Catalyst

Journal of the Amateur Yacht Research Society

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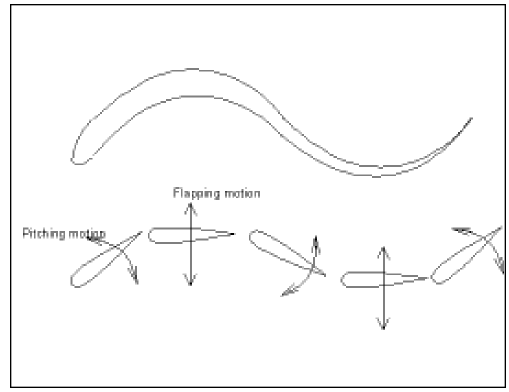
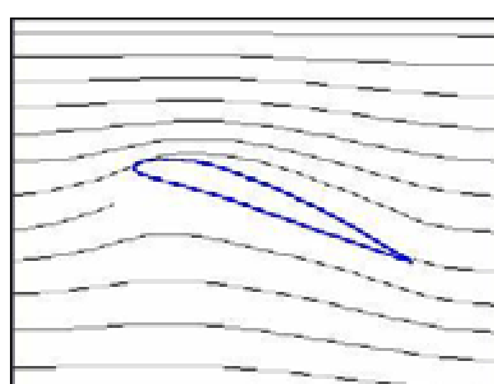
Features

Regulars





Cover Photo - Richard Tostevin's sailing models on a seawater pond in Guernsey

Catalyst

Journal of the
Amateur Yacht Research Society

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Life goes on

It's always sad to say goodbye to old friends, and as you will see from the news opposite, AYRS has to say goodbye to the last of the original Vice-Presidents, and indeed its last UK Vice-President. However life goes on, and so we need to refill the vacancy left by "Clarence". we have one nomination already, but if anyone has any strong views as to who should be an AYRS Vice-Presdent, please contact the AYRS office.

On a lighter note ...

... now that the summer has come to the Northern Hemisphere – or, for those Europeans who have been suffering storms of late, now that the longer days are here – I expect people are out sailing and experimenting, and if I wasn't working on this word-processor I would be too.

However the days are at their shortest down South, sothere's only a little time to go sailing, it's time you all put your pens to paper and wrote to *Catalyst* about the things you have been doing for the past eight months or so.

...and finally

Next year (2005) is the 50th year of AYRS. We ought to mark the occasion somehow. A retrospective display at the Boat Show is almost a certainty, but what do you think we ought to do, either there or more genarally? Write and tell us!

Cheers
S Fishwick

AUSTIN "CLARENCE" FARRAR CEng FRINA

Austin Farrar, known as "Clarence" to his friends and colleagues, died on Tuesday 6th July, 2004 aged 91. A man of remarkable innovation and skills, he was also a kind and thoughtful gentleman who took a great interest in his friends lives and achievements. In a short piece we can only touch on a few of his achievements, though many are still in use today.

Austin's father was lost at sea in 1917, and he was raised by his mother and his grandfather, Edward Packard, who ran a company that would eventually be known under the name Fisons. The Packards shared a passion for sailing, with Austin's mother being a noted helm in the Orwell Corinthian Class, and, by the age of six Austin had started on a life with boats. Living at the time in Felixstowe, he started Prep School where he was proud to have been taught to write by Enid Blyton, then a trainee teacher. He continued at the Imperial Service College in Windsor, making model steam engines, and then to Philips and Son Ltd, Dartmouth, for an Apprenticeship as a Marine Engineer.

It was his last year in the Drawing Office that showed his true innovative designing skills. His first paid job before he left Dartmouth was an independent design for two "Holiday Maker" speedboats. One to just "look fast" for use inside the harbour, and one to "be" fast for use out in the bay. Despite being a fine design, the latter boat had to be modified to remove the spray rails when the customers complained they were not getting wet! During his free time Austin was fortunate to race with the "family uncle" Sir William Burton on a succession of Twelve Metre Class Yachts, and in his own Dart One Design Dinghy; although Austin always admitted he was a better crew than helm, saying he always knew the right tactic just to late!

By way of a short spell at John Samuel White Ltd at Cowes, and racing in the Solent aboard *Dolly Varden*, the Ratsey & Lapthorn Sailmakers yacht, Austin joined the drawing office of the designer Robert Clark in 1936. He worked on many famous yachts and drew the first "Pulpit" to be fitted to the yacht *Ortac*. A great success, every yacht today is fitted with a pulpit to protect the crew on the foredeck. 1938 saw Austin start his association with the International 14 foot class, and a lifelong friendship with Charles Currey. Together they worked on the development of the trapeze, now so common on racing dinghies, which was used so effectively by Peter Scott and John Winter during the championships of that year. War was looming and Austin joined the RNVR, but as a designer was better used in the business he joined the Sussex Yacht Works in Shoreham, working on HDMLs and their engine installations. More important work beckoned however, and in 1941 he moved to the Admiralty building in London to work with Captain Currey (Charles Currey's father) on the Torpedo Nets Project. This became his work for the rest of the war, but it was only many years later that he realised that over 50 ships had actually been saved.

After the war, Austin established the Woolverstone Shipyard where he designed and built the most successful International 14 Foot dinghies of the post war period, such as *Windsprite* and *Bolero*, as well as many other craft. He developed the cold-moulding technique, setting the standards for others to follow. He designed the curved sliding seat now used on all International Canoes and paid attention to all the fittings and details required in racing boats.

In 1954, Austin sold the yard, and moved on to establish the renowned Seahorse Sails with Leslie Widdicombe. At the forefront of developments in Terylene sail cloth, Austin was ever the innovator with sail shape and he designed and made many of the fittings that today we take for granted, including the headsail furling gear still made by Sailspar. Many of today's sailmakers started their time with Seahorse Sails: Eddie Hyde, Eddie Warden-Owen and Andy Cassell to name but a few. Austin worked his own spherical trigonometry programmes for his famous spinnaker designs, and also spent time on the development of stable spinnaker cloth. He worked in the wind tunnel with rigs for the Twelve Metre *Kurrewa*, and continued with the "Little Americas Cup" races for C-Class catamarans. Britain successfully defended this trophy for many years in the 60s with the Hellcat boats and Austin's rigs on first *Emma Hamilton*, which when modified, became the Olympic catamaran Tornado rig, and then the groundbreaking wing rig on *Lady Helmsman*.

