Features

Regulars

Cover Photo - *Dr Elkaim's research catamanaran under trials in Redwood City harbor, January 2001. The "crew" were there as live ballast in case a sudden wind gust overwhelmed the control system.*

Congratulations to Steve Fossett and the crew of *Cheyenne* on their "Round the World" record of just under 58 days 9 hours 33 minutes from Ushant, round Antarctica, and back to Ushant!

This record leaves the Jules Verne Trophy (for which we understand Cheyenne had *not* signed up) and its Committee with a certain amount of egg on their faces – they have the Cup, but someone else has the record, and it seems *Cheyenne* very carefully crossed the Jules Verne start and finish lines on her departure and return!

It's a pity though that they just missed satisfying the purists who ask that at least one point on a circumnavigation be diametrically opposite (an antipode) of some other point. As can be seen from the graph below, Cheyenne missed this by a few miles. However the WSSRC does not require that, and *Cheyenne* more than satisfied *their* requirements for the Record, so they deserve all the plaudits they will undoubtedly get.

Simon Fishwick
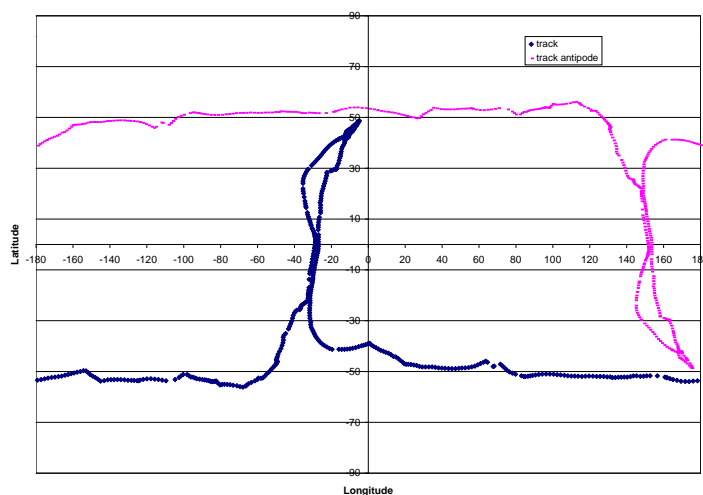
Index to *Catalyst* etc

George Chapman has very kindly indexed all the *Catalysts* up to No 11, and all the AYRS Newsletters from 1991 to 1999. By the time you get this, his Index should be on the AYRS website (under "Catalyst")

*Yves Parlier's new catamaran - now named "Médiatis Région Aquitaine" - on trials on 31 March.
Note the step on the hull. - photo © Twin*

International Conference on Small Craft Regulations

20 - 21 October 2004, RINA HQ, London

This international conference on Small Craft Regulations will provide a forum for discussion on the various present or future National, European and International regulations applicable to small craft. Such regulations include: the MCA Harmonised Code for craft less than 24 m, MCA Large Yacht Code (presently applicable to charter yachts of and over 24 m length), ISO Standards for Small Craft for compliance with EC Directive on recreational craft, for craft less than 24 m in length, EC and UK regulations for inland waterway craft and safety standards for RIBs, and rescue craft. These are examples only and papers on small craft regulations other than those mentioned will be equally welcome.

The regulations mentioned above vary in content but all are concerned with safety of life and protection of the environment. Most delegate structural strength to classification societies or refer to classification strength standards. Some such as the ISO Standards for Small Craft include structural strength standards. This conference will provide on update on present regulations as well as giving an introduction to new regulations. RINA has invited papers on the following subjects as they might apply to aluminium, FRP, steel or wood vessels. Development of and experience in the use and application of the regulations in general or on specific topics such as;

· Fire safety & structural fire protection,
· Structural strength standards,
· Materials,
· Watertight and weathertight integrity,
· Stability,
· Life saving appliances.
· Stability and floatation tests for small craft
· Environmental protection

The conference hopes to attract a large international audience and to provide a forum for all those interested in safety regulations for small craft.

Contact: Conference Department, RINA, 10 Upper Belgrave Street, London SWiX 8BQ fax: +44 (0) 20 7259 5912; email:conference@rina.org.uk

Ondulo - a French fish-tail boat

New to us at the Paris Boat Show (although in fact it was the second year it had been there) was this little craft with its flapping fin/"fishtail" propulsion. Driven by foot-pedals attached to crankwheels, with an auxilliary crank to control the angle of attack of the fin, this little boat is 3.25m (10ft9in) long (including the fin) by 90cm (36in) beam.

It has fixed fins foward and aft; the forward fin is retractable and used only in strong crosswinds, the after fin serves to counteract the lateral force from the propulsion. Steering is by halting the propulsion fin when it is as a suitable angle so that it acts as a rudder. It is also possible to turn on the spot by oscillating the propulsion fin through less than its full arc. It can even reverse. The boat carries a French Class D approval (protected waters, 50cm waves, wind Force 4).

The manufacturer is Pierre Chatelain, Longefonds, 38930 Clelles, nr Grenoble, France. http://www.ondulo.com

Seeing this craft in the wood (OK plastic) as it were prompts a question - Does anybody know what the relative efficiency is of this kind of propulsion (or a yuloh) vs a propellor, or even oars? We know from the British Admiralty trials of 200 years ago that propellors are more effecctive than paddlewheels, but what about these (or their horizontal relatives - whaletails)? Do any of our members with an interest in human-power boats know?
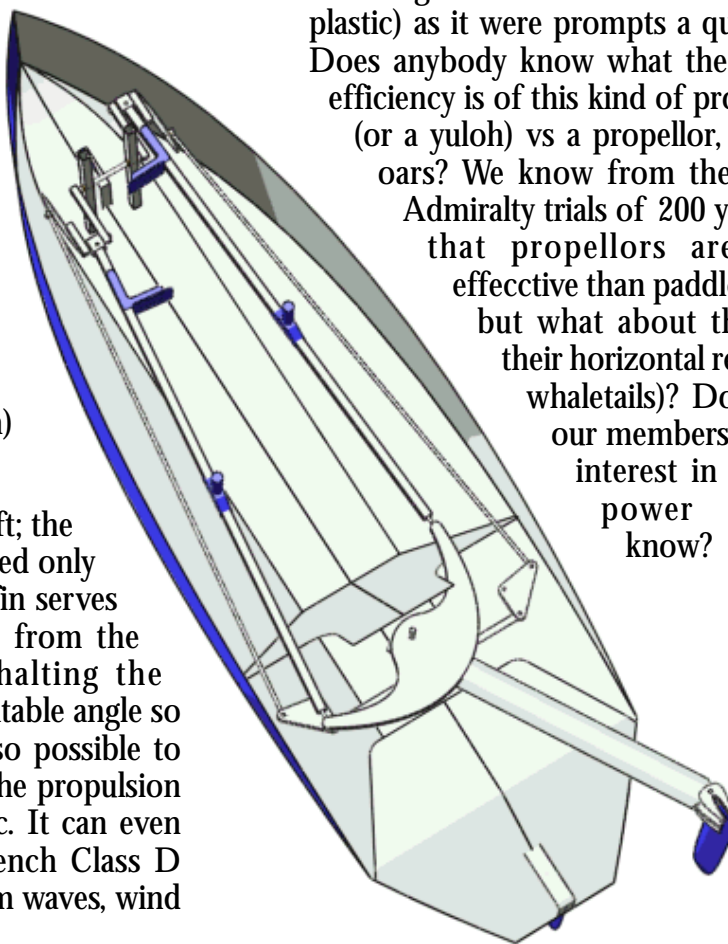
A Balancing Act

Your Toad Hill Note in CATALYST No 13, with the photos held over to No14, about helm balance, makes a statement about the centres of hydro and aero efforts "At first thought it could be reasoned the two points should be both on a vertical line for correct balance.".. Absolutely !

Unfortunately many teachers have taught that the aero CE should lead the hydro CE by a percentage of boat length, because they always illustrate this mantra with a side elevation of the craft. Hours have been spent debating the correct percentage "lead". The novice, with no preconceptions but thinking "at first thought", asks why they are not in a vertical line WHEN SHOWN ON THIS SIDE ELEVATION.

Some of us have been aware that the CEs should, as far as possible, be one above the other at all times for perfect helm balance. And the correct view to depict this is the PLAN. See AYRS AIRS No 9, February 1975, page 51 where Joe Norwood sketches three proa configurations IN PLAN and illustrates this fundamental truth. I quote this page because I was the fool who built TIGER and learnt my error the hard way ! Didier Costes experienced the problem in his series of EXOPLANES but as far as I recall never discovered, or was told, the truth. Mea culpa.

Quite recently, in the RINA's new publication "International Journal of Small Craft Technology" (Vol 145 Part B1 June 2003 - ISSN 1740-0708. It's online, but I have been unable to extract it from http://www.rina.org.uk. Members only?) Kenning and Vermeulen discuss yaw balance of yachts upright and heeled, and significantly their Figure 1 is a PLAN view of the forces involved. They discuss ways of determining the CEs and how best to predict them, because with the increasing size and cost of tycoons' yachts designers need to get the balance correct right from the start of sea trials, for every likely combination of sails..

It is almost impossible to arrange for the CEs to be one above the other (i.e.in a vertical line). Normally the best that can be done is for the aero CE to be downwind of the hydro CE. The CEs and their likely lines of action can be drawn on a plan of the craft. When balance is achieved the lines of action will coincide. If they do not, a small divergence can be corrected with the rudder. If you consider the forces as pulling at the ends of a (horizontal) rod, then small automatic adjustments in their directions and magnitude will achieve co-linearity and balance. This is the condition for self steering and can be achieved on most boats if you can trim and fix the tiller, as experienced sailors well know..

Yacht design teachers need to read the paper quoted above and tailor their teaching of the positioning of the rig relative to the keel(s) accordingly, using a plan rather than a side view.

Another common misconception in books etc is that there is a positive pressure on the underside of a foil. Not so, generally! A symmetrical section foil only starts to experience a positive pressure - i.e. above ambient - at about 8 degrees incidence. Below that the reduced pressures above and below are doing their best to tear the foil apart. I know, I have had this happen.

George Chapman
The Rock, SOUTH BRENT, Devon,
TQ10 9JL, UK.

Video Timing

In Catalyst 14, Graeme Ward is reported as seeking synchronised start and end videos using a wireless link.

I believe a wireless video link would be very expensive and a better alternative would simply be two synchronised cameras. The two videos can then be played together on a single monitor.

The obvious way to achieve synchronised video is to include synchronised clocks in the pictures. Just use two GPS receivers set to time display. To synchronise the video, just import it into a computer and use a video edit program to slide the two sequences back or forward until the times match. Superimpose, then click play!

Cheers, Dave Howorth
<Dave.Howorth@acm.org>

Yacht skiing- is it a new sport?

Last summer, on the Veerse Meer (Southwest Netherlands), we saw several cruising boats motor sailing with skiers behind them. They were skiing at slow speed (6-8kts),   using an extended halliard from the top of the mast, which was attached to a ski handle. This gives them the combination of uplift and foreward pulling power to perform at slow speeds . It seemed just as exciting as high speeds skiing and allowed slaloming and wave jumpimg up to some 12ft over the wake, if they timed it right on a sharp turn. Evenings were the best time, when the water is calm and clear of most boats.

Tim Daley
<tim_daley39@hotmail.com>

Some issues relating to the Self Stabilising Variable Geometry Kite Sail System

The need to restrict the quantity of information submitted for the John Hogg prize to manageable levels seems to have produced a measure of uncertainty about some aspects of the work. The purpose of this note is to attempt to clarify matters.

It has been questioned whether the increased aerodynamic drag on the hulls as they are lifted out of the water was included in the calculations. In the computations quoted the aerodynamic drag on the boat and crew was included but as a fixed value equivalent to that of a flat plate having an area of 10 square feet and perpendicular to the direction of the apparent wind. This figure was held constant regardless of the amount by which the hulls are lifted out of the water. It is therefore a very crude approximation. However it is difficult to arrive at a more precise value since the aerodynamic drag depends not only on the cross sectional area of the boat but on its form factor (whether streamlined or not) and on the direction of the air flow.

Wind tunnel tests would probably be required to establish reasonably accurate aerodynamic drag figures. Other things being equal, the hydrodynamic drag of the hulls (before being lifted out of the water) will be about one thousand times greater, quite apart from additional energy losses associated with wave generation. All in all, it was felt that the change in aerodynamic drag caused by partly lifting the boat out of the water was of negligible significance given the approximations necessary in order to develop the analysis.

Conversely, the change in hydrodynamic drag caused by partly lifting the hulls out of the water is of profound significance - particularly at high boat speeds. This lift is generated by the inclined sail. The judges query the value of inclining the sail at more than 30 degrees to the vertical. It is, of course, true that the aerodynamic drag angle will be increased by doing so, because the horizontal component of the sail force (perpendicular to the wind direction) has been reduced whilst the horizontal drag force (parallel to the wind direction) remains the same. The aerodynamic drag angle for a sail having a lift to drag ratio of 5 to l would be 11.3 degrees when vertical, 13 degrees when at 30 degrees to the vertical and about 16 degrees when at 45 degrees to the vertical. The effect of this on the beta angle depends on the amount by which the hydrodynamic drag has been correspondingly reduced. This in turn will depend on the weight of the boat and crew, the size and aerodynamic characteristics of the sail and on the velocity of the apparent wind. As pointed out in CATALYST No. 14 p16, when heeling is eliminated the vertical lift of the sail can be increased (in theory) up to the point at which hull drag becomes negligible. Hydrodynamic drag is then generated only by the keel and rudder. The aim of the self-stabilising sail is to produce this situation as an inherently stable condition.

The judges compute a beta angle of almost 30 degrees for one particular set of values for course, wind speed and boat speed. If the sail is assumed to have the characteristics outlined above, the hydrodynamic drag angle would be about 14 degrees with a corresponding hydrodynamic lift to drag ratio for the hull and appendages of about 4 to 1. This seems to be achievable with a reasonably efficient keel providing there is negligible drag from the hull, and no serious problems from cavitation. These were the conditions assumed in the calculation.

It is hoped that the above comments will serve to clarify some of the uncertainties which might have been present in the original paper.

J.G. Morley

Hull Aero Drag

(Extract from a letter to Fred Ball copied to *Catalyst*)

You asked me whether there would be a worthwhile reduction in hull aerodynamic drag on *Ceres* [the Chapman's 19ft hydrofoil cat - see *Catalyst* No 10] if we could point the hulls into the apparent wind at all times. I didn't manage to answer then; and I won't give you a straight answer here!

Look in *Catalyst* No 2, June 2000, page 23, bottom right, and the enclosed diagrams [below and overleaf].

Our wind tunnel tests showed that the hulls of *Calliope*, similar to *Ceres*', with one crew, develop aero 'lift' horizontally as well as drag, and both lift and drag vary with beta angle and with height off the water. To the extent that the hulls are long very low aspect ratio aerofoils, this is to be expected. When pointing into the wind there is no lift, and the trampoline will contribute its maximum drag.

Lift is a maximum around 45°, and falls to zero again at 90°. We did not go further but I think the curve would repeat itself to 180°, the drag then acting ahead on the boat.

Later tests of a model of *Disa* (front cover AYRS 76) as part of Joddy [Chapman]'s work for the JRA and his PhD show similar characteristics.

The 'reference area' I have selected is the plan area of the hull(s), so that to calculate drag one uses the formula Drag = $C_d \times$ Area $\times$ Velocity$^2 \times$ whatever constant is appropriate. In Imperial:

Lift/Drag in lbs = $C_l/C_d \times$ Area in sq ft $\times$ Knots$^2 \times 0.0034$ (in air)

For *Calliope* the sail area is 119 sq.ft, the hull 'area' 148 sq.ft which effectively includes the crew's area. So you can calculate the forces at a windspeed and beta angle of your choice, choosing a Cl for the sail as you wish.

According to the VPP, in a nominal 12 knot true wind, (14.42 at sail CE) *Calliope's* best speed is 18.5 at beta 43.4, apparent wind 19.2, gamma 110, total aero C_l is 1.14, total aero C_d is 0.44. Total hydro drag is 75 lb. Calculating the hull aero lift and drag and subtracting from the totals would give the sails' lift and drag and hence their coefficients, which is what we had to do to the wind tunnel figures. I will not confuse us both by trying to explain what the VPP does.

I take consolation from the fact that the hulls are helping the sails a little, though at a severe cost in drag, for closehauled work. Once the apparent wind is abeam the hulls are a dead drag to leeward, simply increasing the side force.

