the water is important for the feel: oars with the right length and spring or large propellers permit feeling the act of acceleration with one's body, whereas small paddles or propellers feel like stirring soup or whipping cream: not the sort of feeling to convey a sense of speed or exhilaration.

In pleasure boating, the fun or enjoyment of a trip is its very purpose, and the feeling of speed is vastly more important than the actual speed (this is actually true for "serious" travel as well). Another prerequisite is comfort, and the most successful craft are those which best combine the above two attributes with others such as practicality, price, design, etc. Human-power drives go a long way in achieving this, but nowhere is it more important to get the hull and drive optimised together. Nobody likes propelling a high-drag craft with a low-effectiveness drive, e.g. a heavily loaded inflatable with a single paddle. A sleek well-designed hull pedalled by an efficient propeller drive is in contrast extremely enjoyable. Add a small electric motor, a few solar cells and maybe a kite and we have indeed the fitting 21st century analogue to the highly popular centuries-old canoe, just as the 21st century hybrid boat described earlier combines the best of conventional sailing and motor cruising boats. These new craft will not replace the older ones; they are rather a further diversification to be used where and when appropriate.





Yachting beyond 2000

Ian Hannay

INTRODUCTION

In some ways there have been great changes in yachting over the last hundred years and in others much is still very similar. What is likely to happen beyond the year 2000 ?

The main difference has been the introduction of new materials and in particular glues has enabled much stronger and lighter construction. Whereas the old wooden boat with cotton sails had to stop sailing (heave to) when the wind was much over 25 knots (force 6) for fear of breaking something, with modern yachts (and good nerves) racing continues with the wind blowing over 60 knots and spinnakers remain set in the Southern Ocean with it blowing around 50 knots !

This kind of performance would have been impossible only a few years ago. It will soon be the survival problems of the crew rather than the boat that will become the long term performance limit of this situation has already been achieve with the latest high performance military aircraft and they have the great advantage of usually staying in the air for less than an hour. The market for yachts and boats is very much image led, in that people sail craft that they are impressed with in some way or another, so that even when cruising many people insist on having totally irrelevant racing features such as tall rigs, deep keels or excessive beam with doubtful handling characteristics.

MOTOR BOATS

These are the marine version of the camper van that move from campsite to campsite (marina) and occasionally stop in a quiet layby (bay) for lunch or tea. The design allows for fast travel in fair weather and the accommodation is in no way designed for use on the move. They appear to be more like country cottages complete with their inevitable patio doors than real seagoing vessels. The short fat powerboat will never be suitable for extended sea trips (due to comfort and fuel supplies) but it is unlikely that their owners would ever contemplate such discomfort, so the design is dominated by the requirements of a holiday cottage and may use any fashionable styling that the architect might think appropriate. The practical demands of the sea have little influence on the design and layout of these craft. The long, narrow hull designs are more efficient (in terms of comfort and fuel consumption) than the usual style, but the lack of beam offers less attractive accommodation and these craft are also more expensive to park in a marina. The squat fat plastic holiday cottage style of vessel will continue to dominate the motorboat market for many decades yet. At least the motorboat fraternity do not attempt to race their camper van craft as cruiser-racers. The high speed racing versions of motorboats will be continue to be like racing cars — they are completely impractical for any other use.

SAILBOARDS

This has been the only new type of sailing craft to be developed this century totally free from all artificial preservatives (rules, restrictions or prejudice). The development has been entirely along the lines of trial and error, and there is a lot that can be usefully learnt from them. The rigs appear to be particularly efficient, but too flexible if transferred directly onto a more stable hull. The flexibility of their rigs has been developed to cope with the low stability and they use a single unreefable sail for purely practical reasons. In theory a slit sail plan (main & jib) can produce more power if the area is limited, and tends to be easier to handle and reef. The sailboard has also reinvented the principle of sailing without a rudder. The big square riggers had to alter course by trimming their sails as the rudders were far too small for anything but minor adjustments of heading. For the sailboard the lack of a rudder greatly simplifies the construction. Various forms of wing sail have been tried on boards, but if they are to be strong enough to cope with being dropped in the water at times, they are too heavy for good performance, and they do not have the natural camber and twist control that is inherent in the more conventional board sail. Sailboards have probable gone through their greatest development already, their future development will be one of continuing small refinements, but they are unlikely to go much faster than their current 45 knots without a major redesign — probably by greatly reducing the wind resistance of the crew and increasing the available stability in some way. Sailboards will continue to provide a practical means for many people to go sailing with minimal hassle. They have taken over from the dinghy as the way in which most people now start sailing.