However, back in 1948 Austin had competed in the Olympic trials in the Swallow class, finishing second, and subsequently became a measurement advisor, being invited to the 1960 Rome Olympics. This led to many years working with the International Yacht Racing Union and the Royal Yachting Association on technical matters.

As far as we can tell at 50 years distance, Austin had been in contact with AYRS from the start. It is possible that he was one of those with whom John Morwood corresponded when he wrote his book in the early fifties, and Austin, along with Eric Manners and Dr C N Davies become one of the original Vice-Presidents of the Society following the second AGM in January 1957. He has served the Society since, never in the foreground but always there in the background. In 1963, when the Society was incorporated, Austin was one of the signatories to the Memorandum of Association, and he has been there ever since.

Although officially retiring in the late 1980's Austin never really stopped working and designing. As well as his AYRS position, he was also an Honorary Vice-President of the Society for Nautical Research and worked on the design of *HMS Victory's* cutters and other marine archaeological projects. He wrote for many magazines, and was a keen follower of wind energy. He worked with school children on engineering competitions and at home was renowned for his homemade wines and marmalade. He quietly restored his beloved vintage Bentley "*Bumble*" and took a keen interest in the restoration of his White Steam Car. He mastered lost-wax casting, making commemorative medals and his own miniature working replica cannons. Music from Mozart to Gershwin and humour from the Marx Brothers to "Wallace & Gromit" all combined to make this special man. It is very difficult to do justice in such a short piece to the amount of achievements and character that made Austin the person he was, but it can be said that every person that had the privilege of knowing or working with him will treasure that always.

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AYRS Sailing Meeting, Weymouth

The May week (24th to the 28th) at the Castle Cove Sailing Club took place with the usual pleasant atmosphere and collection of boats and windsurfers. We were made very welcome by the Club, and especially by Brian Wilkins, whose bout of ill health seems to be behind him.

George and Joddy Chapman arrived with *Ceres* and as usual impressed everyone with the smooth ride. John Peperell led the Catapult charge, and Slade demonstrated his hybrid Catapult mutant. Fred Ball was seen 100 yards offshore mucking about with kites and I believe HAPAS. Naturally Torix Bennett produced a new Catamaran with his latest ideas incorporated and Norman Phillips made tea and coffee all week to go with the biscuits.

Arthur Lister was testing his Hydrofoil Catapult and I had the doubtful pleasure of taking Jon Montgomery out on Arthur's RIB which sports a largish engine for a photo shoot on the Wednesday.

The wind was blowing sufficiently hard to produce a vicious chop towards the middle of the harbour just outside the 6 knot limit. We had the power to keep up but not the strength, and I don't think Jon will be riding with me again! We both got thrown all over the place trying to get near the *Lister Flyer*. By golly it goes well!


Torix Bennett

He was of course sailing smoothly up and down while we were alternately laying in wait for him to come by or picking up speed hoping we could get near enough to get pictures. I was quite glad when Jon informed me he thought he had enough pictures and suggested we head for the slipway. We did not get any readings of Arthur's speeds but he seemed to be moving right along. We will find out in October!

Bob Downhill's garage door was not in evidence as it has outgrown the trailer and he is trying make other arrangements for towing trials.


Arthur Lister

Norman and I went across to the Sailing Academy to have a look at Malcolm Barnsley's *Sailrocket* but we were disappointed it had not turned up yet. I understand it is now at the Academy and Malcolm and Paul Larsen are preparing to work it up to an attempt at the record. – Good luck to them.

The idea of the May week is to test the equipment for October but unfortunately we were too busy drinking tea and coffee and eating biscuits to really do anything constructive although we did have some constructive discussions on future timing developments.

I suppose about 20 or 30 people turned up during the week including Michael Ellison whose attempt to bring his yacht foundered on a rough running engine, and Nick Povey and Bob Spagnoletti who spent much needed R & R on the water on their windsurfers.

It is a week I really enjoy and the only difficulty we are going to have keeping it our little secret

Bob Downhill

Bauer Vehicle

The essential characteristic of science as opposed to magic is that scientific results are repeatable - and are in fact repeated - by other independent investigators.

I have the impression that the Bauer vehicle demonstration, of an unpowered vehicle remaining stationary indefinitely on a moving belt in a windless room, has never been repeated by an independent researcher.

If indeed this is the case, then as long as it remains true I think there should be a moratorium on the publishing of papers containing statements like "Bauer propellor vehicles can sail directly downwind faster than the wind" (P.A.Sharp, AYRS Catalyst, July 2003, p13).

I suggest that at the next Boat Show AYRS provide a moving belt and a challenge to demonstrate a Bauer vehicle. A successful vehicle would be a VERY popular exhibit!

John C. Wilson, London
johnwilson@pocketmail.com

[I take your point, although I don't share your scepticism. Theory certainly permits travel faster than the wind, directly downwind, (and Peter Sharp has already listed many possible ways), but as far as I know Bauer's vehicles are the only ones of their kind. If there are other such vehicles (or, better still, boats) we should like to know of them and how well they performed. Secondly, if someone (probably in UK) would like to build a test belt that could be displayed at AYRS meetings, Weymouth Speed Week, or even at the London Boat Show taking account of the need to keep little fingers clear of the works, could they please contact the AYRS Secretary. - Editor]

Sailboard Pioneer Dies

The president of the world's first free sail system sailboard business, Kenneth S. Darby, died unexpectedly April 17, 2004.

To day the dictionary calls these sailboards 'windsurfers'. Kenneth Darby was 69 years old. He was still the active president of Darby Industries, Inc., which he and his brothers Newman Darby and Ronald Darby formed in late 1964 to manufacture and sell f.s.s. sailboards. Ken claimed they built about 160 sailboards. They all had a universal joint adaptor on their decks for the sail rig and did not need a rudder to steer. They sailed beautifully but were a hard sell item because people believed that such a way of sailing was impossible. They were not making enough money so used up their materials to make fishing boats, fiberglass bath tubs, sinks and many other items. Then in 1980 they went back in the sailboard business. Kenneth's family will now run the Darby Industries Inc..