If one could angle the hulls, straight into the apparent wind might not always be the best thing to do; tedious to work out and decide. And then if they are angled, what happens when you come down off the foils? Your circular (seen in plan) boat may be the answer, as it will never develop [horizontal] lift and hence the additional induced drag. But how good will it be hydro-dynamically? OK on foils, I suppose you could have a conventional under-water hull for a displacement craft. This would amount to encasing a normal boat in a discus-shaped fairing above the waterline - and then remaining upright. Try it

George Chapman

WIND TUNNEL RESULTS
CALLIOPE MODEL - FLYING 2 HULLS

4-12-96
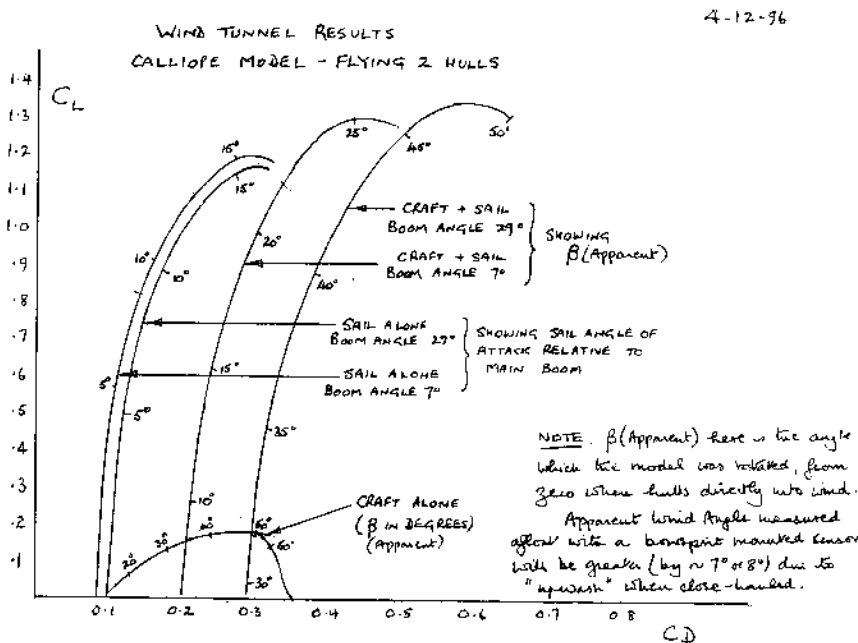
NOTE: Reference Areas to which Coeffs apply: CRAFT + SAIL & SAIL ALONE: 119 ft'. CRAFT ALONE 148 ft'. Each

HULL + CREW MODELS - IN WIND TUNNELS   12-1-00

DISA - 14' RNSA DINGHY - 2 CREW
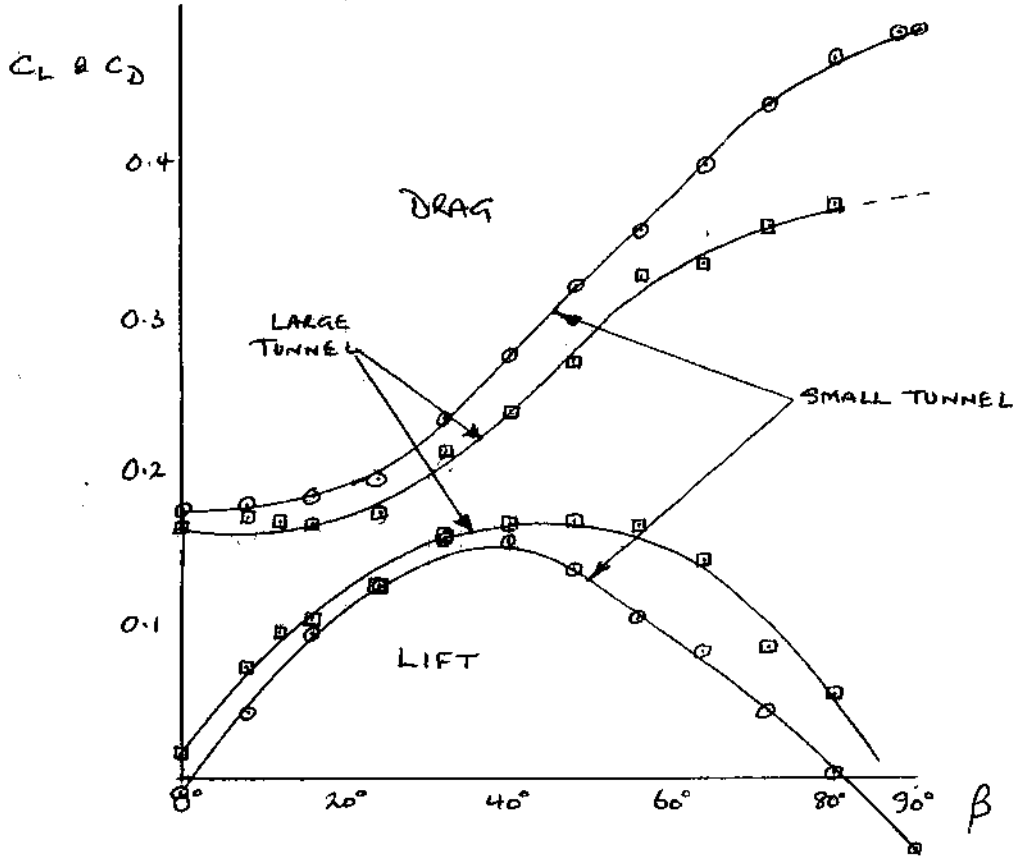
CALLIOPE - FLYING HYDROFOIL
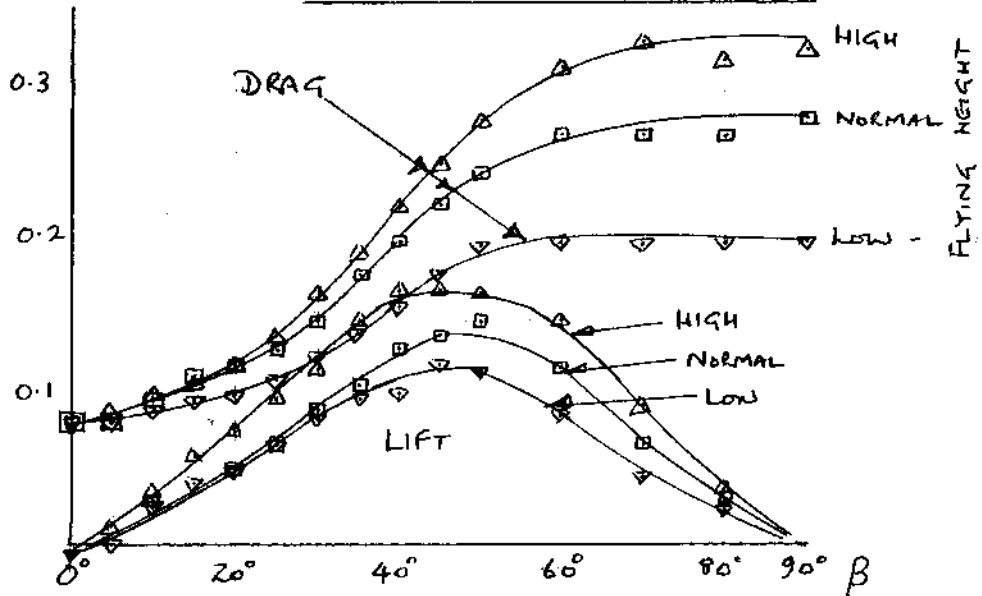
The Marine Engine – A Necessary Evil?

James Crafer

As a form of marine propulsion, the internal engine has been with us for so long that we accepted its welter of disadvantages without giving too much thought to a practical alternative.

Since its inception, countless brilliant engineering minds – and billions of Dollars – have been devoted to quietening, smoothing, and generally trying to improve the reciprocating engine stubbornly ignoring the fact that it is founded upon a grossly inefficient engineering principle.

After years of blood, sweat and tears, and even with the aid of modern high-tech. materials and techniques, they still haven't cracked it!

On the contrary, in their quest for yet more power and. speed, economy, and trouble-free operation, the designers of marine/marinised engines have created an ever more complex nightmare with which one is supposed to cope in frequently tough sea and weather conditions.

It is the absurdly confined and inaccessible places 'below stairs' where so-called yacht designers unthinkingly place the auxiliary engine, that make me boil.

The succinct message: 'K.I.S.S.' (Keep it simple, Stupid!) should be riveted prominently above the drawing board of every marine engineer and yacht designer responsible for the horrendous engine-installations that I have encountered aboard otherwise notable yachts.

As a dedicated skipper of large catamarans over the years, I was foolish enough to let a friend persuade me – against my better judgement – to help him sail his new 'toy' (a 46ft. motor-sailor ketch, complete with clipper bow and 'great after cabin') from Port Lauderdale down through the Bahama Island chain.

With her 6ft 6in draft (positively frightening in the shoal waters of the Bahamas) this romantic-looking 'sow' – whose designer should be hung, drawn and quartered – sailed predictably badly and, with the prevailing S.E. headwinds, relied heavily on her massive 60 hp Diesel to get her anywhere at all.

Suffice to say that after two weeks of constant juggling with this monstrous engine in the Hell-hot, foul-smelling, gut-wrenching bowels of this vessel, I re–learned all the hate and loathing I had experienced in the past with plodding, corkscrewing monohulls and their badly installed propulsive machinery.

Not a day went by without a mechanical problem of some sort and, apart from sediment in the fuel-tanks, constant stoppage of the engine, fuel leakage into the bilge, and bleeding the fuel system while the old tub was rolling its guts out, the vibration factor from this rigidly mounted engine was so high that it was impossible to stay in the adjacent galley, let alone cook!

The vibration fatigued and fractured the mounting bracket on the alternator; the gear-change and throttle cables constantly worked loose from their mountings causing us to lose these vital controls, especially on one occasion when we were making a tortuous and difficult harbour approach, and the heat from the engine

in its cramped and ill-ventilated compartment made any maintenance doubly hazardous.

In our rare moments of idyllic peace and quiet (that is when we were not nursing the vile thing to make it charge our batteries) I jotted down a Crime Sheet of charges against marine engines in general... this is how it reads:

1) High initial cost of marine engine and installation.

2) High weight factor of all the above, including fuel-tanks & fuel.

3) Ongoing running-costs (fuel, lubricating oil and maintenance)

4) Costly overhauls and spares

5) High noise, vibration and pollution factors.

6) Unreliability when most needed (bad weather, emergencies etc.)

7) Inaccessibility, due to poor design/installation.

8) Complex exhaust and water—cooling systems.

9) Messy and dangerous fuel-filling.

10) Bilges frequently swimming with oil and stench.

Having thus addressed myself to the sheer weight of evidence against marine engines and the urgent need to look for a better, cheaper, simpler, quieter and cleaner means of auxiliary propulsion, I examined the following proposition:

All-Electric Propulsion Units:

By using a combination of wind-turbines and solar photovoltaic panels, it should be eminently possible to charge big banks of modern lightweight batteries which could not only drive an electric main propulsion motor, but could also supply sufficient power for the vessel's ancillary equipment.

Before the pessimists and traditionalists dismiss the concept as impractical, let us look at the advantages in greater detail.

In the first place, modern technology says it can be done. Solar photovoltaic panels are becoming more efficient and cheaper all the time. Special electric motors are now being produced which put out twice the power of a conventional electric motor of the same size and weight.

Storage batteries are constantly being improved in terms of increased capacity and output for a given size and weight.

Most good quality electrical and electronic equipment for marine use has shown that it can survive and continue to function perfectly under brutal marine conditions.

The time is, therefore ripe for the development of an all-electric auxiliary propulsion system such as I have outlined.

There will, of course, be those who argue that even a combination of wind-turbines and solar charging panels will be insufficient to provide adequate power both to drive the vessel and power her other electrical equipment.

In Northern Latitudes, this may well be the case with development in its present stage but I have no doubt that, as technology advances swiftly, an 'all-electric' scenario will be a very practical proposition, no matter what the Latitude.

Certainly in a Caribbean environment, where there is an abundance of sunshine, and plenty of wind both day and night, the system would operate perfectly using present 'state of the art' components.

Detractors may well say that they don't want to load their boats with big, unsightly wind-turbines ... and where would they mount them anyway?

For answer, I would point out that efficient wind-turbines can be designed to blend aesthetically into the vessel's superstructure without destroying her overall appearance.

After all, you only have to observe the electronic and other unsightly gadgetry festooning the decks and rigging of the average yacht which has succumbed to the commercial blandishments of the 'navaids' vendors. If you can live with a giant radar scanner grinding away on your mizzen mast, or a big plastic radome mounted on your coach-roof, you can certainly suffer a streamlined array of wind-turbines which do a vital job of providing kilowatts of electric power for all your onboard needs. With the solar panels also pumping in power to the batteries during daylight hours you will always have ample reserves, and won't have to suffer the aggravation of a generator thumping away for hours in a quiet anchorage.

Let us assume that we have a new vessel ready to be fitted with auxiliary propulsion, and see how the typical internal combustion unit and the 'all-electric, unit compare in the Table below.

Conclusion:

It will be immediately apparent from the above list of components that the I.C. Pack needs no less than eleven essential parts. They are weighty, complicated and take up considerable boat space. Moreover, the I.C. Pack is difficult to install, noisy, dirty, and costly to maintain and operate.

By comparison, the 'All-Electric Pack' has only six major components, all of which are compact, clean, silent, easy to install, require no exhaust system, no cooling, minimal lubrication ... and no combustible fuel.

It only remains to demonstrate, to the vested interests who currently dictate the use of conventional I.C. marine propulsion systems, the outstanding advantages of an 'all-electric' system and persuade them to bring it to commercial reality.

Already developing an 'all-electric' system along these lines for a very large and advanced charter catamaran, I would be pleased to hear readers views on the subject.

James H. Crafer
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Email: jcrafer@yahoo.co.uk

Typical I.C. Pack:	**'All-Electric' Pack:**
1) Main motor (Diesel or Gasoline)	1) Main Electric Motor
2) Gear-box.	2) Bank of Batteries
3) Starter-Motor.	3) Array of Solar Panels
4) Alternator.	4) Array of Wind-Turbines
5) Water Pump & Seacocks	5) Wiring & Switch—Gear
6) Cooling System. Strainers.	6) Sterngear including reversible propellor
7) Exhaust System	
8) Fuel Tanks Fuel, & Oil Filters.	
9) Lubricating Oil, Oil Filters	
10) Batteries	
11) Sterngear/drive.	
12) Separate Generator for Battery-charging.	

Making Water Sports Easy for Disabled People

Mario A. Rosato and Giovanna Barbaro

The present article is a theoretical development performed by the Authors, who are concerned by the attitude of the boat manufacturers, who seem to be somehow insensitive to elderly or disabled people. We think that water sports should not be restricted only to young bundles of muscles, as the current tendencies in commercial design seem to target. Brains are also necessary to enjoy life at the sea, and speed (sometimes also exhibitionism) should not be the only condition to have fun.
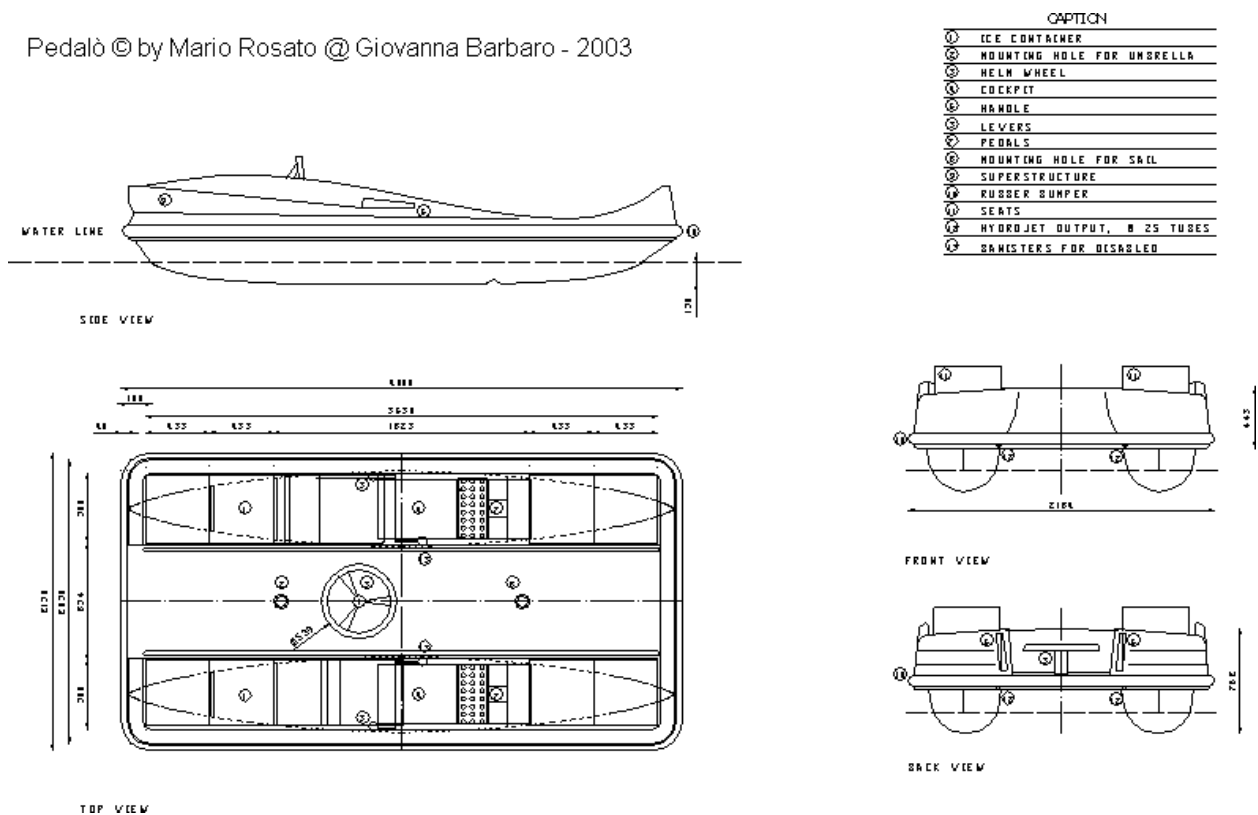
Pedalò is a human powered boat that can also be fitted with a simple sail. It is intended for use on holiday beaches, lakes and resorts. Its innovative features can be summarised as follows:

- Instead of the inefficient paddle wheels common in this type of craft, the propulsion is obtained by means of a hydrojet system. The water jet is produced by four piston pumps, which are driven either by pedals and / or levers.