SAILING DINGHIES

Over the last hundred years we have seen a fundamental change in dinghies. Due to the weight and strength of traditional boat building methods it was not possible to build hulls that were light and strong enough to plane regularly. Uffa Fox started the trend, but it was not until the new materials became generally available that regular high performance and reasonable durability was achieved. The current designs of dinghies have become much more powerful due to the use of multiple trapezes and hiking racks to get the crew weight further and further outboard. The whole aim is to achieve the highest possible righting moment for the all-up weight without adding undue windage. This style of boat would have been totally impractical in the days of wood, cotton and copper nails. For the next twenty or so years we can expect dinghies to develop along the current lines, with lots of subtle refinements to make them more efficient. The skiff's idea of changing rigs for different weather conditions will always be too complicated and expensive to be adopted generally. Hull structures will become even lighter and stiffer. The insides will become cleaner and open transoms will become universal on performance boats. Carbon will probably be used for all spars and foils. The development of rigs will be to improve handling and reduce drag. The aerodynamic integration of the mast section, sail and battens will improve. The foils will change from the present elliptical profiles to shapes that are much less prone to stalling and the dynamic flexing of the foils will become important for the best performances.

COMMERCIAL PRESSURE FOR ONE-DESIGNS

MULTIHULLS

The actual performances achieved by multihulls have always been a little disappointing and monohulls are now achieving performances close to those of multihulls. Multihulls have not yet truly reach the peak of their development due to the very small number of development classes that race actively. Real developments come when you have a hundred designers and a thousand owners competing for development goals. Anything smaller, and most development stays along established lines and alternatives do not get a look in. Currently too large a portion of the total fleet are one-designs or close-restricted classes. This severely restricts active development. It is only by plenty of close racing that the finer techniques of design and trim are discovered. The all-up weight on a multihull these days is not very different from that of a racing monohull and the greater windage reduces the windward potential despite the greater stability. The real advantage of a wing sail is off the wind where its potential power is about twice that of a soft sail of the same area, but they are too fragile for use in fleet racing and are usually destroyed in capsizes. When area is not limited the optimum is probably a wing mast and fully battened sail.

RACING YACHTS

Racing yachts have completed a circle in the last hundred years and, unless the rule makers change their methods, there is every chance of the same happening again in the next century. During the second half of the last century there were several types of handicap rule devised to allow yachts of different sizes and designs to race together. These included formulas using Length and Sail Area or Length and Beam only. These were reasonable in measuring yachts that already existed, but all universally failed once designers were asked to build yachts to a particular formula. The designers not only tried to produce the fastest possible yacht, but also exploited any apparent shortcomings of the rules. This resulted in the over-canvassed plank-on-edge designs and the skimming-dish Raters, with their deep fin keels that kept falling off (sounds familiar!). These yachts were fast, but rarely held together for longer than a season. In order to try and cope with these problems, the Metre Classes (6, 8, 12 etc) were created by the newly formed IYRU at the beginning of this century to try and counteract the ills. This rule first introduced the girth measurement to prevent fin keels being used.

RACING

Serious yacht racing has for half a century been based upon the Olympic circle course. This is now falling out of favour and being replaced by a simple upwind downwind course as it is only on these legs that any passing can be expected and the real efficiency demonstrated. All boats may be fastest on a reach, but it has been shown that places change very infrequently on these legs, yet they require considerable additions to the sail wardrobe. Top level racing is now dominated by sponsorship, and this requires good television coverage to get the support required. This means that the racing needs to be close and understood by the general public. This means that any form of handicap racing is out at the top level, as is cruiser racing. All serious competitions are day races with yachts designed for such. If they want to go round the Fastnet then all that is done is load a supply of thermos flasks and sandwiches. The traditional cruiser racer is totally inappropriate for any form of modern top competition.

CRUISER RACERS

These yachts are neither one thing or the other, but satisfy a real need in that for most of the year racing is the most convenient way of sailing in the same waters every weekends, but for annual holidays they can be used to do some cruising and visit strange waters. Just like any other yacht these are purchased on the basis of image and accommodation. Unfortunately this type of yacht is a compromise that is far from ideal for either cruising or racing. Serious racing will move away from yachts with any accommodation, and now that there are large fleets of charter yachts available the annual holiday excuse has all but disappeared.