Kenneth Darby was buried in the Mountain View Burial Park in Harding, Pa., U.S.A. on the river near their factory.

Ken was still an active sailor when he passed away. It is unclear as to what happened to him.

Ken was well loved, hundreds of people came to his funeral.

S. Newman Darby

Whale Tail Efficiency

This regards your question on the efficiency of fin propulsion related to the article in Catalyst nr 16 about the *Ondulo*.

I have for years an interest in high efficiency human marine propulsion systems. I have designed a number of products like a fin for double speed swimming, but also a kind of 'shitfin" to pull a dinghy out of the leebank reeds into free water. Furthermore as I am rowing more or less daily in a Sprite skiff I am interested to improve sliding seat rowing performance.

The (theoretical) efficiency of a fin can be as high as 90%. Important parameters are the aspect ratio of the foil, a high lift over drag ratio of the foil in the working point, and then especially the ratio of boatspeed versus tangential speed of the foil. For practical purposes and at a sustainable human output level in the order of 100 watt (which I already call the output of a slave) efficiencies of 85% seem possible. I have compared the figures with propellor efficiencies but they will become very large in diameter for equal results. In HPV systems one sees very large diameter props at low speed doing well.

A point of observation here is that an oscillating movement may be hampered by too low Reynolds numbers over part of the trajectory. There are however clever foils designed by Prof. Michael Selig that could do a great job. It is amazing to see an outboard motor efficiency in this light!

I hope you find an answer in my reaction.

Pieter G. Kuipers
<postbus@nvision.demon.nl>

"Plus Vite que le Vent à la Voile" (Sailing Faster than the Wind) – Bernard Coat an Hay

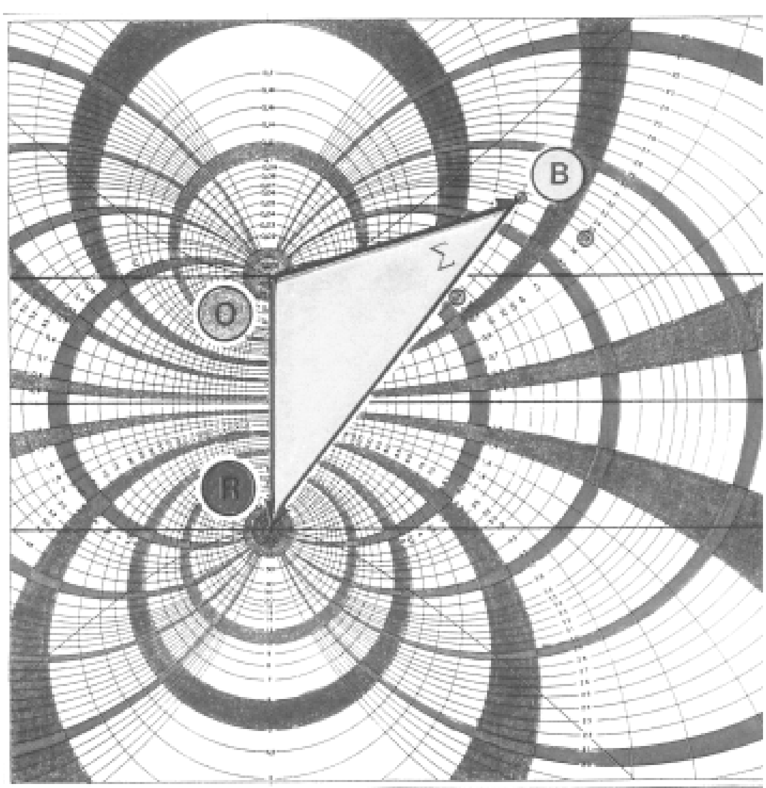
Privately published from Le Bourg, 22420 Lanvellec, France, 2 Volumes, in French, ISBN 2-9510213-1-3& 2-9510213-2-1

It's not often that AYRS receives unsolicited books for review, but every now and then a milestone appears and this is one such.

Bernard Coat an Hay (a Breton surname I suspect) has set out to collect and codify a method to determine the performance limits of sailboats. He sets himself to answer the following basic questions:

1. Can a sailboat sail faster than the wind?
2. Can a sailboat go upwind as fast as the wind? Or faster?
3. Can a sailboat go downwind at windspeed or faster?
4. In the absence of wind, can a sailboat go up a river, or downstream, faster than the current?
5. Can a sailboat cross a river if the wind has the same speed and direction as the current?
6. What pairs of speed & direction are possible for sailboats, if one varies the angle of incidence of sail or keel?
7. What is the ideal angle (off the true wind) for sailing upwind given a certain ability to sail close to the apparent wind?

Coat an Hay starts from the basic equations of course and speed taking into account all the possible viewpoints – from the underlying land, the water, the true wind and the apparent wind, and combines then into a coherent whole considering a boat in steady state. He uses these equations to generate a graphical calculator (he calls it an Abacus) that exploits the relationships and allows the prediction of sailboat performance from a few measurements.



(The figure is typical of the process. It show the derivation of part of the Abacus (the background pattern) from a vector triangle relating windspeed and boatspeed and directions). He does this is no more than about 50 pages of clear if mathematical argument. A tour de force indeed.

For the average reader, the drawback is the amount of mathematical notation used, frequently vector notation. As a textbook though for French-reading marine engineering students it should hold no fears and should be useful.

S Fishwick

THE CASE FOR A NEW MUG

Charles Magnan

The International Catamaran Challenge Trophy, more often referred to as the Little America's Cup, appears now to have become no more than another one-design championship competition. There is in principle nothing wrong, or in any way illegal, about such a thing having happened, but it has removed the innovation and design aspects of the original C Class competition. Dennis Connor has been quoted as saying after losing to Australia II, "The better crew lost to the better boat"; most people seem to agree. The choice of a one-design class deliberately eliminates the "better boat" part of the competition.

It was the latter which was in my and I suspect in many people's opinion, the essence of the Little America's Cup. Certainly to me it was the main focus of interest, the thing that made it special.