Pedalò © by Mario Rosato & Giovanna Barbaro - 2003

Propulsion and helming system
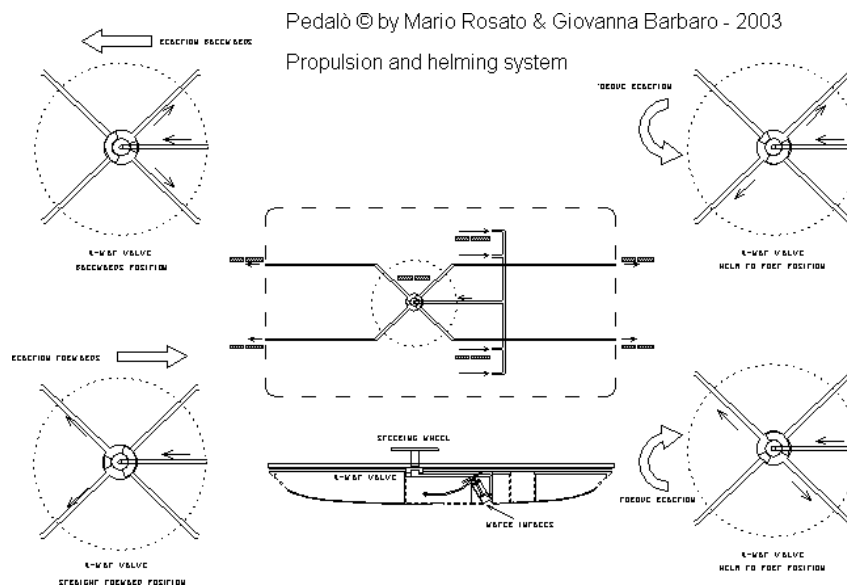
- • The craft is steered by means of a 4-way valve which directs the flow from the pumps in four combinations: straight forward, straight backwards (or for braking), clockwise turn, counter clockwise turn. In this way, no rudder is needed and the drag is kept to a minimum. This also improves the manoeuvrability in comparison to conventional pedal boats, where the minimal speeds sometimes make the rudder inefficient. Pedalò can turn 360º in its own length!

The underwater part of the hulls is a modified Sears-Haack body. It can be demonstrated that this particular shape minimises both the wave and friction drag coefficients (supersonic aircraft are designed on this concept). In calm water probably 5 to 6 kts could be reached by two adults pumping on a fully loaded craft (400 kg overall). This is a very good (theoretical) performance, considering that the critical speed for these hulls is Vcrit = 1.25 $\sqrt{L}$ = 4.5 kts.

The hulls and deck are highly symmetrical. Hence, only a half-mould of each is necessary to produce the craft.

The ergonomic design has taken both extremes of the population into account: the "1-percentile woman" and the "99-percentile man".

The pumps are independent of each other, so they can be driven in several modes:
- • Pedals only: for people just wanting to relax
- • Pedals and levers, reciprocating strokes (one pushing while the other pulls): for fitness of legs and arms.
- • Pedals and levers, simultaneous strokes (pushing or pulling with both legs and arms, performing a movement similar to rowing): for total fitness of legs, arms and abdominal muscles.
- • Levers only: for disabled people, or for those wanting just to develop their arm muscles.
- • One lever (or both) and one pedal (or both): also for disabled people, depending on which limb or limbs are impaired.

Pedalò © by Mario Rosato & Giovanna Barbaro - 2003

CAPTION
① WATER INTAKE
② PISTON PUMPS
③ FOAM FILLING OF HULLS
④ PUMPS LEVERS
⑤ ICE CONTAINER
⑥ SLIDING, REGULABLE SEAT
⑦ SUPERSTRUCTURE
⑧ SKIN-FOAM SEATS
⑨ BUMPER

SECTION B-B MAN PERCENTILE 99

SECTION A-A - WOMAN PERCENTILE 1
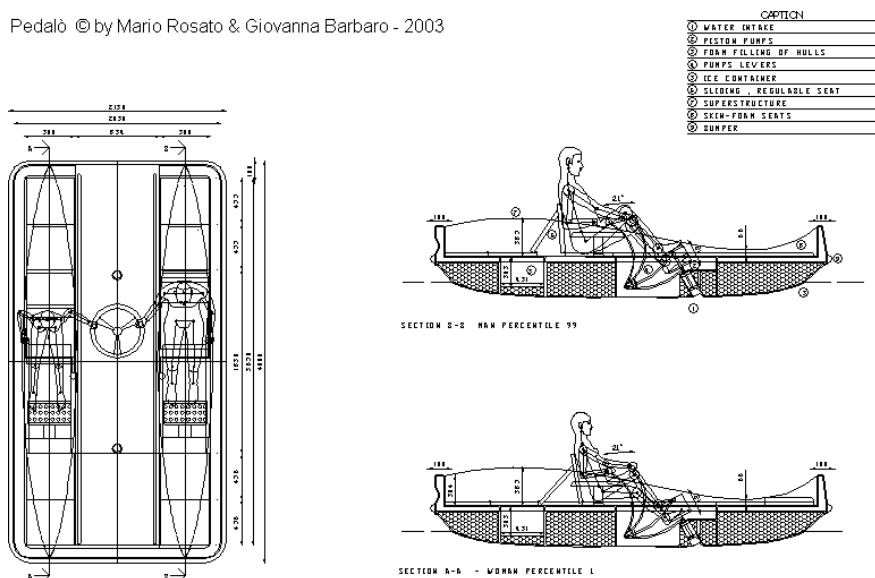
The deck should be fully covered with polyurethane skin-foam (high density polyurethane which makes a tough skin when moulded) cushions for maximum comfort. These could be fixed by several systems (for instance, the mould-in fasteners already used by the Author for wheel-chair cushions of high density polyurethane). These cushions not only provide comfort but also offer extra safety (they float well) and fun (it could be possible to link them making a kind of floating mattress). The deck also has two sliding lids, which can either cover the cockpits, leaving a perfectly flat surface; or be mounted as back rests while pedalling. Existing pedal boats have fixed, rigid seats, making it impossible to lie completely flat to sunbathe or sleep. A fully cushioned flat deck is also suitable for disabled people to move more easily and be self-sufficient when on water.

The hulls must be filled with foam (usually polyurethane) to ensure compliance with the safety regulations. For increased comfort it could be possible to leave some box-shaped volumes without foam filling, using the skin-foam cushions as covers. Thus, the boat could have some well-insulated, built-in room to keep drinks or food fresh in ice, at no extra cost.

Two mounting holes are foreseen in the deck, either for mounting a mast and a simple sail (e.g., a crab-claw rig) or just a beach umbrella. With an accessory rudder, the craft could be transformed into an enjoyable catamaran, or simply be used for a picnic on the water with the family.

Anybody having interest in building and testing a prototype is kindly invited to e-mail the Authors. Comments and constructive critics will be welcome!

Mario A. Rosato and Giovanna Barbaro
maralejrosato@hotmail.com

A paddle wheel design

A. G. P. Jankó CEng. MIMechE
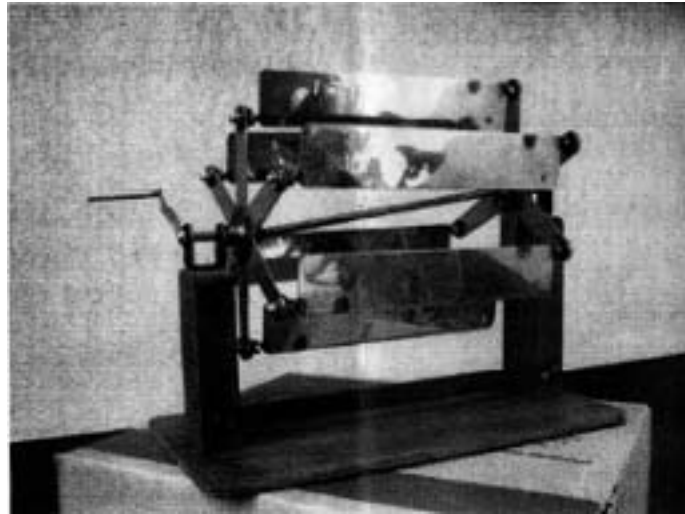
Introduction

The propulsion of ships and boats has attracted the inventors of old and it has only been overshadowed during the second half of the last century by the space age, nuclear power and domestic machinery. Now that intermediate technology for the developing world and watersports for the well-to-do societies have become fashionable, there is some interest in propulsion of boats again. In 2000, this design was awarded Bronze Medal at the Inventors' Olympics in Budapest by an international panel of judges

Boats and ships are propelled by:

Sail, Manpower, Machine power

Poles, Oars, Paddles Paddle Wheels, propellers

Fixed Blades Adjusting Blades Water Air

American Stern Wheeler Feathering Blades
ld Fashioned Side Wheel (most old river ships)
(Great Eastern, pedalo) **Fixed Angle Blades**
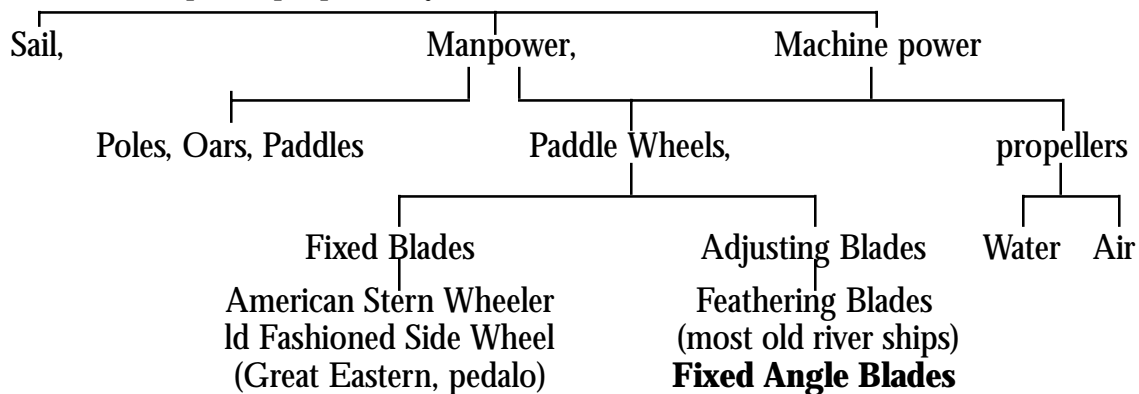
The fixed blade wheels suffer from the disadvantage of the blades entering and leaving the water at the angle of the spokes of the wheel to the water surface. This can be made better by

large diameter wheels and narrow blades, but an almost perfect solution, the feathering of the blades, spread to all the rivers of the world from the Danube. The blade angle is controlled by connecting rods to an eccentric hub, which has caused a little problem to the engineers of these ships, mainly because the wheels were large in comparison with the rods. The smallest ship I saw was on the Lake St. Wolfgang in Austria. The heaviness of the mechanism compared with the wheels and the ship was noticeable. The advantage of this system is that the blades enter and leave the water at an angle that is optimum for the drive, and are almost free from either spanking or tearing the water. Also they turn nearly horizontal in the air, reducing air resistance. The fixed blade angle wheel aimed to retain the same clean driving motion or better it, and reduce the size and the complications of the now outdated (but still the most successful) wheel.

The blade angle can be kept constant around the whole revolution by driving the blades within the wheel assembly by a gear train. This, however, is still a complicated mechanism, and has to be contained in a sealed lubrication box and protected from flotsam.

A two-sided drive can be used to make a simpler mechanism. The blade angle is fixed by the use of two wheels rotating at the same speed. One has its centre axis positioned one blade depth higher than the other. One drives the top edge, the other the lower edge of the blade, which is set between the two. Synchronism and stiffness between the two wheels are the essential requirements of this design. On small wheels and small boats the wheels are connected with a shaft that has sealed universal joints at both ends. (Fig 1). If a large wheel is considered, two interconnected synchronized drivers may be the solution. Such a wheel assembly may be made narrow to be placed either side of a long, narrow ship to replace the old blade feathering wheels, but in my opinion, the best way to use it is between the hulls of a catamaran.

There are the established ways of working out blade sizes and RPM of paddle wheels; all depend on experience and laboratory tests. Neither should be ignored, but in this paper I shall consider the basic physics of this "Paddling Wheel", set up algebraic expressions, and work out a possible boat propulsion in numerical terms. I shall also define the critical component of the assembly, and work out its strength for practical purposes in order to show the proportions of components. In the conclusion of the paper I shall point out what further study has yet to be done, and finally where can all this be used.
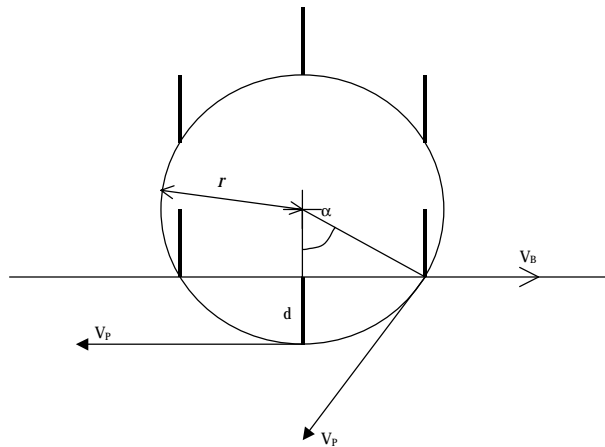

Fig 2.

Relationships

It is stating the obvious that at a constant speed the propulsion force of a boat is equal to her resistance. The propulsion force acts on the paddle of the Paddling Wheel, which is a flat sheet of steel, wood or whatever is chosen in the design. This paddle moves along the length of the boat in one direction propelling her in the other. This is similar to the case of evaluating the force on a plate set across a fluid flow. The values obtainable from this expression depend on the coefficient of drag, which is the result of numerous experiments and varies from 1.06 for a square to 19.9l for a very long rectangle, according to Giles: Fluid Mechanics and Hydraulics. I use the middle value.

$$R = C_D A \frac{\rho}{2} (\Delta V)^2 \qquad (1)$$

where:
R = Force on the paddle, N
C = Drag coefficient
ρ = Density of water, Kg/m^3
$A = dxb$ = Area of paddle, m^2
ΔV = Effective velocity, m/s

Since the boat moves, the speed of the blade driving the water at the middle of the stroke has to be the difference between the peripheral speed of the wheel and the speed of the boat. (Fig 2.) This also defines the efficiency of the system:
work done / energy input = power out / power in =
$\eta = 100 V_B / V_P$ %
where: V_P = Peripheral velocity, m/s
V_B = Boat speed, m/s

$$Z = \text{number of paddles} = \frac{360}{\alpha}$$

$$?V = V_P - V_B$$

$$V_B = V_P \cdot \cos^B \alpha$$

Hence:

$$V_P = V_B + \sqrt{\frac{2R}{C_D \rho A}} \qquad (2)$$

The aim of the design is to avoid splashes at the entry and at the exit of the blade. This requires the horizontal component of the peripheral velocity of the wheel to be equal to the speed of the boat, as expressed above. Fig 2 also represents the relationship between the depth of the blade, which is sensibly equal to the submersion of the wheel, the radius of the wheel, and the angle of the radius to the surface of the water at blade entry.

$$\frac{V_P}{V_B} = \frac{r}{r - d} = \frac{1}{\cos\alpha} \qquad (3)$$

and

$$n = \frac{60 V_P}{2\pi r} \text{ RPM} \qquad (4)$$

where

r = radius of wheel, m
d = depth of paddle, m
b = width of paddle, m
n = revolutions per minute

These expressions can be used to determine the principal measurements of the paddles of the Paddling Wheel. The required scantlings of the boat are usually given by the service for which the boat is intended, from which the propulsion force can be determined. Some sizes can be assumed by their proportions to the given data, some from subjective preferences. This may require reorganising of the equations from case to case.

In reality there are minor deviations from the above model. For example, the submerged paddle increases the speed of the water forward of itself, in respect of the boat, so the next paddle enters into a faster flow than the speed of the boat. The overall effect however can be covered by the right choice of drag coefficient, and tested. It follows that the next paddle should enter the water after the suction is filled in; so let the angle between paddles be large, which means fewer paddles in a wheel. At the exit this effect is not likely to be important since the paddle preceding the one at its maximum horizontal speed is already leaving the water.