CRUISING YACHTS

The majority of cruising yachts will continue to be sailing versions of the camper van and the comments about motor boats given previously apply. These yachts are sold at boat shows on the basis of accommodation and image, being basically daysailers with overnight accommodation designed only for use in harbour. There is a strong tendency to follow racing fashion regardless of how irrelevant it may be. This is the same urge that causes people to buy a car with spoilers, alloy wheels and the latest registration. Image is a fundamental part of buying any boat, but it can lead to impractical and sometimes unsafe products. Any real cruising yacht need to capable of being handled by only one or two people, and it is unfortunate that the designs are influenced so much by racing. After all, racing yachts are neither the most comfortable nor the most seaworthy - they are purely the result of optimising to an arbitrary set of rules that have very little to do with any true cruising requirements. A new breed of serious cruising yacht will emerge that owes more to the current 60 foot offshore racing yachts (Whitbread & BOC) than to the present cruiser-racers or production cruisers. They will be easy to sail with all controls in the cockpit or in a protected deckhouse, and water ballast will be used when good performance is required. These yachts will sail for hundreds of miles with minimal attention, but will probably require a generator to be run for much of the time. Construction methods will change as most yachts are still built of fibreglass in a way that was developed over thirty years ago. New methods will bring in lighter and stronger hulls, with sandwich construction and more attention paid to watertight compartments. At present it is possible to make hulls unsinkable up to about 10m (33') and over 15m (50') with foam or compartmentalisation. Unfortunately the most popular sizes are the most difficult to make less vulnerable, but this may not be a real problem as it is likely that the current trend will continue and the average boat will spend less than four hours at sea per year. We are all in reality picnickers and caravan dwellers at heart — the rugged sailors are few and far between.

TECHNOLOGY

Electronics will continue to expand at a very rapid rate and it will make possible all sorts of possibilities that can only be imagined at present - for instance anti-collision or grounding warnings and actions activated from the vessels GPS. Radar would only be used as a backup to the system.

Communications will mean that it will be possible to cool the beer before arriving onboard and those at home will be able to check up where you are. The yacht (unfortunately) will no longer be remote from the home or office.

New construction materials will be developed that will in the long run give all boats the potential to be much lighter and stronger, but it will only be by public pressure that they will be made safer. It has been suggested that with virtual reality there will no longer be any requirement to actually go afloat, it will only require a visit to the computer room at the yacht club, or at home in a cold bath if you want the discomfort as well !

There already is a proposal to have a radio controlled model yacht race around the World. These would be about 6 metres (20') and controlled directly from the siting room. So here is your opportunity to sail around the world without leaving your armchair !