In the various articles, both in print and on the Internet, that I have read concerning this event a number of things appear to be fairly clear:

1. The C-Class has been described in various places as either dead or dying.
2. The cost of developing and campaigning a competitive C-Class catamaran of the required standard to have a realistic chance of winning such a competition has become prohibitive for most individuals or amateur groups. It is still a long way from the costs of the "Big" ("Old"/"Classic"/"Slow") America's Cup (where in the latter days of the Twelve Metre boats there was a rule of thumb that one could expect a tenth of a knot increase in boatspeed for every million dollars spent in research and development), but we are now talking in terms of million dollar budgets for a serious campaign.
3. The Little America's Cup competition itself has almost died as a result of the lack of suitable entries, probably largely due to the factors mentioned above. Although a recent C-Class challenge and a new trophy has been announced, it remains to be seen whether this will herald a revival of regular challenges or if it turns out to be a one-off event.

A 25 foot open catamaran without accommodation is a rarity, C-Class or otherwise, because it falls into a gap between the dinghy-style beach-cats which are normally kept ashore and launched as desired, and the trailer-sailer pocket cruisers which are often kept afloat. You have only to look around to see the popularity of beach cats in the 16-20 foot range, and of 25-30 foot trailer-sailers such as the Dragonfly, Firebird and many of Ian Farrier's folding trimarans.

Because C-Class catamarans fall between two stools in this way, and because their trademark wing sails that are such models of efficiency, are also impractical in that they cannot be left up throughout the sailing season in the manner of a normal mast, and are too big to be easily stepped and unstepped every time the boat goes sailing, there is no interest in commercial sponsorship from manufacturers of boats that the rest of us sail.

A Suggested Solution – A True Open Daysailer Racing Class

The following is presented as a discussion document with a view to getting a consensus of opinion.

Suggested name: *The (Un)Restricted 20 Foot Class.*

Ideally this should simply be an *Open 20 Foot Class*, but one already exists, although with a beam restriction of 8' 6" which outlaws boats such as the Tornado, it does not seem all that open to the Author.

Philosophy:

Restrictions as few as possible to encourage the development of better craft, only being imposed where necessary to prevent costs being excessive or to prevent unsafe or impractical craft being developed purely to win races.

Suggested Rules:

Hull(s)

- LOA – Maximum 6.1 metres (a whisker over 20 feet) in sailing trim. Where hulls are moveable or not aligned in the same fore and aft position, LOA shall be taken as being from the aft end of the aftermost hull to the forward end of the forward hull.

20 foot LOA has proved to be the biggest beach cat or dinghy that people feel like manhandling (womanhandling?) up and down beaches on a regular daysailing basis. Very few boats in a typical beachcat / dinghy park exceed this length. By opting for the maximum practical daysailing beach launchable size, almost all current beach cats or skiffs will be within the limit.

- BOA – Unrestricted.

Alternatively, it has been suggested that BOA should be subject to the same maximum restriction as LOA, i.e. 6.1 m.

- Number of hulls – Unrestricted.
- Materials of hulls and appendages – Unrestricted.
- Use of hydrofoils - Unrestricted.

The best way to answer questions about the true effectiveness of hydrofoils around a course which includes windward legs is to allow them to be raced on such a course against more conventional craft.

Rig

- Sail area and materials – Unrestricted.

Should a maximum area be set? If a maximum is set, it should be fairly generous.

Cruising sailors are restricted in their sail area by the available spars on the boat and not by an artificially imposed rule. It is intended to encourage the development and use of variable sailplans with reefing systems to enable large areas to be deployed in light winds rather than just simply maximising the power available from a restricted sail area.

- Wing masts/sails – Plan area restricted to 20% of upwind sail area unless there is provision for allowing the mast to weathercock by freely rotating through 360 degrees.

Sails need to be able to be derigged easily without taking the whole mast down if the boat is to be of practical use, so permanent, non-reefable wing mast area needs to be restricted unless a weathercocking capability can be demonstrated for any wind direction, allowing the rig to be left up unattended.

- Spar materials – Unrestricted.
- Spar length – Unrestricted

Should a maximum mast height/spar length (11m or 36 ft suggested) be introduced to prevent rigs being too tall and spindly? The latter are great for light weather, but unmanageable and possibly fragile in heavy weather. Board sailors have multiple rigs of varying sizes for use in different weather conditions, and while this is a practical arrangement given the relatively small size and cost of the rigs, it is likely to lead to a major cost escalation if allowed in a larger craft.

- Kites –

Spinnakers attached to poles or bowsprits are clearly allowed. Traction kites/spinnakers on long lines would also be allowed, but should their use be unrestricted, or should kite type/size/geometry and line length be restricted on safety grounds?

An Interim Solution:

As an interim step while the above is being discussed, the Author has proposed that the Amateur Yacht Research Society (AYRS) offer a trophy to be based on a simplified version of the above rules, to be administered by an established UK sailing club as part of their normal racing programme.

The AYRS Unrestricted 20 Foot Class Trophy

This is a rosewood shield, to be given to Worthing Yacht Club, and contested annually, initially at their Open Day on 15th August, celebrating the club's centenary.

Rules

The proposed rules are as follows. They are subject to revision by the Class Authority in the light of experience. References to specific IYRR are to the Racing Rules of Sailing for 2001-2004 (or equivalent rules in later editions).

Class Authority

The Class Authority has responsibility for the maintenance of the Class Rules, settling of disputes over interpretation, measurement, etc.

Until such time as a Class Association is formed and able to assume responsibility for the administration of the Class, the Class Authority shall be the Committee of the Amateur Yacht Research Society.

Hull(s)

- Number of hulls – Unrestricted.
- Overall Length – Maximum 6.1 metres in sailing trim, *excluding* rudders (and hydrofoils integral thereto), bowsprits, boomkins, and flexible stays. Where hulls are not all in the same fore and aft position, LOA shall be taken as being from the aft end of the aftermost hull to the forward end of the forward hull.
- Overall Beam – Maximum 6.1 metres, including all outriggers, trapezing rails, etc, in their deployed position. The use of trapezes is permitted; IYRR 49 shall not apply.
- Materials of hulls and appendages – Unrestricted, with no minimum weight.
- Use of hydrofoils – Unrestricted, but all hydrofoils when deployed shall be contained within the LOA and BOA limits.