The suction effect

Consider a paddle as it moves across the water. The driving force derives from the pressure built up behind (astern) of it and a suction forward of it, looking at it from the boat. [Fig 3] The concern is that the next paddle may enter an accelerated volume of water, and may become an obstacle, until the horizontal component of the peripheral velocity increases to the speed required for propulsion. For easy visualisation, assume that a sinusoidal wave is set up before and after the paddle by the suction and pressure (Fig 3). The assumption is that half of the propulsion pressure is given by increased pressure astern the paddle, and half of it as suction before.

Having estimated the half-length of the wave, we can calculate the angle under which the next paddle should follow the one before into the water. Using Example 2, with its 6-blade design, where one paddle follows the other at 60º intervals while we should have 68º, that is 5 paddles instead of 6.

When a paddle reaches its maximum effective velocity, the one before is just about leaving the water, so it is not likely to cause an obstruction to the accelerated water. As Fig 3 shows, maximum pressure is generated at the paddle, and within a half wavelength the water is accelerated and the wave surface goes below the undisturbed waterline as the paddle leaves the water.

This calculation does not include the internal friction of the water due to viscosity. As the Reynolds Number is high, the viscous force relative to the propulsion force on the paddle is low; so including it would not improve the result significantly, and test would in any case be needed.

Strength of a paddle bracket

Figures 1 and 4 show what a paddle bracket may look like expecting that a more streamlined design would be adapted in an actual construction.
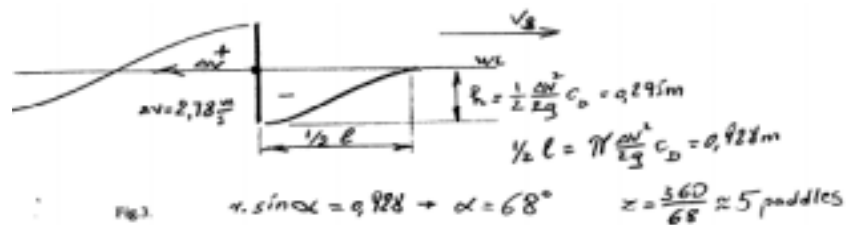

Fig 3

Examples

Catamaran: Overall length   10 m   Boat speed v = 10 km/hr = 2.78 m/s = 5 knots
             Overall beam   3.5 m   Density of water = 1000 kg/m³ (river, lake)
             Between hulls   2 m
             Draft   1 m
             Resistance   400 N   Drag coeff. c=1.5   (A. C. Hammitt: Technical Yacht Design)

Example 1.   Paddle width, b = 1.5 m; Paddle depth, d = 0.33 m.

$$V_P = 2.78 \times \sqrt{\frac{800}{1.5 \times 10^3 \times 0.5}} = 3.812 \, \text{m/s}$$
$$\frac{r-d}{r} = \cos a \text{, where } r = 1.11 \text{ m}$$

$$n = \frac{60 \times 3.812}{2\pi \times 1.11} = 3.27$$
$$\frac{V_B}{V_P} = \cos \alpha = 0.73 \text{, } a = 43.1^\circ$$

$$z = \frac{360}{43.1} = 8.33 \quad \text{(8 paddles)}$$
$$\text{Efficiency } \eta = \frac{2.78}{3.81} = 73\%$$

Power = 400 ´ 3.81 = 15.24 kW

Example 2.   Paddle depth, d = 0.5 m; 6 paddles; α = 60°; cos α = 0.5; $V_P = 2V_B$, so V_P = 5.56 m/s

$$A = \frac{2r}{C_D \rho V_B^2} = 0.67 m^2$$
$$1 - \frac{d}{r} = 0.5 \text{, } \therefore r = 1.0 \text{ m}$$

$$b = \frac{A}{d} = \frac{0.67}{0.5} = 1.35 \text{ m}$$
$$n = \frac{60 \times 5.56}{2\pi} = 53.12 \text{ RPM}$$

Efficiency = 50 %

Example 3.   3 paddles; α = 120°; cosα = 0.5; d = 1.0 m (max); b = 1.5 m

$\Delta V = 0.64$ m/s $V_B = 2.78 + 0,64 = 3.42$ m/s

$n = 3.42 \times 60 / 6.28 = 32.6$ RPM   Efficiency = 100 V_B / V_P = 81%

   This example serves to show that the larger the paddle, and the slower the wheel revolves, the better the efficiency that can be expected. Against which, the cost of making it and the space it occupies has to be considered; but in this case, there is the practical difficulty of realising the common drive for the two sides of the wheel. The suction effect of a paddle before the next paddle enters the water may be reduced or even eliminated, but that could cause a rhythmic slow–fast–slow motion.

Discussion and Conclusion

Paddling Wheel is the name specifically for this design of the whole family of paddle wheels. Its advantage is the simple construction in small sizes, making it suitable for use in special applications. The design is such that a moderately skilful person can build it in his home workshop, while there is not everywhere in the world is there access to a foundry to cast a propeller. Travelling in the shallow branches of rivers and in lakes holds great attraction to many people and may be even for scientific explorers. There are communities in the world where a boat propelled by a paddle wheel could perform various services. Ferry service is the most obvious requirement; but it could even be moored stern on the shore at the opening of an irrigation canal and river water paddled in.

The disadvantage is that a paddle wheel is large and occupies useful room on the boat as both Jankó and Vedres designs show (illustrations). This was also indicated by a number of requests I received for advice on wheel design. Vedres and Jankó are co-operating in the design of an electric boat that would make use of the Paddling Wheel and offer the relative silence of the electric drive with some ecologically preferred features (illustrations).

One must not overlook the fact that most powerboats are driven by propellers, and many of those by outboard motors. Their number proves their advantage. Apart from some justifications
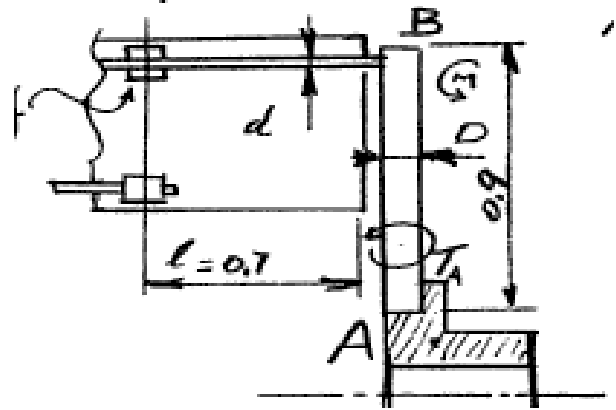
Fig 4

mentioned above, designing, fabricating and using paddle wheels on boats is, mostly, a recreation in itself with a hope that it may become commercial and will benefit many people.

Suggested further work: the design process followed above should be tested to establish a reliable value for the Drag Coefficient upon which the process depends. The test could be carried out on a full size wheel in a tank as well as on a moving boat as long as the resistance of the boat is known at various speeds. Equally important would be to discover the "size of the market" in order to estimate the extent of investment.
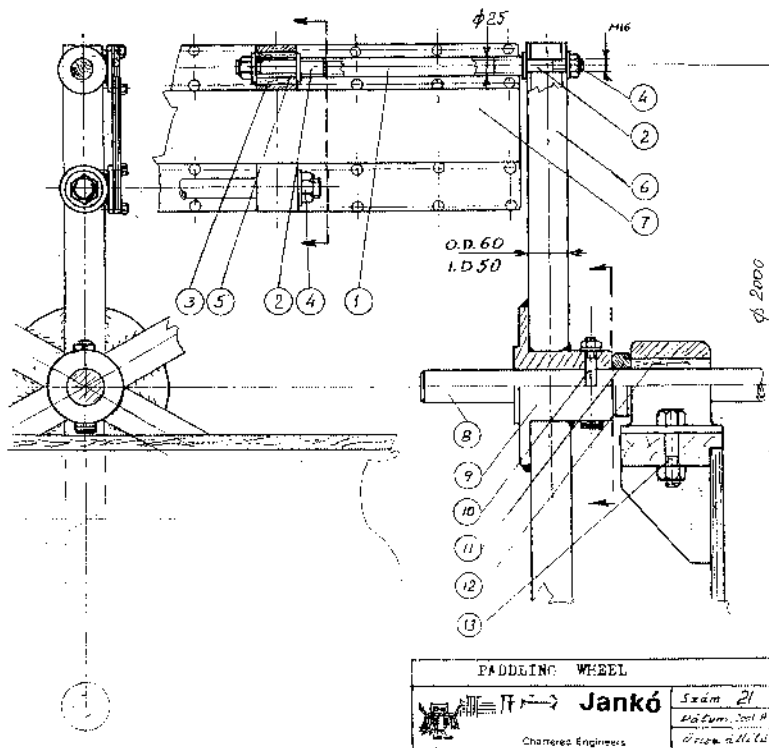
PADDLE BRACKET OF A PADDLE (PADDLING WHEEL)

Parts List
1. Paddle spindle
2. Threaded end M16
3. Bearing (aligning 5 deg.)
4. End nut
5. M16 thread
6. Spoke
7. Blade (plywood or metal)
8. Drive shaft
9. Main bearing
10. Shear pin
11. Spacer
12. Bearing bush (nylon)
13. Bolt to beam

(top) Ambrus Janko's design for a River Boat

(bottom) Dr A Vedres's "Ecoboat" Design

An Autonomous Wing-Sailed Catamaran

Gabriel H. Elkaim
Ph.D.Thesis

Is it a boat, a plane, something in between?

This presentation details the Atlantis project, whose aim is the design, development, and experimental testing of an autonomous wind-propelled marine craft. Functionally, such a vehicle is the marine equivalent of an unmanned aerial vehicle (UAV), and would serve similar purposes. The Atlantis project has been able to demonstrate an advance in control precision of a wind-propelled marine vehicle from typical commercial autopilot accuracy of 100 meters to an accuracy of better than one meter with a prototype based on a modified Prindle-19 light catamaran. The project involves substantial innovations in three areas: windpropulsion system, overall system architecture, and sensors.

The wind-propulsion system is a rigid mass-balanced wing-sail mounted vertically on bearings which allow free rotation in azimuth about a stub-mast. Aerodynamic torque about the stub-mast is trimmed using a flying tail mounted on booms aft of the wing. This arrangement allows the wing-sail to automatically attain the optimum angle to the wind, and weathervane into gusts without inducing large heeling moments.

[This article is an extract from Gabriel Elkaim's PhD thesis which was submitted as an entry for the John Hogg Prize. The thesis, for which Dr Elkaim was awarded his PhD by Stanford University, centred upon the autonomous control of the craft, however we have extracted for Catalyst readers only those (less-mathematical) parts dealing with the design and (next edition) the construction of the wingsail.

Please note that the euqtions and figures are numbered as in the original document. - Editor]

The sensor system uses differential GPS (DGPS) augmented by a low-cost attitude system based on accelerometer- and magnetometer-triads for position and velocity measurements.

Experimental tests were performed, requiring the catamaran to sail on a precise track through the water, in the presence of currents, wind, and waves. Using the identified system models, a high-performance estimator/controller was implemented and tested on the full-scale prototype. These controllers were indeed quite successful, tracking the line to within 0.3 meters.

The Wingsail

The concept of using a wing upon a sailboat has been around almost as long as aircraft themselves. Many previous designers have come to the false conclusion that adequate lift coefficient could only be achieved with an asymmetric (cambered) wing. This led them to designs that tack by flipping up over the top of the mast, often leaving the wing inclined at 45 degrees (the flip does not rotate the wing a full 180 degrees). The disadvantage of this arrangement is that the weight associated with the flipping mechanism is usually large enough to negate any increased propulsive efficiency by virtue of increase hull drag. Also, with the inclined wing designs only the vertical projection of the wing acts to propel the boat. This again results in a loss of propulsive efficiency.

Design Choices

The most visibly unique aspect of the Atlantis project is the wingsail propulsion system, as shown in Figure 5-1. The design considerations and goals are: equivalent performance to the original sail system, low actuation force, and the ability to precisely control the resulting system.

A sloop rig sail can achieve a maximum lift coefficient of 0.8 if the jib and sail are perfectly trimmed. Realistically, an operating maximum lift coefficient is 0.6. The design goal of the Atlantis wing is to achieve a maximum lift coefficient of 1.8. Since this allows the wing to generate three times the force of an equivalently sized sail, the wing area is reduced to one third of the area of the original sails. Because the drag characteristics of the wing are much improved, the performance of the wingsailed catamaran should be superior to the original configuration. At worst, the wing will yield equivalent performance.
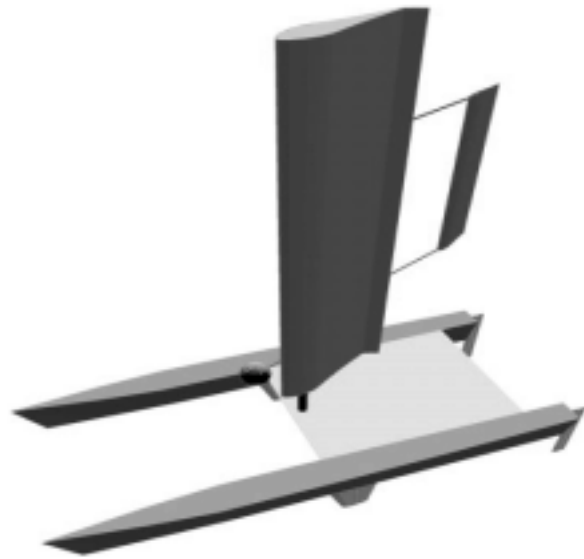
Fundamental to the goal of autonomous operation is the requirement that the actuation of the sail be simple. In the case of a conventional sail, this would be extremely expensive in terms of actuator cost and power requirements as the forces required are quite large. Additionally, the complex nature of the aerodynamics of a sail makes any sort of precise control of the sail difficult to accomplish. In order to achieve precision control of the catamaran, the disturbances generated by the propulsion system must be minimized. Fundamentally, this requirement forces the design away from a conventional sail.

Figure 5-2 shows the design evolution of the wingsail for the Atlantis. The design choices are on the right of the figure. The choices are designated by the triangles, with the losing choice to the left, and the winning choice to the right. The text explains the problem with the losing choice.

The steps of the evolution are each detailed in later sections. The design evolution begins with a choice between a conventional cloth sail or a rigid wingsail. Then the choice is between a symmetrical or asymmetrical section. Following the symmetry choice, one must choose between an existing section and a custom designed airfoil section. With the section design complete, the next issue is to trim the wing aerodynamically or mechanically. Lastly, four possible configurations for the wing and trimming surface are considered. The series of choices lead the design to a self-trimming wingsail with a conventional tail, using a custom designed airfoil section for the appropriate Reynolds number. The remainder of this chapter considers each choice in detail.

(Opposite) Figure 5-1 The engineering model of the Atlantis. The wing sail is 5.37 meters tall and has a chord of 1.45 meters. The self-trimming tail is used to balance the aerodynamic moments. The model includes a spherical mass attached to the leading edge of the wing to bring the mass center of the wing/tail combination in line with the stub-mast. In the actual prototype, the ball mass was replaced with an electronics pod attached to the forward end of the lower wing section.

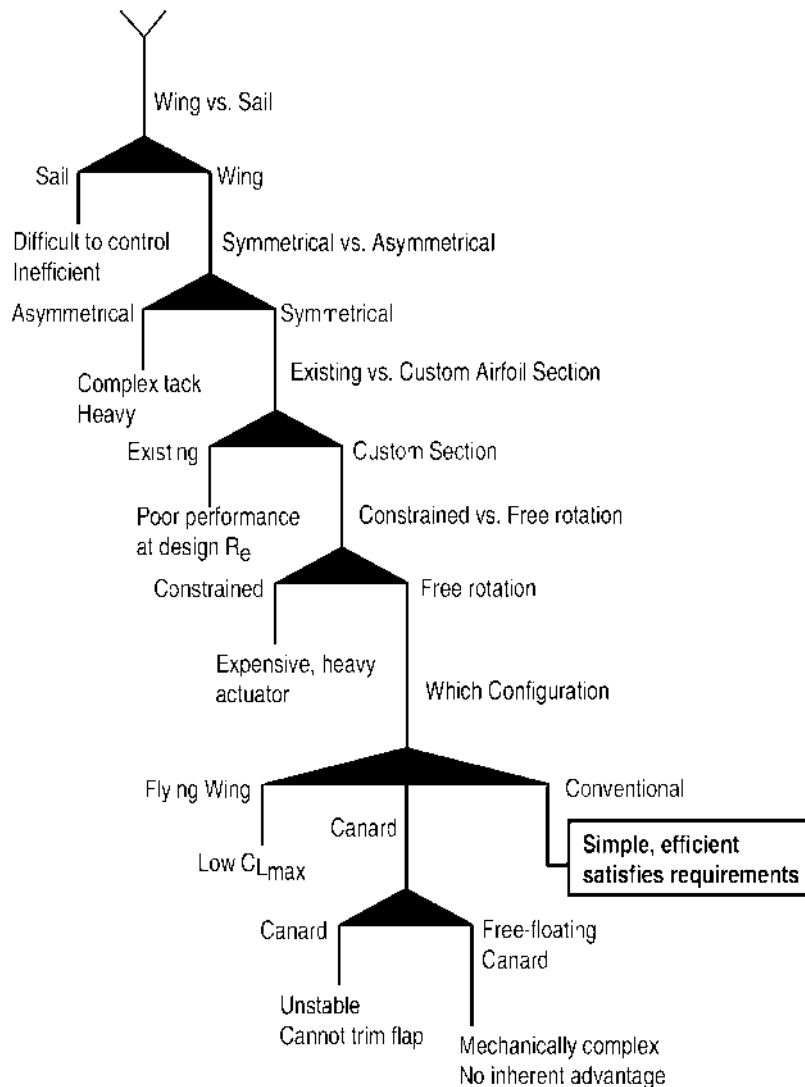*Figure 5-2 The design evolution of the propulsion system. The design choices are on the right of the figure in black. The choices are designated by the triangles, with the winning choice to the right. The text explains the problem with the losing choice. The series of choices lead the design to a self-trimming wingsail with a conventional tail, using a custom designed airfoil section for the appropriate Reynolds number.*

Wingsail Description

The chosen wingsail is 5.37 meters tall and has a chord of 1.45 meters. It is constructed in three sections: the lower section which includes the forward electronics/ballast pod, the middle section to which the tail is attached by twin booms, and the upper section. The wingsail is built entirely of marine grade plywood covered in polyester fabric and is suspended by a spherical roller bearing at the top of the stub-mast. It is stabilized by a needle roller bearing around the stub-mast at the bottom of the wing. This allows the wing to rotate freely through 360 degrees without significant resistance. An engineering diagram of the wing is shown in Figure 5-3.