SPEED SAILING & RECORDS

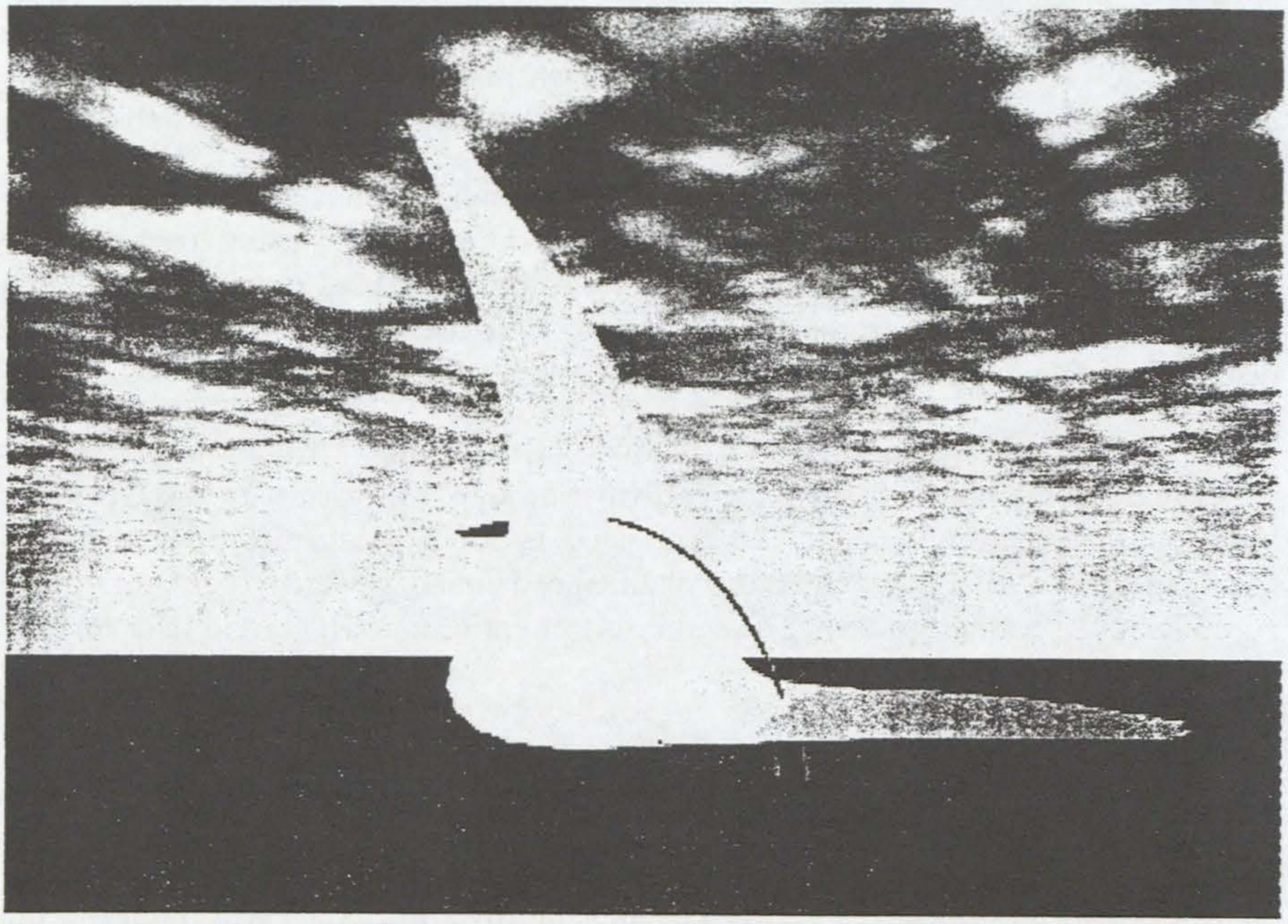
Sailing speed records will no doubt continue to climb, but as the goals become more and more specialised and expensive there will be even fewer attempts. To be realistic the craft has to be matched to the site of the attempt and all these need to be very close to a weather shore with strong clear wind over it. There is a simple fact that the stronger the wind the faster a boat will go, the problem is to make a practical craft that can be rigged, launched and sail in very windy conditions. Crossbow II and the sailboards set their records with the wind around 40 knots. Yellow Pages Endeavour set her record in only about 25 knots of wind. If this style of craft were designed to cope with 40 knots plus, very much higher speeds should be possible. The new 'Red Pages' is a step in this direction with a lower rig and more stability.

We can expect to see 50 knots passed fairly soon and 60 knots is certainly possible with current technology, but it is very unlikely that any of the existing machines will achieve this in their present form. Just as the sailboard needed many refinements to raise its speed potential from 19 to 45 knots over the years so the current speed machines need many subtle improvements to achieve their full potential.

The highest priorities are maximum stability, with minimum weight and very low windage all combined with a robust construction that will cope with the inevitable high loads and strong winds. The real need is for a substantial prize that will encourage more groups to enter the challenge. Human powered flight was made possible by the Kramer prizes. The same sort of enticement is needed to encourage speed sailing to achieve new levels.

CONCLUSION

Whether we see the development of something new like the sailboard or the redevelopment of a traditional style of craft such as the multihull will depend largely upon luck. In the meantime electronics and improved materials will dominate the progress over at least the first half of the next century. The combination of these technologies will allow new styles and combinations that are not possible at present.



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The Amateur Yacht Research Society was founded in 1955 by the late Dr John Morwood to encourage amateur and individual research into nautical science. It is a British Educational Charity (No 234081) and a company (No 785327) without share capital, limited by guarantee. It has a world-wide membership.

AYRS publishes a quarterly newsletter, for its members, and a series of publications which are also sold to the public. It also hold a number of meetings in the UK and the USA.

Membership and other information can be obtained from the head office:

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