Rig

- Sail area and materials – Unrestricted. IYRR 50 and 54 shall not apply.
- Wing masts/sails – Unrestricted. *(Note: A proposal to restrict wing-masts to no more than 20% of the area of the sails they carry is under consideration).*
- Spar materials – Unrestricted.
- Spar length – Unrestricted.
- Kites – kite spinnakers and/or traction kites are permitted, but the use of traction kites (e.g. kite type/size/geometry and line length) may be restricted by Race Committees on safety grounds if they consider it necessary. (Example reasons would include: overhead power cables, proximity to aerodromes, restricted waters, etc). In such cases, advance notice should be given to prospective competitors whenever possible.

General:

Races shall be held under the Racing Rules of Sailing in force at the time of race, as modified by these Class Rules and by the Sailing Instructions. Craft shall be propelled only by the natural action of the wind on sails spars and hulls, and by water on the hulls and appendages.

In general a Race Committee shall retain the right to ban any craft if there are genuine reasons for deeming it unsafe to its own crew or to others, subject to appeal to the Class Authority. Race Committees as well have the right to cancel or postpone the race(s) if they deem weather or other conditions to be unsuitable for safe racing by the yachts entered.

All craft shall have third party insurance cover of a minimum of £1,000,000 or equivalent, unless this requirement is specifically waived or amended in the Notice of Race. A Race Committee has the right ask for evidence of such cover and to refuse entry in its absence.

Proas (yachts that can sail in either direction) are specifically permitted, but the Race Committee may require all proas to carry a distinguishing mark (a double-headed arrow is recommended) upon their sail to signify to other yachts that they may shunt (reverse direction). Proas when shunting are subject to IYRR 13 & 16.1. In respect of IYRR 44.2, a Penalty Turn for a proa that cannot tack or gybe shall consist of four shunts each separated by an alteration of heading of at least 90 degrees.

Race(s) for the above Trophy:

- All races for the above trophy shall be open to all sailing craft that comply with the rules above, whether or not the crew are members of the host club. The host club may however charge a reasonable temporary membership/entry fee.
- All races shall be run over courses containing at least one windward leg. The choice of course and number of races is left to the discretion of the host club. A course which has been set to consist of at least one windward leg, but due to wind shift after being set does not actually have a true beat to windward, shall still be deemed to be valid.
- The trophy is to be awarded on a line honours basis, i.e. to the craft that completes the set course in the shortest elapsed time, without any form of handicapping being applied.

Commentary

The rules have been deliberately set to be as simple and liberal as practicable. There is no restriction on size of rig, but since the club to which the trophy has been offered is Worthing Yacht Club, which is situated on the unprotected coast of the English Channel, the building of huge, ultra light rigs suitable for light weather only is effectively precluded by the notorious unpredictability of the weather/sea state conditions.

It is hoped that the trophy will encourage the development of craft outside the gamut of the current beach cats as well as improvements to them. If that does not happen to a significant degree, and the trophy simply serves to show which of the currently available cats is fastest, it will at least be regularly contested and still worthwhile.

Restrictions on wing masts/sails on the other hand have been omitted for simplicity, but if such craft were to make a significant appearance, then it would be a signal that it was time to launch an international competition of the type described in the first part of this article.

Comments are invited

This set of rules is not a foregone conclusion, even though the first race for the Trophy will have been held before many of you receive this *Catalyst*. We (the AYRS Committee, of which I am a member, and to whom I have proposed this) anticipate that we may need to tweak the rules both as a result of the experience of the first event, and in the light of your comments.

Please send your comments directly to the AYRS Committee using the email address <ayrs@fishwick.demon.co.uk> or by post to the usual BCM AYRS address, preferably in time for a consensus to be published in the next Catalyst at the end of September.

Charles Magnan

ABOUT FISHTAILS, RAYMOTION, AND GONDOLAS

Mario Rosato

Introduction

Reading with much interest the article about the French fishtail boat *Ondulo* on the last issue of Catalyst (April 2004) triggered my will to finish some notes I had began writing after having read another interesting article by Frank Bailey about “raymotion” (Catalyst No 5, August 2001). The present article intends to give some concepts about this very complex and yet little explored phenomenon: the flapping foil. It also has some certain sentimental content because the subject is associated with some episodes of my life: my student times at the University in Argentina, my first contact with the market reality, falling in love in Venice during the Historical Regatta with a Venetian countess who would later be my wife…

Everything began many years ago, when I was trying to develop an oscillating windmill, (also called “wingmill”). The scope was to retrofit existing manual water pumps in developing countries at low cost, and save women, children and animals from the slavery of pumping water by hand (usually under inhuman conditions!). Noble projects never find sponsors, and since good intentions are not eatable, I had to archive the project, quit my University and begin earning my life working for a multinational Company in a completely different field.

I’ll avoid maths (promise!) and hope you enjoy it.

Basic Concepts

Marine animals, birds, gondolas and some small craft – like the newcomer *Ondulo*, the traditional Venetian gondolas and the Swedish *Trampofoil* (*www.trampofoil.com/speedsailing/team.html*) –all share the same propulsion principle: an aerodynamic surface periodically pitching, or plunging, or varying its shape, or a combination of all these movements. Since Leonardo da Vinci, many inventors tried to build flying machines, which basically mimicked birds (technically known as *ornithopters*, from the Greek **ornithos** = bird and **pteros** = wing). The art of the *voga alla veneziana* (Venetian rowing) has been known since at least 1400. Generations of *gondolieri* have efficiently rowed tons of payload along the Venetian channels, and the skilled artisans who built their oars found the optimum shape and dimensions by trial and error. But the first to rationally explore and propose a theoretical explanation were Knoller and Betz, in independent studies, in 1909 and 1912, respectively. They noted that for a slender wing, at a low incidence angle to the incoming flow, the net force on the airfoil was very nearly at a right angle (normal) to the incoming flow, as indicated in Fig 1.