Wing Versus Sail

There are three main reasons to use a wing instead of a sail: efficiency, less actuation force required, and self-trimming. The first and most obvious is that a rigid wing is far more efficient than a cloth sail. Though some attention needs to be given to Reynolds number effects, the coefficient of lift, C_L, has a maximum of 1.8 for the Atlantis wingsail versus typically 0.8 for a perfectly trimmed sloop rig (jib and mainsail). Also, the Lift/Drag (L/D) ratio of the Atlantis wingsail is in the 10 - 30 range, whereas the L/D of the conventional sail is in the 3 - 5 range. Further, a cloth sail suffers from aeroelastic collapse when pointed high into the wind (the sail is said to be luffing). This causes a great deal of drag when sailing closehauled and effectively limits how high the boat can point into the wind. The rigid wing, by contrast, suffers no aeroelastic problems; it can point straight into the wind with very little drag, no flapping, no whipping about, and no noise, while effectively reefing the wing. In fact, the feathered wing-tail combination has much less drag than the bare mast. This is demonstrated in Figure 5-4, which shows two sections (cylinder and airfoil) that have the same net drag (including both viscous and pressure forces). Because the two sections have the same drag, the ability to reef a sail (or reduce the area of the sail) is moot when using a rigid wing because the wing has far less aerodynamic load on it than the bare mast itself.

The second main reason to use a wingsail for propulsion is less force is required to actuate the wing itself. A cloth sail is fixed to the mast, and trimmed from the boom. Since the center of pressure of the sail is aft of the leading edge, the trim force must overcome a portion of the lift of the
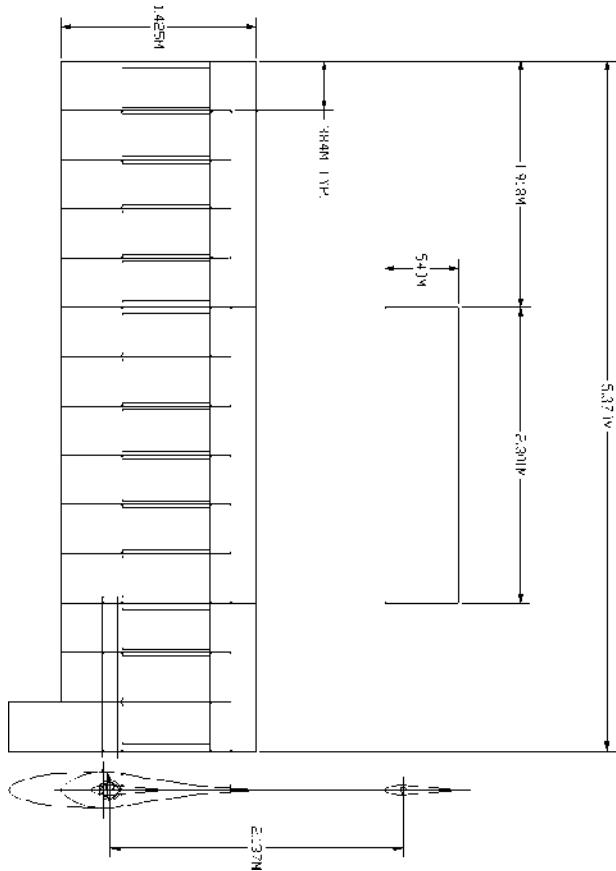

Figure 5-3 An engineering layout of the wingsail. This drawing shows the dimensions of the wing, the three sections, and the rib layout pattern. On the bottom it shows the overhead view, including the electronics pod at the front of the wingsail. (Details of the wing structure and construction will be published in the next part.)

sail. Inspection of a conventional sailboat shows a large blockand- tackle with eight or more loops of line attached to the boom is required to trim the main sail. With a winch, an additional 8:1 mechanical advantage is required to hold the boom in. To control this effectively in an automatic manner, a very large and fast-acting actuator is required. These types of actuators quickly become very expensive and a typical one would cost more than the entire budget for the project. By contrast, the wing can be designed to pivot near the center of pressure of the wing itself. The wingsail is turned to an angle of attack either directly or through an auxiliary trimming surface. In either case, this is accomplished with a small DC motor and can be actuated quickly and inexpensively. The cost effectiveness of this design is the main reason it was used for this project.

The third main advantage of the wingsail over the conventional sail is the ability to make the wingsail self-trimming. The benefit of this is that the wing will absorb gusts without transmitting the force of the gusts through to the guidance system. By decoupling the propulsion system from the guidance system through passive stability (self-trimming), the control system design is greatly simplified. Through proper arrangement of the flying surfaces, the wingsail will readjust automatically to a change in either wind speed or wind direction, with no intervention from pilot or control system.

The self-trimming capability makes the wingsail ideal for an autonomous sailboat because it eliminates the requirement for a very large and fast acting actuator to constantly retrim the sails. The only time that direct intervention into the trim control of the wing is required is when the wing crosses the longitudinal centerline of the boat, or when guarding against excessive heeling moments. During this maneuver, the flap and tail are reversed from their previous positions. Note that in a conventional sense this corresponds to tacking (when the wind is from the bow of the boat) and jibing (when the wind is from the stern of the boat). The maneuvers using the wingsail are both very gentle and controlled because the bearings allow the sail to rotate 360 degrees about the mast without interference, and the wing can point straight into the wind without ill effects.

Conventional sails have one serious advantage: due to their sharp leading edge, they tend to be insensitive to Reynolds number variation. This alone may explain why they have persisted on modern designs even after the preponderance of evidence has demonstrated that wings are vastly superior. The other advantage that cloth sails may have over rigid wings is weight: for sails below a certain size, a rigid wing will almost certainly be heavier. This is due to the square-cubed law with respect to the strength of structures.

Above a mast height of approximately 20 meters, the structure of the mast could just as easily be incorporated into the spar of a wing. In [93], a race between two similar catamarans with a rigid wing and a conventional sail was analyzed. The winged catamaran had superior aerodynamic thrust on all points of sail, but the difference of ~150 pounds required a wind speed of greater than 8 knots for the superior aerodynamics to result in superior boat speed. The greater weight led to greater drag on the hulls due to the extra displacement of water. In the race, all legs that were raced at wind speeds greater than 8 knots were won by the winged catamaran, but all legs below 8 knots were won by the conventionally sailed catamaran.
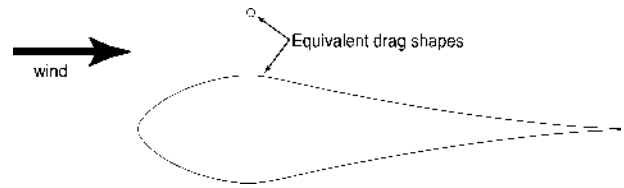

Figure 5-4 Demonstration of the equivalent drag sections at Reynolds number of 229,000. The small solid cylinder and the airfoil section have the same total drag (including both skin friction and pressure drag terms). A rigid wing need not be capable of reefing (or reducing its total area) in order to protect the boat. As demonstrated above, the wing (if allowed to pivot freely) will have much less force on it than the bare mast itself.

Reynolds Number Effects

As mentioned previously, the Reynolds number effects of the wingsail section design must be accounted for in order to maximize the efficiency of the wing. Ignoring these Reynolds number effects has been the largest failing of wingsails to date, resulting in sections with poor performance in the field, and, in turn, delaying the transition to rigid wings on sailboats.

The Reynolds number, Re, is defined as:

$$Re = \frac{\rho V L}{\mu} \qquad \text{(EQ 5.1)}$$

where ρ is the density of the medium, V is the velocity of the flow, L is the characteristic length, and μ is the viscosity of the medium. The Reynolds number represents the ratio of kinematic or inertial forces to the viscous forces in the fluid (that is, the ratio of force required to push the fluid out of the way versus the force required to slip through the "gooeyness").

Typically, insect flight has Re on the order of 100s to 1000s, bird flight and models in the 100,000s, small aircraft in the millions range, and large aircraft in the tens of millions range. The Reynolds number characterizes the flow's ability to negotiate the curves of a section without separation. Illustrative of this is Figure 5-5 which is reproduced from [123] and demonstrates the different drag characteristics of a 2-D cylinder as a function of Reynolds number.

In the case of airfoil sections, several effects come into play at low Reynolds numbers that make design of high lift sections difficult. Most of these are discussed at length in [122]. Flow about an airfoil at low Reynolds numbers is almost entirely laminar.
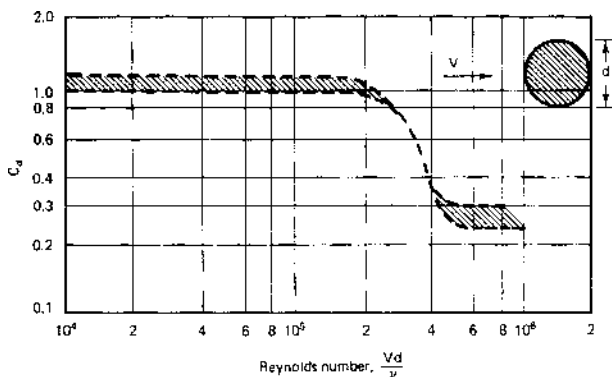
Figure 5-5 Effect of Reynolds number on the drag coefficient of a 2-D cylinder. At low Reynolds numbers, the drag remains constant. This is consistent with separation occurring just aft of the maximum diameter of the cylinder. As the Reynolds number increases, the now turbulent flow is able to negotiate the curvature better. This causes the drag coefficient to drop until the point that the flow remains attached approximately 1/3 of the way down the back side of the cylinder, at which point the drag coefficient once again becomes constant with increasing Reynolds number.

Thus the flow can withstand neither sharp radii nor severe adverse pressure gradients without separation (and consequential very large drag rise). In the case of airfoil sections, the flow separates, but then reattaches causing a laminar separation bubble whose flow eddy results in a very large increase in the base drag of the section. Furthermore, as soon as the angle of attack of the section is increased, the laminar separation bubble bursts, causing large scale flow separation and effectively limiting the maximum lift coefficient, C_L, attainable.

In [25], the designers demonstrate a knowledge of the difficulties in designing good sections at these Reynolds numbers, but fail to capitalize on this knowledge and find an appropriate design. They correctly identify the proper Reynolds number range for sail operation as 200,000 to 1.2 million, and complain that "good low Reynolds number aerodynamic data applicable to sails is not readily available." Unfortunately, low Reynolds number computer codes had not yet reached maturity at the time they were investigating superior sails. Thus, while correctly identifying the problem, they did not find an appropriate solution.

The reason that low Reynolds number airfoil sections do not exist for this range has to do with the unique requirements of sailing vehicles. Typically, this Reynolds number range corresponds to small model airplanes, usually gliders. The differences are

subtle and will be exposed in detail forthwith.

First, both the model glider and the sailboat require a high lift/drag (L/D) ratio. In a glider, this corresponds to glide distance. In a sailboat, this corresponds to the ability to point upwind. Second, both a model glider and a sailboat require a high maximum C_L. In the case of the glider, this corresponds to slow flight while circling tightly in thermals, or a minimum sink condition; in a sailboat, the configuration is maximum speed while sailing across or down wind.

At this point, the requirements are essentially the same and there should be a large body of work on appropriate sections that can be used for the sailboat wing. Given the constraints of designing a low Reynolds number airfoil section for the wingsail, there are a few details to consider. Firstly, the wingsail section must be suitable for the Atlantis to sail on both port and starboard tacks.

Symmetry

An airfoil section can be made either symmetrical or asymmetrical. An asymmetrical section can always achieve a higher maximum lift coefficient and a higher lift/drag ratio than a symmetric section. Symmetric sections have the advantage of identical lift characteristics with both positive and negative angles of attack. Symmetry arguments become important in sailing vessels because a sailboat is required to sail equally well on both port and starboard tacks and thus the section must be symmetrical. The model glider is rarely required to fly inverted, and certainly not for long periods of time. Thus model glider sections are always asymmetrical in order to maximize the L/D. Certain sailboats, including the designs in [118], [26], and [34], attempt to capture the maximum L/D by using an asymmetrical section, but then tack and jibe "over-the-top." This means that the wing is pinned midway up its span, then flipped to a horizontal position, and finally the bottom and top ends are then switched as the tack or jibe is completed. This is demonstrated in Figure 5-6. Needless to say, this results in an extremely heavy structure at the pin joint as well as an exposed support or mast which greatly increases the overall drag on the superstructure of the boat. It also makes wing control during this maneuver difficult in strong winds.

Using modern airfoil design techniques and a simple plain flap, one can achieve very close to the maximum C_L of an asymmetrical section. Thus, the increased weight, complexity, drag, and loss of the
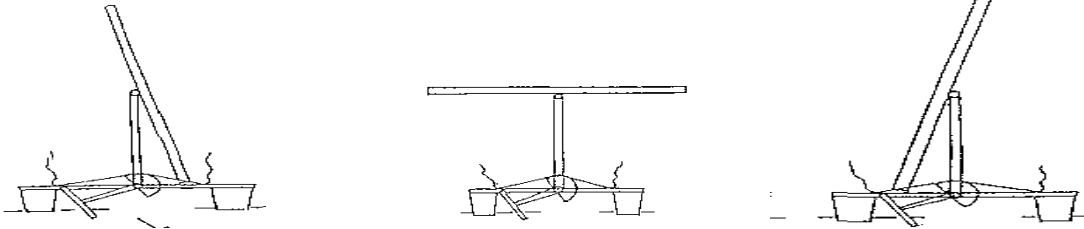
Figure 5-6 Frames from video showing the Boatek wingsail performing an over-thetop tack. From left to right, the boat is first turned into the wind. As the angle to the wind approaches zero, the wing (in this case, wings) are pivoted horizontally midway up the wing. As the boat turns through the wind, the wings are lowered to the opposite position from the first frame and secured. The top and bottom ends of the wings having been swapped, the tack is now complete

ability to self-trim in an asymmetrical design seem hardly worth the effort. Indeed, the ease of handling a symmetric section which does not pivot horizontally about the mast allows an increase in wing area, thus making up for the lower maximum lift coefficient. Although some continue to advocate over-the-top designs, they seem to stem more from novelty than an true understanding of aerodynamic trade-offs.

Airfoil Section Design

The first step in designing the best performing airfoil section is determining the appropriate Reynolds number, then achieving the best lift with the most benign characteristics.

It is desirable for the section to achieve a maximum lift coefficient of 1.8 at a Reynolds number range of 200,000 to 250,000. This can be aided by a simple plain flap of constant flap/chord ratio. The pitching moment coefficient must be small with the flap in trail so as to be easily balanced by the tail. Then, the greater the lift/drag ratio, the better will be the upwind performance of the Atlantis. In order to match the total force on the original sail at a wind speed of 5 knots with a theoretical lift coefficient of 1.8, Equation 5.1 is solved for a resulting Reynolds number of 229,000. Figure 5-7 shows the wind velocity required to achieve this Reynolds number as a function of angle from the true wind. This is based on the assumption that the sailboat can sail at one third of the true wind speed. The figure shows that the range of minimum wind speeds is from 3.8 to 6 knots.

The wing has one third the area of the sails, but generates three times the lift at its design point. This was chosen to enable a comparison of performance between the wing and sail. Note that the final design gets better as the Reynolds number increases. The difficult thing to achieve is performance at low

Reynolds numbers. Once that has been achieved, the same airfoil section can achieve a higher coefficient of lift at greater Reynolds number. In order to achieve the desired goals of maximum lift coefficient of 1.8, lift/drag ratio of better than 20, and optimization for a Reynolds number of 229,000, a rather unusual design emerges. First, in order to achieve the high lift coefficients at low Reynolds numbers, a very thick section is required, where the entire lift is generated on the forward section, typical of the Liebeck "rooftop" sections. The boundary layer requires a trip-strip that will force the transition from laminar to turbulent, placed symmetrically on the top and bottom surfaces. Typically, these trip-strips are a thick material with a zig-zag leading edge that is affixed to the surface at the desired location. The zig-zag causes a small-scale vortex to form which pulls in the higher energy flow outside of the boundary layer, and though viscous drag increases, separation (and thus form drag) is delayed.

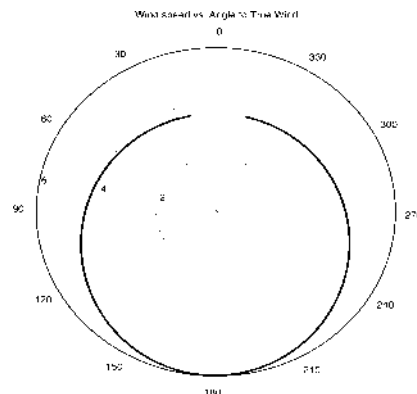*Figure 5-7 Polar plot of the true windspeed versus the angle to the true wind. This plot shows the velocity of the wind to reach a minimum speed necessary to have a Reynolds number of at least 229000. The sailboat is assumed to be able to sail at one third the speed of the true wind. This results in a range of 3.8 knots at 15 degrees to the true wind to 6 knots running directly before the wind.*

In addition to the short, flat pressure distribution on the section, the entire aft portion of the section is given to pressure recovery of the flow preventing flow separation from the section surface. Thus the back three quarters of the section do not contribute at all to the lift, but merely ensure that the airflow can recover to free stream conditions gracefully.

Analysis Tools

In order to design the wing and tail sections, modern computational fluid dynamics (CDF) computer codes are used to predict performance and refine the design of the sections. The two main codes utilized for this are Ilan Kroo's PANDA and Mark Drela's XFOIL.

PANDA, which is an acronym from **P**rogram for **AN**alysis and **D**esign of **A**irfoils, was developed by Professor Ilan Kroo in the 1980's at Stanford University[84]. The program computes and graphically displays the pressure distribution (in coefficient form) on airfoil sections in subsonic flow. For a particular airfoil with coordinates stored in a standard text file, the program calculates the inviscid pressure distribution over the airfoil at a specified angle of attack and Mach number; lift and pitching moment about the ¼-chord point are also computed. The analysis is done with remarkable speed (less than a second) so that the effects of changes in angle of attack or airfoil geometry can be studied easily.

The program also computes the boundary layer properties based on this inviscid pressure distribution. The location of transition, laminar or turbulent separation, and total drag are computed based on integral boundary layer methods. It is possible to specify a position for "transition grit" or "trip-strip" on the upper and lower surfaces to force transition or model surface roughness.

A major feature of the PANDA program is its provision for rapidly changing the airfoil geometry. This is done by positioning the cursor over the part of the airfoil to be changed and clicking the mouse button. A smoothly-faired bump (with specified but editable height and width) is added to the section at this point and the new pressure distribution is quickly redrawn (the normalized pressure is referred to as the coefficient of pressure, Cp). In this way the airfoil can be rapidly reshaped to produce a desirable Cp distribution.

XFOIL is a computational fluid dynamics (CFD) code that was written by Mark Drela in 1986 at the Massachusetts Institute of Technology (MIT), see [39], [40], and [41]. The main goal was to combine the speed and accuracy of high-order panel methods with the fully-coupled viscous/inviscid interaction method used in the more sophisticated codes developed by Drela and Giles. A fully interactive interface was employed from the beginning to make it much easier to use than the traditional batch-type CFD codes. Several inverse modes and a geometry manipulator were also incorporated early in XFOIL's development, making it a fairly general airfoil development system.

XFOIL is a much more full-fledged code than PANDA, able to operate well into the low Reynolds number regimes with excellent predictive capabilities. It also includes the ability to use either free or forced boundary layer transitions and to predict lift and drag polars to just beyond the maximum lift coefficient.

Wing Section

Section development starts with a National Advisory Committee for Aeronautics (NACA, the predecessor of the present NASA) 00xx section to probe the design space. The NACA section is then modified using PANDA until reasonable performance was achieved. At this point, the section coordinates are transferred to XFOIL which is used to iterate on the pressure distribution and boundary layer trip-strip location until the desired results are achieved.

The first attempt used a NACA 0015 airfoil section. Originally developed in the 1930's, the NACA 0015 is a symmetrical section with a thickness to chord ratio of 15%, and designed as a turbulent section. While this airfoil section is known to have poor performance at low Reynolds numbers, as the *de facto* standard for symmetrical sections, it functions as a benchmark against which to compare all other attempts. Further, land yacht designers are using NACA 00xx sections almost exclusively in their successful designs.

Part of their rationale behind this choice is the observation that the main drag source is not parasitic drag but rather induced drag. Since induced drag is largely a function of the aspect ratio of the wing and the load carried by the wing, the effect of airfoil section is minimal. This gross analysis, however, fails to take into consideration the loading variation of the wing and the problems of stall and separation. While the wing might be flying at a coefficient of lift below stall, sections of it might be above due to variations in wind speed with height (wind gradient) or effective twist due to the same effect. These problems can only be addressed with high maximum lift coefficient and the NACA 0015 simply cannot provide it. Figure 5-8 shows the poor performance of the NACA 0015 at low Reynolds numbers, where the flow is largely laminar. Note the laminar

NACA 0015

Re = 0.229×10⁶
α = 13.0000°
C = 1.1208
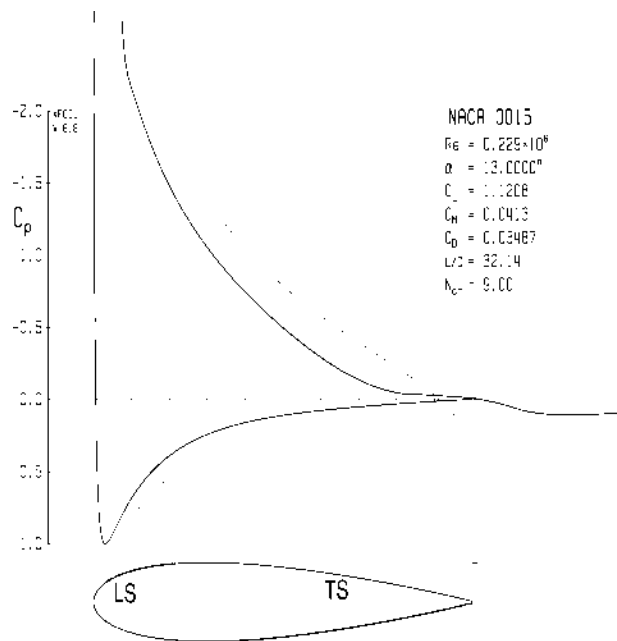Cₘ = 0.0413
Cᴅ = 0.03487
L/D = 32.14
Nᴄ = 9.00

Figure 5-8 XFOIL results for NACA 0015 airfoil at Reynolds number of 229,000 and CL of 1.12. This is a turbulent boundary layer section. Note the very sharp pressure spike corresponding to the leading edge of the airfoil (with a Cp < -4.0 for a lift coefficient of 1.12) that will most likely cause separation. Indeed the laminar separation bubble is marked by "LS" and the trailing edge turbulent separation indicative of stall is marked "TS.".
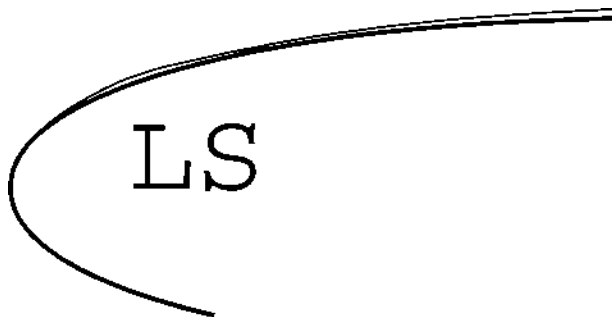

Figure 5-9 Close up view of the laminar separation bubble on NACA 0015 airfoil at Reynolds number of 229,000. At this scale, the enlargement and then, farther along, contraction of the boundary layer is clearly visible. Inside the enlarged section an eddy vortex is stationary and consumes energy in its rotation. This results in increased drag. As the angle of attack increases, the vortex tightens and eventually bursts, resulting in turbulent boundary separation and stall

separation bubble ("LS") on the top surface, the turbulent separation ("TS") indicating a stall, and the rather low lift/drag ratio at this condition.

The laminar separation bubble, indicated by the "LS" in Figure 5-8, can be seen more clearly if we zoom into the section. In Figure 5-9, we take a closer look at the laminar separation bubble and can clearly see the effect of the boundary layer growth and subsequent contraction as the flow reattaches following the laminar separation. While the presence of the laminar separation bubble is invisible from a macroscopic view, it nonetheless affects the entire flow of the section. The maximum lift coefficient attainable is directly related to the presence or absence of the laminar separation bubble and the manner in which the section stalls is also driven by its presence. When a laminar separation bubble is present, the stall is likely to occur at the point of the bubble rather than at the trailing edge. This results in a sudden loss of lift and increase in drag, rather than a gradual loss of lift and increase in drag.

The final design, after many iterations, results in a rather unusual shape. First, the final wing section is enormously thick, with a thickness to chord ratio of over 21%. The distribution of that thickness is predominately toward the nose of the section. This is consistent with the requirement that most of the lift is generated at the front part of the section, in front of the boundary layer trip-strip, while the entire aft section is there only for pressure recovery.

Close inspection of the section will show that the post boundary trip curvature is in fact concave, making construction using a normal cloth covering somewhat of a challenge. As the cloth covering shrinks, it will tend to pull off of the curved rear section of the airfoil since a straight line connecting the point of maximum cross section and the end just before the flap hinge is shorter than the actual surface. Looking at the pressure distribution in Figure 5-10, one can immediately see the design challenges that were presented and how they were solved. Note the absence of either laminar separation bubbles or turbulent separation at the end of the section. This is at a C_L of 1.04, with no flaps deployed.

Again, it is important to point out the salient features of the pressure distribution shown in Figure 5-10. Observe the flat top of the pressure distribution, corresponding to a uniform suction on the upper front surface. The pressure begins its recovery just after the trip strip located at the 22% chord point and very smoothly recovers back to free stream pressure without separation. Note that the flow is actually accelerating on the lower surface

below the stagnation point. This causes the upward slope of the lower line in the pressure distribution, indicating some suction existing at the maximum chord point of the final wing section. Also, just after the trip-strip lies a very smooth pressure recovery all the way to the rear point of the airfoil section. Reemphasizing, there are no laminar separation bubbles and no turbulent separation. This airfoil section is not close to stall but will stall gently from the rear progressing forward, resulting in a very gradual loss of lift and increase in drag. This is important due to the varying nature of the wind. When the wind is highly variable, a conventional section like the 0015 will often abruptly stall and lose lift.

Tail Section

The design methodology for the tail section is virtually identical to that of the main wing section. The differences here are that the tail section will not be flapped, and because of its narrower chord, the design Reynolds number is much lower, around 44,000. Again, the same methods are employed, first using PANDA and then converging on the final design with XFOIL. A trip-strip is needed and has been placed at the 20% chord-wise location due to the inability to withstand adverse pressure gradients. Figure 5-11 demonstrates the flat forward rooftop pressure distribution along with the gradual recovery to free stream pressures. Further investigation demonstrates that the tail has an expected lift coefficient of 0.75 before turbulent separation begins at the rear of the section. This once again allows a gradual and smooth change in the lift and drag characteristics of the section without compromising the maximum lift that can be generated. Note that there are no laminar separation bubbles, and at the lift coefficient of 0.5, there is no trace of turbulent separation at the rear of the section. Thus, all of the design requirements of the tail section are met and the relatively large thickness to chord ratio allows a robust structure to be built using conventional materials such as foam, plywood, and polyester fabric.

Flap/Chord Ratio

In order to increase the coefficient of lift of the main wing section and obviate the need for "over-the-top" tacking and jibing, a simple plain flap is used to increase the camber of the wing. Figure 5-13 shows the pressure distribution with the flap deployed at 45 degrees. Note that the flow separates off the back of the flap causing an increase in drag. Unfortunately, at these low Reynolds numbers, the flow cannot negotiate the curvature of the flap hinge
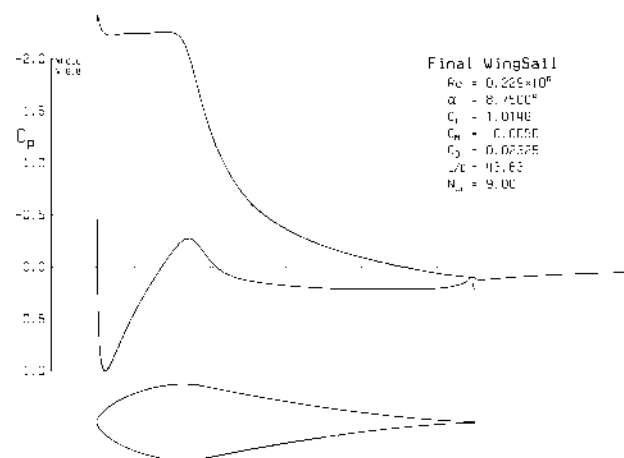

Figure 5-10 Final wing sail airfoil section and pressure distribution, Reynolds number of 229,000 and a coefficient of lift of 1.0. The pressure distribution is shown in the standard manner, with -Cp along the y-axis, and the normalized chord along the x-axis. This section demonstrates a "rooftop" pressure distribution that rises immediately to a value of -2.5 and stays there for the 25% of the airfoil section. There, the boundary layer is tripped to force a transition to a turbulent section, and a long slow pressure recovery is used to prevent separation.
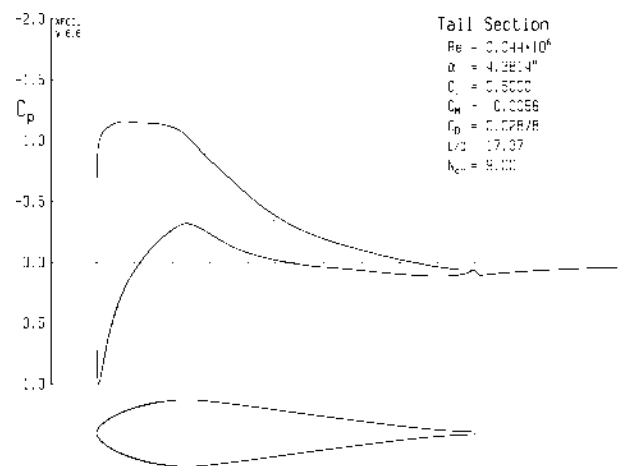

Figure 5-11 Pressure distribution of the final tail section at a Reynolds number of 44,000 and a lift coefficient of 0.5. This section is very similar to the final wing section. It shows the same "rooftop" flat forward section on the pressure distribution. The lift coefficient is 0.5, with no trace of laminar separation bubbles nor any turbulent separation. Further analysis using XFOIL indicates that this section can reach a CL of 0.75 before stall.

regardless of where it is placed on the airfoil section. This means that the flow on the low pressure side of the flap will separate as soon as it is deflected more than a degree or so. With this constraint, the issue becomes one of trading the separated flow and subsequent drag for increased effective camber of the section and increased lift. Thus, the low Reynolds number pushes the design toward a very small flap/chord ratio and large deflection. In other words, a small trailing edge tab deflected a great deal will turn the flow enough to give effective camber, while giving the flow only the smallest area from which to separate.

In order to find the optimum flap/chord ratio, a grid point search is performed using XFOIL in order to find the minimum drag at a coefficient of lift of 1.8. The flap/chord ratio is varied from 1% to 40% in 1% increments and the optimum is found to be at 13%. Figure 5-12 shows the results of these computations. Both the maximum attainable lift coefficient as well as the lift to drag ratio at that lift coefficient are presented. It can be seen that both reach their maxima close to a 13% flap to chord ratio.

The final shape for the main wing section is presented in Figure 5-13, with the flap deflected 45 degrees. The aggregate plots of the lift to drag coefficients for the final section with the flap deployed can be found in Figure 5-14. The plot shows that there exists an "efficient boundary" where the lift/drag ratio is maximized for a given lift distribution.

This will then become the basis of control: once the desired lift coefficient is determined, the correct flap setting can be chosen to minimize the drag. Note that above a C_L of 1.8, the drag continues to increase without any further increase in lift. This is expected from the increase in separation of the flow, and as predicted is gradual. Looking at the data in a different way, it is useful to visualize the lift/drag ratio as a function of either lift, drag, or angle of attack. Note that the angles of attack involved are uniformly small, implying that the control over the tail must be precise or the tail, and subsequently the wing sail, will be stalled for the duration of the sail test. The lift/drag ratios are plotted against the above-mentioned parameters in Figure 5-15. It can be seen to have a peak at an angle of attack of 2-3 degrees, with the flap set at 25 degrees.