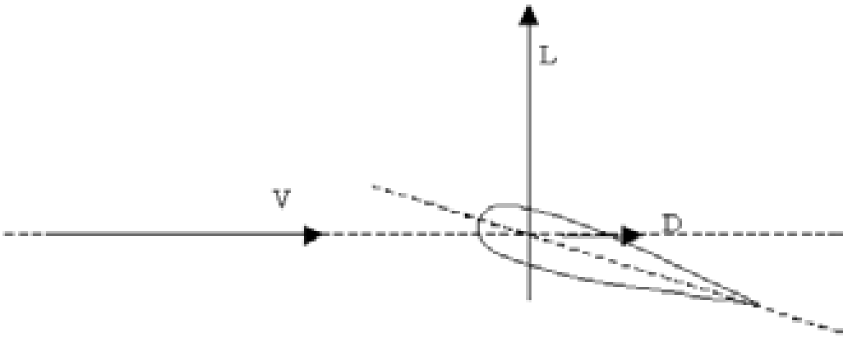


Fig 1.

Their theory assumed that the drag on the wing was very small in comparison to the lift, (usually 30 to 100 times for standard profiles). Their simplified theory, sometimes referred to as linear theory, assumes that the resultant force is normal to the incident flow. They observed that, if the airfoil is moved up or down at a fixed speed, the airfoil sees an induced vertical velocity due to this motion, which results in an incoming velocity with an incidence to the real free-stream direction. In the figure below we can see an airfoil with its chord parallel to the main flow. If moved down, the composition of the vertical and horizontal speeds V_v and V_h, V_{app}, will form a certain angle with the chord of the profile, thus causing lift and drag, which are respectively perpendicular and parallel to the direction of V_{app}. The horizontal component of L, F_h, is bigger than the horizontal component of D, so a net thrust is obtained. (Fig 2).

Knoller and Betz went one step further, and they noted that if the wing was flapped (periodically plunging it up and down vertically) while the lift force would be both positive and negative during the cycle, averaging to zero, the thrust force would always be non-negative, so the average thrust would be a positive value. These early researches should be downloadable from http://naca.larc.nasa.gov .

A similar phenomenon is observed if the same foil is pitched periodically around its lift centre (usually a point near the 25% of the chord). A net thrust will appear, while the average lift will be practically zero. (Fig 3).

In this example, the foil is pitching down with angular speed ω, so the vertical speed that the leading edge "sees" is $V_v = \omega * r$, where r = 0.25 c (c is the chord of the profile).

Conceptually similar, but more difficult to model numerically, is the case in which the foil is varying its camber periodically, while keeping constant its angle of attack. In Fig 4 the angle of attack is always 0, the average lift would be nil, but a net thrust would be observed, although the linear theory fails to explain it. The thrust is a result of the vortex trail, which is generated, which changes the pressure distribution along the chord.

Fig 5 shows yet another case: the so-called Katzmayer effect. A static foil placed in a swinging stream also generates thrust (basically, is the same situation of the Knoller-Betz effect, the air is moving while the foil is fixed, instead of the foil plunging in a static stream (just a question of relative movement).

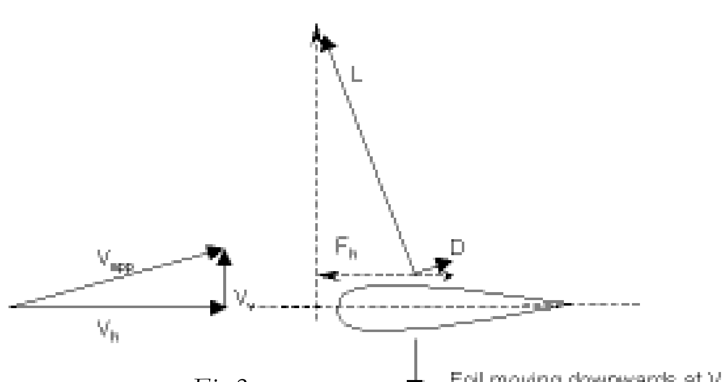


Fig 2

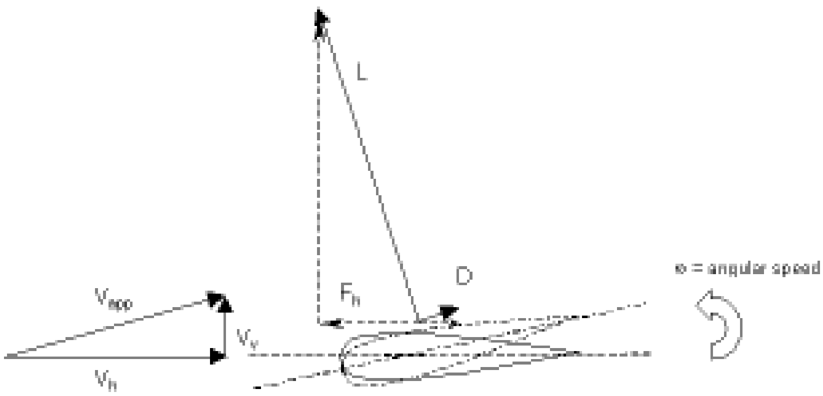


Fig 3

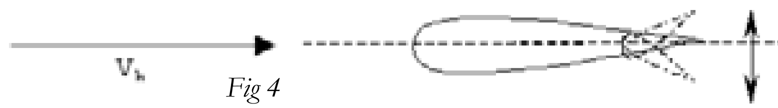
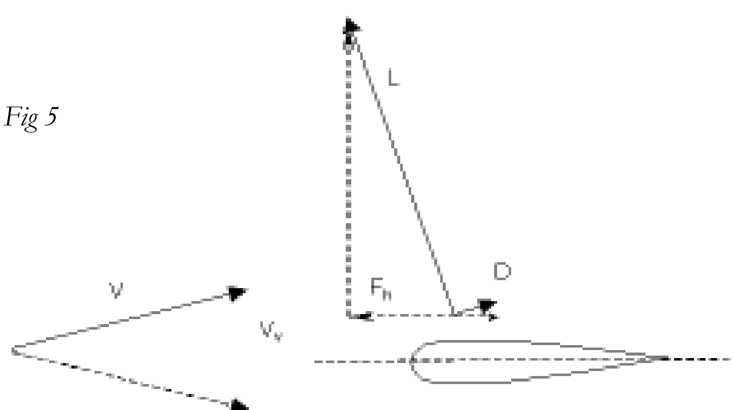


Fig 4

Concrete cases of flapping wing propulsion.