This, then, is the most efficient configuration at which to sail upwind. All other points of sail require that the wing sail provide the maximum force and then be modulated downwards as the threat of capsize increases.
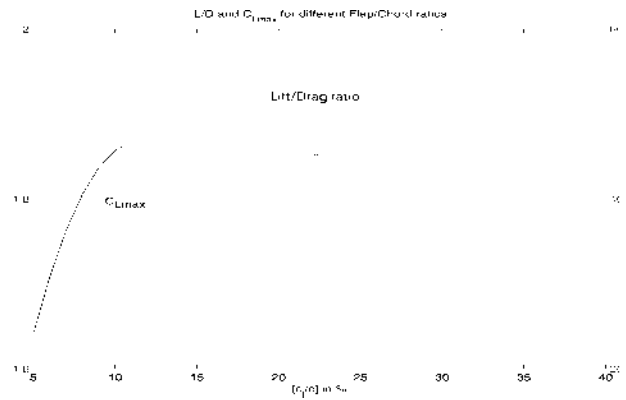

Figure 5-12 Results of the grid point search for optimum flap performance. Maximum attainable lift coefficient is plotted in blue and the lift to drag ratio is plotted in green. Note that while they both have a maximum in between 10% and 15% flap to chord ratios, the lift/drag maximum is much sharper in the area of 13%.
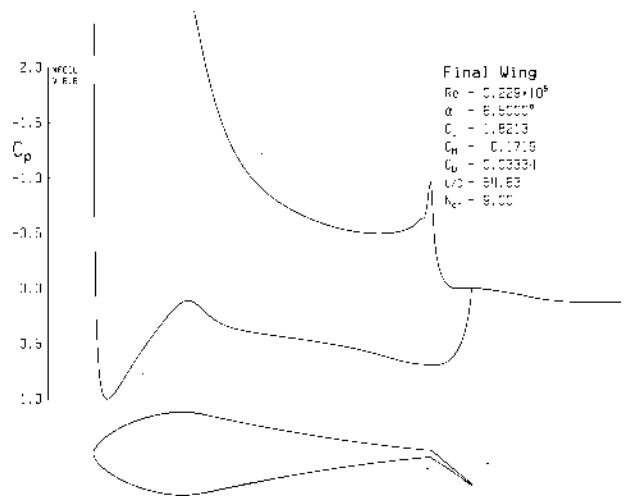

Figure 5-13 Pressure distribution of main wing sail section with flap deployed, Reynolds number of 229,000 and a coefficient of lift of 1.8. In order to preserve the lift/drag ratio of the section with the flap deployed, while attaining a high CLmax, a small trailing edge flap is used. At this Reynolds number, any flap deflection will result in separation. Thus, a narrow chord flap is deflected a large amount to generate a high effective camber. At the same time, this design minimizes the area of separation, and hence drag.
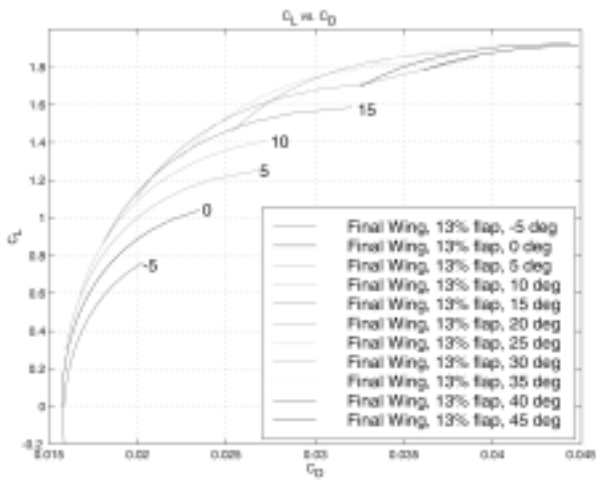
Figure 5-14 Coefficients of lift vs. drag for the final wing section with flap deployed at a Reynolds number of 229,000. For a given CL, there is a unique flap angle that yields the minimum drag for that lift coefficient forming an efficient boundary This will later be used to control the wing; once the desired lift is set, the flap is tuned for minimum drag based on that lift coefficient.
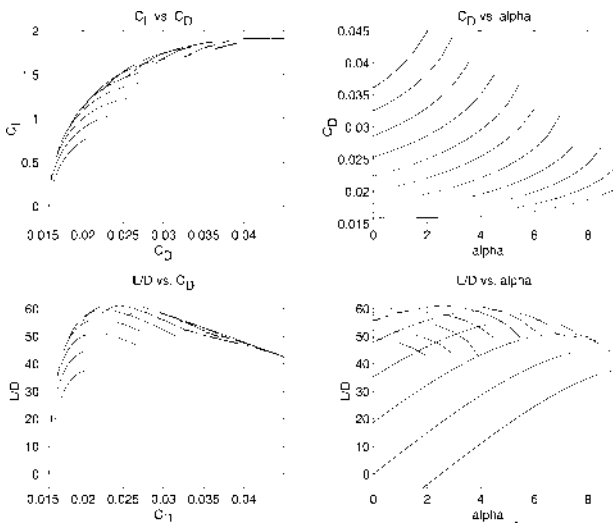

Figure 5-15 Aerodynamic polars for the main wing sail with flap deployed at a Reynolds number of 229,000. The lift/ drag ratio peaks at around 62 with a corresponding angle of attack of 2 degrees. This corresponds to a lift coefficient of approximately 1.3 and a flap deflection of 20 degrees. Note that at this flap deflection, the lift/drag ratio remains high over the range of 0 to 4 degrees angle of attack

Wing/Tail Configuration Analysis

Two possibilities exist for actuating the wing and controlling its angle of attack.

The first possibility is to control the angle of attack mechanically using an actuator that rotates the wing about the mast. This has the advantage of quick actuation, and correct placement of the rotation axis can keep the forces low. However, the variability of the wind will require high frequency actuation to keep the wing correctly trimmed. Furthermore, the entire range of angles of attack between zero lift and stall is less than 10 degrees. This translates into the actuator requirement to track the wind very closely indeed. The other possibility for angle of attack control is to use an auxiliary surface to trim the wing aerodynamically. The auxiliary surface can take the form of a tail behind the wing (conventional), a tail in front of the wing (canard), or attached to the trailing edge of the wing (flying wing). The actuator requirement in this case is to move the trimming surface only. By designing the auxiliary surface in such a way as to have the wing/ surface assembly be passively stable with respect to angle of attack, the entire system will track the relative wind automatically. This is a great advantage over active control in terms of actuation effort, simplicity of design, and overall performance.

With the main wing section and tail section designed, the various arrangements of wing and tail needed for the Atlantis to sail can now be considered. The first requirement for wing and tail consideration is stability with respect to change in wind direction or velocity. Based on the design of the wing section and the conclusions reached above, the configuration must be able to hold a C_L of 1.8 with a flap deflection of 45 degrees. This is important because the deflected flap will cause an increase in the pitching moment of the wing section about the mast. Formally, these requirements can be written as:

$$C_m = 0 \qquad \text{(EQ 5.2)}$$

The pitching moment of the entire wing/tail system about the mast should be zero. That is, the system is in trim, and:

$$\tfrac{d}{d\alpha}\left(C_m\right) < 0 \qquad \text{(EQ 5.3)}$$

The change in pitching moment with a change in angle of attack should be negative. The wing/tail system should be stable with respect to angle of attack.

The other considerations are mechanical complexity, control power, and a minimum swept

radius of the farthest point away from the mast. The minimum swept radius constraint is due to the fact that in order to remove the coupling between angle of attack of the wing sail and heeling angles, the wing/tail assembly must be mass balanced about the mast so that pitch and roll angles do not induce changes in angle of attack. A tail heavy wing/tail assembly would result in an increase in angle of attack with roll angle, thus inducing instability in close hauled conditions.

Fekete et al. in [48] perform a simplified analysis of the conventional and canard configurations. In this section, that analysis is refined by using higher fidelity models for downwash and induced drag as well as correcting for aspect ratio effects. Furthermore, two other configurations, the "flying wing" and the "free-floating canard," are analyzed using the same tools.

Conventional Layout

The conventional layout is what would occur if a normal airplane were sliced in half down the longitudinal axis, turned on its side, and affixed to the mast through the quarter chord point of the wing. The arrangement, pictured in Figure 5-16 has the wing forward, followed by a tail some distance back. This has the immediate disadvantage of being tail heavy. This requires ballast forward to place the center of mass at the quarter chord point of the main wing. In terms of a wing, ballast is useless weight. Because the weight must be attached to the wing, it raises the center of gravity of the boat. This makes the design more prone to capsizing. Additionally, the swept radius of the tail is quite far back. This means that in close quarters (such as berthing), the tail may swing out beyond the catamaran hulls and strike an adjacent ship.

A top down view of Figure 5-16 is presented in Figure 5-17 and shows all of the force and moment vectors acting on the wing sail and tail. Note that in order to balance or trim the wing sail, the moment about the pivot point must be zero. To guarantee passive gust stability, the derivative of the moment equation with respect to the angle of attack must be negative. This implies that a perturbation of the angle of attack in a positive sense will cause a negative (or nose down) pitching moment which will reduce the angle of attack, and likewise a negative angle of attack perturbation will cause an increase in the pitching moment (nose up) and will increase the angle of attack. Also note that the reference to up and down is simply a convention to relate the wing terminology back into the intuitive reference of flight. In fact, there is no up or down, rather port or
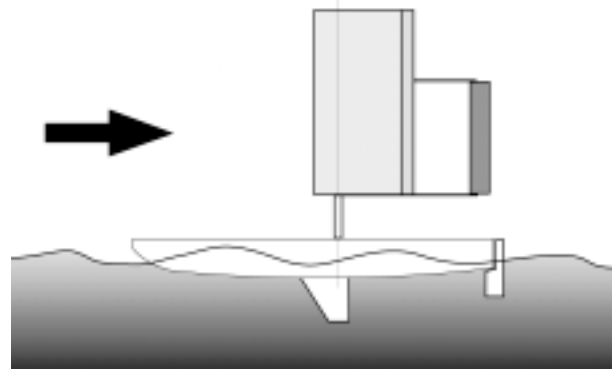

Figure 5-16 Conventional configuration for the wing sail and tail arrangement. This is the equivalent of a conventional airplane sliced in half down the length of the airplane, turned sideways and mounted on the stub-mast. This configuration has the inherent disadvantage that the wing design is tail heavy. This requires ballast to bring the mass center of the wing/tail assembly in line with the stub-mast. Additionally, this configuration has the farthest point of the wing/tail far away from the stub-mast. Thus, it sweeps out a large radius, making it impossible to use external stays on the stub-mast above the wing.
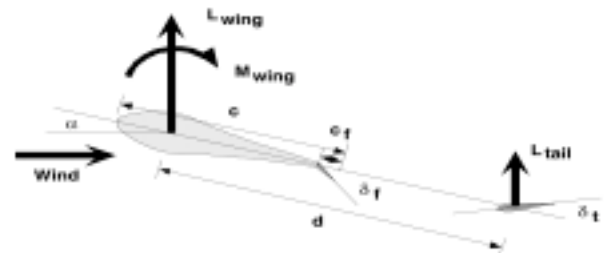

Figure 5-17 Force vectors on the conventional configuration. The forces and moments on the conventional configuration are displayed along with the relevant angles and distances. The wing is "flying" at an angle of attack, a, which in turn generates lift and pitching moment associated mostly with the trailing edge flap. This pitching moment must be resisted by the lift force on the tail.

starboard, and that the important feature which is missing from these equations which would be present if this were in fact an aircraft are the gravity terms. They do not, however, come into play in this stability analysis.

Canard

An alternate configuration is the "canard," where the tail is placed in front of the wing as pictured in Figure 5-18. The immediate advantage professed for this arrangement is that both the main wing and the tail are lifting in the same direction and therefore must be more efficient. In an aircraft, this turns out to be untrue. A canard aircraft has trim and stall problems that must be dealt with and can usually be designed for either passive stability, or efficiency (i.e., reduced induced drag), but never both.

The overwhelming advantage a canard has for the sailboat propulsion system is that it is more easily balanced about its neutral point, making the entire setup lighter. Also, depending on the distances that occur for trim and stability, it is possible that the radius swept by the canard arrangement can be made small. If the swept radius is small enough to fit within the existing guy wires of the original mast, then the canard can be fit around the existing mast like a sleeve. This would negate the need for a free-standing stub-mast making the structure of the mast much easier to design. Figure 5-19 shows the vectors and key distances on the canard configuration. Once again, it is required that the moment balance be zero (trim) and that the change in moment be negative (stability).

The problem occurs with the robustness of this approach. The solution to the equations exists for only one value of flap deflection. For instance, if the trim and stability criteria are solved for a flap deflection of 45 degrees and a coefficient of 1.8, then when the flap is deflected less than 45 degrees, the canard configuration is not stable, and will attempt to swap ends. Furthermore, if the trim and stability criteria are solved for zero flap deflection, then at a high lift coefficient the canard will not be able to hold the main wing at a sufficient angle of attack. The canard itself will not be able to generate sufficient lift to balance the nose-down pitching moment induced by the large lift on the main wing.

Unfortunately, the canard configuration must be chosen to be stable, or to have a high maximum lift coefficient, but it cannot do both! Thus the canard configuration is not acceptable for this project. If the additional complexity of a flap on the canard is included, then it would be possible to adjust the flap on the canard in such a way as to compensate for the additional moment generated by the deflected flap on the main wing.

This is exactly the same problem that canard aircraft have. Very few of them have flaps on the main wing for decreased landing speeds. In fact, those few that do have flaps on their main wings
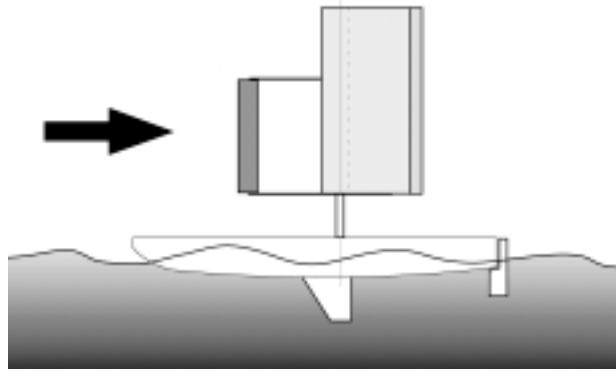

Figure 5-18 Canard configuration of the main wing sail and tail. The canard configuration has the trim surface (or tail) in front of the main wing. The advantage of this is that is can be made to have its mass center coincide with the stub-mass. Also, there exists the possibility that the swept radius can be made such that it is possible to have the entire canard/wing assembly fit inside guy wires that stabilize the mast.
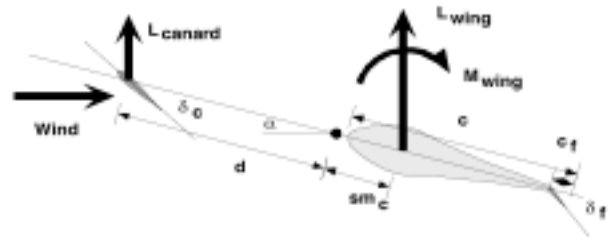

Figure 5-19 Force vectors on the canard configuration. The canard configuration has the purported advantage of efficiency, due to the fact that both the main wing and canard lift in the same direction. It truth, canard configurations can be made to be efficient (low induced drag) or passively stable, but never both. As a wingsail, the canard offers the advantage of already having its mass center near the pivot point. This minimized the ballast required and results in a lighter overall rig.

look to some rather exotic solutions, such as having a variable sweep canard that changes the longitudinal center of the canard as the flaps are deployed. For an excellent treatment of the subtleties of canard designs, see [85] and [98].

Flying Wing

If the desire were to minimize the swept radius of the wing, then certainly the flying wing would represent the optimal approach. Flying wings, however, almost always rely on washout of the tips to provide stability. That is, the tips of the rearward swept wings are twisted nose down and act somewhat like a conventional tail. To make a symmetrical flying wing sail requires both trim and stability without any wing twist whatsoever. This represents a difficult design challenge.

This problem is common in flying wing aircraft as well. If the washout is taken away, then the only way a flying wing can be both stable and trimmed is to reflex the trailing edge of at least a portion of the wing. There is an alternate solution in the case of the wing sail, which is to use a multi-segment flap and trim part of the flaps in one direction and part in the other. By definition, however, this means dumping lift. Therefore, this cannot be as efficient as any other viable solutions.

Free-Floating Canard

The last configuration analyzed was the free-floating canard configuration, pictured in Figure 5-23. There are also tri-surface configurations, but these were considered too complex for implementation. The free-floating canard is an unusual configuration that was first used on the 1942 Curtiss XP55 Ascender, without a great deal of success. Anecdotally, the Ascender suffered from spin recovery problems that caused its test pilots to mispronounce the aircraft's name in a pejorative sense, describing the attitude in which it flew once stalled. Note that after much work, the Ascender's problems were solved, but it remained an army project that never went into production.

What makes this configuration unique is that the canard itself is allowed to pivot freely in pitch, and is trimmed via a trailing edge flap. Thus, a change in wind direction or a gust causes the canard to rotate into a new trim position, which then, in turn, rotates the wing to its new equilibrium position. The key is that the canard itself is passively stable, and that the entire system retains stability.