To make things more complicated, also combinations of the above periodical movements are possible, i.e., a wing could be plunging and at the same time varying its camber and/or pitching, and all of them with different frequencies or phases. A very interesting site to see some animations explaining this phenomenon is the one of the Monterrey Naval Postgraduate School where Dr. Kevin Jones' research is presented. See *http://www.aa.nps.navy.mil/~jones/research/images*, it's really worthy and easy to understand, even for the layman! An interesting bibliography is also presented, and some of his papers are downloadable. The most stimulating thing for amateurs like us is an interesting reference to a study by Theodorsen and Garrick. It seems that by the mid 1930's it was well known that a single flapping wing generated thrust at an efficiency of between 50 and 100 percent; 50 percent at higher frequencies, and a theoretical limit of 100 percent as the frequency is reduced to zero (which is physically non-relevant). In practice, to generate significant thrust values with a flapping wing, relatively high frequencies were needed, reducing the efficiency to around 50 percent. As Dr. Jones points out (quote), *the loss in efficiency at higher frequencies was primarily due to energy lost into the flow in the form of shed vorticity. In the 1950's, Schmidt noted the experimental results of Katzmayer (1922), where it was shown that a stationary airfoil in an oscillatory flow field also produced thrust (this is called Katzmayer effect). Schmidt took advantage of this by placing a stationary wing in the oscillatory wake of a flapping-wing, recapturing a portion of the energy lost into the wake. Since the second airfoil was not moving, it required no work, so any thrust it provided was essentially free (not quite free, as the*

Fig 5



The speed V is constant, but the direction is varying periodically. The airfoil sees a varying angle of attack, as if it was pitching

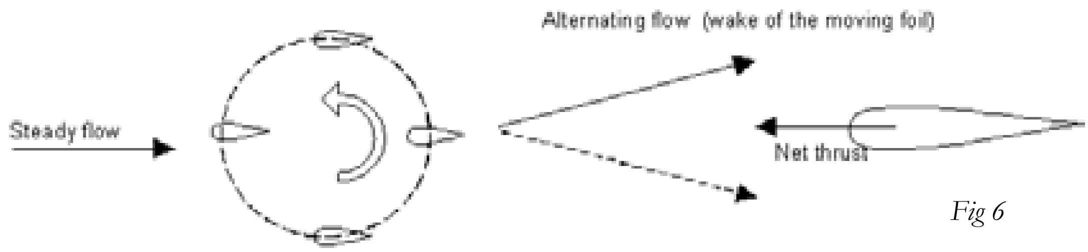


Fig 6

second airfoil has additional profile drag). In the referenced site, Dr. Jones presents an animation of the *Schmidt wave propeller* (Fig 6). This is a flapping airfoil moving along a circular path, with the geometric angle of attack fixed at zero degrees. The circular motion makes the incidence of the flow to vary along its path, and causes an alternating wake. The static wing placed downstream recovers part of the energy dissipated in the wake. Unfortunately, no numerical values of the overall efficiency are presented.

Another interesting device is the *whale tail propeller*, also called *trochoidal propeller*, presented in *http://www.marin.nl/original/publications/cpp_1996_manen_newway.html*, in an interesting paper by J. Van Manen and T. Van Terwisga entitled "*A new way of simulating whale tail propulsion*". (The paper can also be downloaded from *http://books.nap.edu/books/0309058791/html/946.html*). Personal comment: this kind of propeller seems to be the reverse case of a Darrieus turbine. A foil rotates around a point with tangential speed V_t. The central point moves linearly with speed V_a.

If $\lambda = V_t/V_a > 1$, then the path described by the airfoil is a shape called a trochoid. The Authors claim that a whale tail moves following this law, and that the propulsive efficiency of the system ranges from 50% to 80%. The advantages against conventional propellers are: reduced draft, particularly suitable for catamarans, and less noise, hence reduced environmental impact.

(*Personal opinion: whales probably swim even more efficiently because their tails are flexible. I suspect that the camber varies together with the angle of attack, thus increasing the L/D ratio of the tail, and hence the overall efficiency*). Anyway, I don't find any difference between this trochoidal propeller and the special case of a Voigt-Schneider propeller with fixed pitch blades, apart from the rotation axis being horizontal in the first case and vertical in the second.

The complex art of the Venetian rowing, – another example of flapping wing propulsion.

Romantics will hate me now: I'll destroy some of the poetry of the Venetian gondolas with hydrodynamic analysis. The reference I strongly counsel on this subject is a beautifully illustrated and technically very interesting book by Carlo Donatelli, which title is "*La Gondola, una straordinaria architettura navale*" (ISBN 88-7743-090-7; also available in English, ISBN 88-7743-137-7). The word gondola seems to be a corruption of the ancient Greek *concula* (small shell), or perhaps from *kondylion* (case) or even from the Greek-Latin *cymbula* (small boat). Gondolas have been known at least since 1400 – 1500 AD. Today they are built on a standard plan designed at the end of the XIXth Century, which Mr. Donatelli digitised and analysed with a CAD program. There are many variants of similar boats in Venice: the *caorlina*, the *s'ciopon*, the *sandolo*, the *gondolino* (a very interesting race version) ...