There remains a quandary about stall into which this simplified analysis did not delve, but which requires some discussion. At stall, the main wing will lose lift, however the free-floating canard will not. The main wing will also gain in nose down pitching moment at stall, due to the separated flow off the back of the main wing section. The loss of lift on the main wing tends to pitch the nose upwards, increasing the stall. The increase in pitching moment
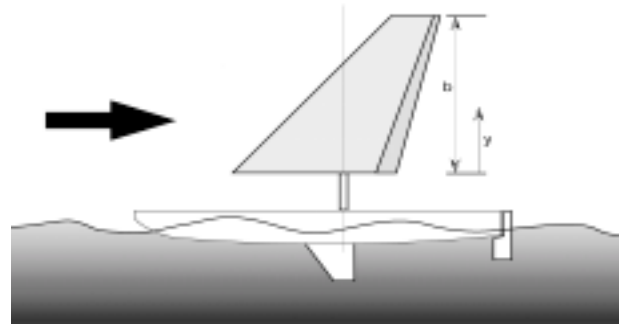

Figure 5-20 Flying wing configuration for wing sail propulsion. The flying wing has many obvious advantages. The flying wing can be made mass balanced with little or no additional ballast. Additionally, it can have the minimum swept radius of any design. The difficult is in achieving both trim and stability with no twist. Flying wings on aircraft rely on wing twist to provide both stability and trim
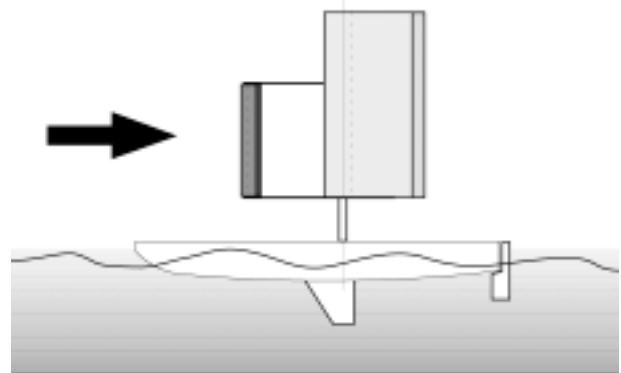

Figure 5-23 The free-floating canard configuration as it would be applied to the Atlantis. The front canard has its own trailing edge flap and is allowed to rotate about a pivot forward of the canard quarter chord line. This, in turn, drags the wing around to a new angle of attack. This system was used on the 1942 Curtiss XP55 Ascender. While it can be made passively stable, the configuration suffers large excursions during stall.

tends to pitch the nose down, decreasing the stall. The canard itself contributes nothing but its steady lift, which tends to increase the stall. Thus, at stall, the main wing must increase its pitching moment faster than the moment generated by the loss of lift and the moment arm to the center of mass. The original design of the Ascender did not achieve this balance and suffered from a divergent stall that pitched the aircraft over onto its back. Eventually, the designers realized the problem and fixed the aircraft. The only fix was in the main wing, as the canard played no role in the transient.

Results

After analyzing the four different possible configurations for trim and stability, it can be seen that only two configurations are viable: the conventional tail and the freefloating canard. The normal canard cannot be both stable and trimmed with a trailing edge flap, and the flying wing needs to reflex the trailing edge for stability, thus reducing the attainable maximum lift coefficient.

The tail volume requirement for the free-floating canard is almost double that of the conventional configuration. In addition, the free-floating canard is mechanically much more complicated, with another pivot point and an additional flap on the trimming surface. The main benefit is a much reduced swept radius, which might allow the wing to be built inside the original mast's guy wires.

Upon completing the calculations, however, the required tail volume for the free floating canard was found to be such that it, too, would require a freestanding stub-mast, without guy wires. Thus, the only advantage of the free-floating canard is effectively cancelled, and the Atlantis was fitted with a wingsail and conventional tail layout, as shown in Figure 5-16.

Conclusions

This thesis is a systems work, with contributions in structures, fluid mechanics, and guidance navigation and control areas. The main contribution detailed in this [extract from the] thesis [is]: *To describe an optimization scheme for symmetric wingsail section based on requirements unique to sailing vehicles.*

The basis for the propulsion system is a symmetric wingsail that was designed to achieve a high maximum lift coefficient with a simple flap at the Reynolds numbers appropriate to sailing vehicles. The details of this design include the requirements, development of specifications, and full analysis. The wing and tail sections are developed with a flat rooftop pressure distribution and boundary layer transition strip followed by a very gradual pressure recovery.

Using a simple trailing edge flap obviates the need for the more exotic solutions to maximum lift coefficient, such as over-the-top tacking, while preserving the ability to sail on either side of the wind. The optimization of the flap to chord ratio of the trailing edge flap results in the non-intuitive answer of a small (13%) flap with large deflection to retain the high lift to drag ratios at large coefficients of lift.

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[The next extract from Dr Elkaim's PhD Thesis will address the structural requirements and the construction of the wingsail. Copies of the full thesis are obtainable from Dr Elkaim, who is now Assistant Professor of Computer Engineering at the University of California at Santa Cruz; webpage: <http://www.soe.ucsc.edu/~elkaim/> - Editor.]

DATA ANALYSIS

A Narrative

Once upon a time, after a few months of searching for work, I finally got a job in a small boatyard that put together workboats anywhere from 20 to about 30 feet on the waterline. Construction was almost entirely of steel, although an aluminium hull was turned out on occasion. After sitting at my drawing board for about a week doing nothing - because nobody had given me any work to do - the chief marine engineer, even though we hesitated to call him that in such a small organization, asked me if I could come up with a chain locker for the next hull for which we had just got a contract. Things were a bit slow still I think. I didn't actually know anything about chain lockers so I wandered over to Joe the draftsman and an old timer and asked him if he had any data. You had to be careful when talking to Joe as he had a spittoon by his high stool and you had to watch your pant legs but nobody was about to tell me anything they knew because they thought I knew everything after having had four years of college. However, I set out to accomplish the assigned task.

The obvious problem was to figure out how large to make the locker and how many feet of chain it was to hold and what was the size of the chain. The last two items were sort of known but the size of the locker had me stumped for a while and the drawing room had very little in the way of any kind of data.

I put on my boots as the yard was quite muddy as usual and stumbled about here and there around the piles of steel and timber blocking and avoiding getting under the loads on the crane looking for odd pieces of chain that were not too long. We used some chain and small hoists, or come-alongs, to pull into place the heavier plates of steel. I finally assembled about ten small cut off chain ends and then started figuring how I might analyse the pieces and try and come up with a factor that might tell me how many cubic feet a piece of chain might take up when put into a box or something.

Here are the basic parameters I started with:
- Chain Length
- Length of a single link
- Cross section diameter of a single link
- Weight of chain

After recording these facts for ten pieces of chain, I set about finding a small container such as a bucket or can into which I could fit the chain pieces, shake it a bit and then measure the volume the chain took up in the can. For example, I recorded the diameter and height of a coffee can, dropped a piece of chain in the can, shook it a little, and then measured how high the top of chain pile was from the top of the can. You shake the can until the top of the pile in the can is reasonably flat. So by subtracting the height of the chain in the can from the can's total height and knowing the diameter of the can you can figure out what I call the Bulk Volume of the chain. Also, knowing the total weight of the chain you can figure out its actual net steel volume by dividing the total weight by 493. In other words, by dividing weight by pounds per cubic foot, we get cubic feet. Then we can divide the Bulk Volume by this net cubic feet figure and get some sort of factor for various pieces of chain; thus being reasonably assured the chain locker would be of the right size. Admittedly this whole process may not be very precise but what was I to do?

Frank Bailey

All of the calculations are shown on the two tables opposite. We must make a distinction between the experimental data and the derived data, which you can easily do by reading the headings of each column. The summary on the second sheet is arranged in increasing pounds per foot of chain, which seems like the right thing to do. On the second sheet is shown the ratio of Bulk Volume divided by Net Volume. The average is 3.72 + 36%. This figure is independent of the foot factor. If you take the reciprocal of 3.72 we get a specific gravity figure of about 0.27 - which seems reasonable. I also calculated the cubic feet per foot of chain but the spread here was anywhere from about –60% to + almost 100%, a peculiar result which I won't try and figure out. So now it apparently was a simple matter to design a chain locker. Get the weight of the chain to be put into it, divide this by 493 and multiply that figure by about 3.7 plus something.

Since the chain weight was read to only one decimal place, all the other decimals beyond this are probably superfluous, but what the heck… I had to use two different sized cans to be able to contain the longer pieces of chain and this may be a factor for the spread. The weighscale I used I suspect did not read too accurately in the lower range and it was even difficult to get the nearest half-pound. Notice that I had to deduct the weight of the can from the total chain weight weighed.

I was not quite satisfied with these results; so working late one evening (for which I was not paid) after a poor dinner at the local diner, I reasoned thusly: *The Bulk Volume should be proportional to the length of the chain, and inversely proportional to the link diameter, the links per foot and the weight per foot.* For example, if there are more links per foot, the individual links are smaller and should nest closer together. The result is not a dimensionless number, and actually showed no correlation to anything. So I threw out the calculations.

After researching the subject thusly, I finally put my design on paper. It was built. It was too small; and I was fired. But I must tell you that Joe of the famous spittoon came over and picked up all my chain data before I left!

A Closing Comment: *Although the above story is fictional and not completely non- autobiographical, all the numbers are factual as shown on the data sheets. They were re-copied so there may be an error here and there. It was an interesting little experiment in gathering and analyzing data and was done as usual in a hurry. No doubt my samples were not varied enough. Indeed, I did not realize I had duplicate pieces of chain until I had gathered the data. With this experiment I have learned that it is important to be neat in recording the data otherwise one can waste time in checking the calculations, thus the data sheet form enclosed here. Recording the units used is also very important. It would be nice if measuring tapes were more readily available in decimal feet and decimal inches. It may be that out there somewhere there is a better bulk factor. Perhaps, dear reader you can come up with one. On the other hand, I am sure chain manufacturers have these figures readily available (I hope). On the other hand, most of us yachties are not interested in chain except for a bit between our anchor and our rode.*

Chain Data
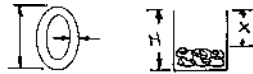
Item No	Chain Length, Ft - Inches	Link length Inches	Link Dia., Inches	Pot Dia., Inches (6.875 or 3.875)	Pot height, Inches (7.3125 or 5.25)	X, Inches	Total Chain Weight with Bucket. (Bucket Wt 0.5 lbs)	Chain Length, Feet (& decimals)	Chain lbs/ft (excl Bucket)	(H-X), Inches	Bulk Vol ft3,	Actual Chain Vol, ft3 = Chain Wt (493 lbs/ft3
1	24 - 41/2	1.675	0.196	6 7/8	7 5/16	4 1/2	8.0	24.375	0.31	2.813	0.0604	0.01521
2	8 - 10	1.675	0.196	3 7/8	5 1/4	2 1/2	3.5	8.833	0.34	2.75	0.0188	0.00609
3	3 - 5 1/2	1.810	0.342	3 7/8	5 1/4	2 1/8	4.9	3.458	1.27	3.125	0.213	0.00892
4	5 - 7 1/2	1.678	0.200	3 7/8	5 1/4	3 1/2	2.2	5.625	0.30	1.75	0.0119	0.00345
5	3 - 6	1.575	0.275	3 7/8	5 1/4	3	3.0	3.5	0.71	2.25	0.0154	0.00507
6	6 - 7	2.343	0.275	6 7/8	7 5/16	5 1/8	5.0	6.583	0.68	2.188	0.047	0.00913
7	6 - 1 3/4	1.375	0.220	3 7/8	5 1/4	3	3.0	6.15	0.41	2.25	0.0154	0.00507
8	3 - 5 1/8	2.068	0.410	6 7/8	7 5/16	5 5/8	4.0	3.427	1.02	1.688	0.0362	0.00710
9	6 - 7 1/2	2.344	0.273	6 7/8	7 5/16	5 1/8	5.0	6.625	0.68	2.188	0.047	0.00913
10	9 - 6	2.00	0.400	6 7/8	7 5/16	3 3/8	15.0	9.5	1.53	3.938	0.0846	0.0294

Summary

Item	Chain lbs/foot	Feet of Chain	Bulk Volume ft3	Net Volume, ft3	Bulk Factor, ft3/ft3 of chain	Cubic Feet per foot of Chain x 104
4	0.30	5.625	0.0119	0.00345	3.46	21.2
1	0.31	24.375	0.0604	0.0152	3.97	24.8
2	0.34	8.833	0.0188	0.00609	3.08	21.2
7	0.41	6.15	0.0154	0.00507	3.02	25.0
6	0.68	6.583	0.0470	0.00913	5.15	71.4
9	0.68	6.625	0.0470	0.00913	5.15	70.9
5	0.71	3.5	0.0154	0.00507	3.03	43.9
8	1.02	3.427	0.0362	0.00710	5.10	105.7
3	1.27	3.458	0.0213	0.00892	2.39	61.7
10	1.53	9.5	0.0846	0.0294	2.88	89.3

This is a free listing of events organised by AYRS and others. Please send details of events for possible inclusion by post to Catalyst, BCM AYRS, London WC1N 3XX, UK, or email to **Catalyst@fishwick.demon.co.uk**

April

7th   AYRS London meeting
Materials. 19.30 for 20.00hrs at the London Corinthian Sailing Club, Upper Mall, London W6. Contact: AYRS Secretary, BCM AYRS, London WC1N 3XX; tel: +44 (1727) 862 268; email: ayrs@fishwick.demon.co.uk

25th   Beaulieu Boat Jumble
Beaulieu Abbey, Hampshire - the AYRS stand will be in the usual place (so we are told!)

25th   British Model Multihulls Association meeting
Yeovil. Contact:Robbie Nevitt Tel: +44 (1963) 370058

BMMA meetings are informal affairs with usually a number of races over the day with breaks to allow beginners and interested onlookers to have a go. During the breaks there will be more time to help set up and trim boats. This format also provides opportunity to sail 2Metre boats and other experimental craft.

May

15th   British Model Multihulls Association meeting
Portishead. Contact:Mike Dunkley Tel: +44 (1252) 721439

24th-28th   Weymouth Warm-Up Week
Sailing Meeting at Castle Cove Sailing Club, at the end of Old Castle Road, Weymouth; sailing in Portland Harbour, all boats welcome, but please note that neither AYRS nor the Sailing

Club can provide continuous rescue facilities (just the RNLI), so please ensure that you and your boat are capable of looking after themselves. There will be a charge for temporary membership of the Club and use of their facilities (launching, changing room, showers, bar, etc). Contact: Bob Downhill; tel: +44 (1323) 644 879

June

13th   BMMA meeting
Guildford. Contact:Mike Dunkley Tel: +44 (1252) 721439

July

3rd   BMMA meeting
Cotswold. Contact:Mike Dunkley Tel: +44 (1252) 721439

August

15th   BMMA meeting
Yeovil. Contact:Robbie Nevitt Tel: +44 (1963) 370058. If numbers permit, this will be the Mini40 championship.

October

2nd   BMMA meeting
Gosport. Contact:Mike Dunkley Tel: +44 (1252) 721439

2nd-8th Weymouth Speedweek
Portland Sailing Academy, Portland Harbour, Dorset UK. Contact: Bob Downhill; tel: +44 (1323) 644 879

6th   AYRS Weymouth meeting
Speedsailing. 19.30 for 20.00hrs at the Royal Dorset Yacht Club, Upper Mall, Weymouth. Contact: AYRS Secretary, BCM AYRS, London WC1N 3XX; tel: +44 (1727) 862 268; email: ayrs@fishwick.demon.co.uk

November

3rd   AYRS London meeting
Subject to be confirmed. 19.30 for 20.00hrs at the London Corinthian Sailing Club, Upper Mall, London W6. Contact: AYRS Secretary, BCM AYRS, London WC1N 3XX, UK; tel: +44 (1727) 862 268; email: ayrs@fishwick.demon.co.uk

December

1st   AYRS London meeting
Subject to be confirmed. 19.30 for 20.00hrs at the London Corinthian Sailing Club, Upper Mall, London W6. Contact: AYRS Secretary, BCM AYRS, London WC1N 3XX, UK; tel: +44 (1727) 862 268; email: ayrs@fishwick.demon.co.uk

January 2005

6th - 16th   London International Boat Show
EXCEL Exhibition Centre, London Docklands. Those who can give a day or two, from 15th December onwards, to help build/staff the AYRS stand (reward - free entry!) should contact Sheila Fishwick tel: +44 (1727) 862 268; email: ayrs@fishwick.demon.co.uk

23rd   All-Day AYRS Meeting
9.30am-4pm, Thorpe Village Hall, Coldharbour Lane, Thorpe, Surrey (off A320 between Staines and Chertsey – follow signs to Thorpe Park, then to the village). Details from Fred Ball, tel: +44 1344 843690; email fcb@globalnet.co.uk

23rd   AYRS Annual General Meeting
4pm, Thorpe Village Hall, Coldharbour Lane, Thorpe, Surrey. Details from the AYRS Secretary (as above)

Catalyst — *a person or thing acting as a stimulus in bringing about or hastening a result*

On the Horizon . . .

Construction of the Wingsail - Gabriel Elkaim
Mini Trimaran - Newman Darby
Flying Proa - Roberto Rampinelli
Unfinished projects - Roger Strube
The 50-Knot Barrier - Peter Jefferson
More sources and resources: reviews, publications and
    Internet sites

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Journal of the Amateur Yacht Research Society