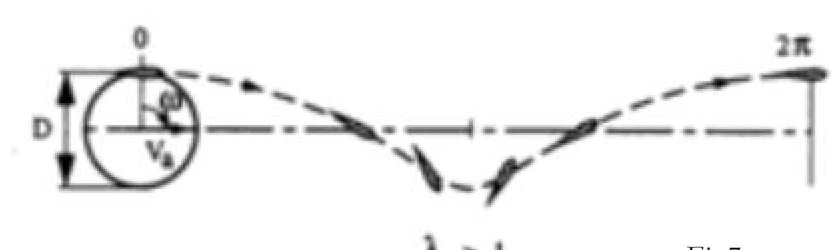


Fig 7

The gondola is unique because its hull is strongly asymmetrical, both in planform and in section.
In its origins, the gondola was symmetrical and two men rowed, one at the port side of the bow and the other at the starboard side at the stern. Since the decadence of the Serenissima Repubblica, it became too expensive to maintain two *gondolieri*, even for rich families, so the boat had to be adapted to be propelled and manoeuvred in the narrow channels by only one man. The *squeraroli* (specialised craftsmen who make gondolas) arrived at the final optimal shape by trial and error, and during the XIXth Century the gondola took its present shape. The oar is placed astern on the starboard side; the thrust creates a torque, which must be compensated by the hull. Usually, the gondolas are 11 m long, and have at least 20 kg of iron at each end. This gives them an enormous inertial momentum (both in roll and yawing), which allows easy manoeuvring in narrow spaces. This inertial moment probably has something to do with flapping wing propulsion, although a deep research should be needed to demonstrate to what extent.

The mechanics of the *voga alla venziana* are quite complex: the oar remains in the water almost all the time. It's a flapping wing working partly in the non-linear field (angle of attack near 90º) during the phase called *premi* (push), and with minimal drag during the phase called *stai* (hold-on or wait). The oar then follows a trajectory (from a fixed viewpoint in the water) with varying angle of attack and almost no regression. Also the lever arm between the CE of the blade and the hull varies both in lateral direction and in depth, creating a pulsating three-dimensional combination of momentum in pitch, roll and yawing senses. The pitching motion seems to create only drag, but the rolling and yawing combination seems to generate some additional thrust, thus recovering part of the energy accumulated in the bow and stern masses. The gondola seems to "swim" moving the tail like fishes or snakes do. Fig 8 shows this concept.

The average yaw angle, α, is necessary to compensate for the average torque. The gondola yaws around this main angle in excursions of +/- 3º.

It must be pointed out that the gondola also rolls periodically, which causes the waterline shape to vary. Mr. Donatelli states in his book that this may increase the efficiency of the hull because of "some effect of the boundary layer". In my opinion the efficiency of the hull he claims is not due to exotic ways of making the flow to remain laminar, but is the unresearched case of a slender body varying periodically its camber and attack angle, hence generating some thrust. Unfortunately, I have no information about researches on slender bodies moving periodically in a stationary flow, but I see no conceptual difference with flapping wings.

From the biometric measures of Mr. Donatelli, it seems that, when moving at low speeds (1.6 m/s – about 3.5kts) one *gondoliere* can transport about 800 kg overall mass (the gondola, the payload and himself) with the same energy needed to walk at the same speed on a flat ground, i.e. about 200 Joule/m (metabolic power), roughly a (mechanical) power of 47 W. In the quoted book, the Author calculates that a propeller should have a diameter of about 84 cm to yield the same performance. At good speed (2 m/s – say 4.5kts) the gondoliere develops about 108 W. Another interesting piece of information: after a series of tug tests, the hydrodynamic drag can be represented with the following expression:

$$R[N] = 12.3 \times v^{2.21} \text{ with } v \text{ in m/s.}$$

Then, the overall efficiency of the system gondoliere-oar-gondola at 1,6 m/s is

$$\eta = 47W / 34.75N * 1.6 m/s = 84.5 \%$$

I checked these results with Theo Schmidt's program Propsim, assuming the equivalent propeller proposed by Mr. Donatelli, and the agreement is good.

Fig 8

Some notes on "raymotion" and other flat fishes swimming

After having read Frank Bailey's article on what he calls raymotion, I spent some hours in Barcelona's aquarium observing the giant devilfish and the small stingrays and other flat fishes. I confess that till then I had only thought of rays just as a good filling for tomatoes, on condition of being boiled and mixed with mayonnaise and some olives. After having seen the small stingrays popping up from water to get the caresses of people, and even turning on a side to get the belly caressed, as dogs or cats do, I will never eat rays again! But let's forget for a moment the ethical question of eating rays and concentrate on their propulsion system.

First of all, it seems to me that there are two kinds of flat fishes with substantially different propulsive modes: the ones with a more or less rounded planform (sole fishes and some rays) and the ones with a roughly rhomboidal shape (like devilfishes). The giant devilfishes flap their fins (or should I say wings?) with a very low frequency (about 0,5 Hz) and high amplitude, so I suppose they must swim very slowly but be very efficiently. They need to, because they must cross long distances filtering plankton. This type of swimming could be roughly explained in terms of the linear theory, although the propulsion is not pure flapping, but it seems to me that the fin also varies its camber while flapping. On the other extreme of fishes' speeds we find swordfishes and other relatives of tuna. They can attain high speeds (about 100 km/h) during some minutes flapping their tails at high frequencies and low amplitudes. They don't need to be efficient, just attain high peak speeds to catch their prey. And finally, we find the round fishes (and also the rhomboidal, when they are laying on the seabed), which let their fins oscillate as Frank Bailey reported.

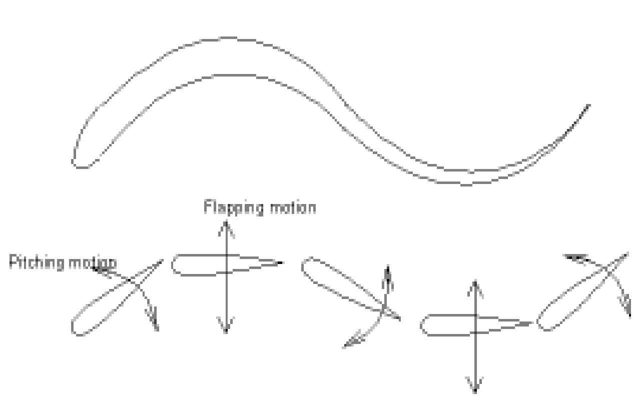


Fig 9

Snakes and eels also swim oscillating their bodies. I tried to develop a model for this motion, but the task exceeds my knowledge of mechanics of fluids. I suppose that the approximate model is a train of foils plunging and/or pitching at the same frequency with a certain phase angle between them. An eel or snake could be considered like a train of slender bodies. Under these suppositions, each elementary foil is subject to both its own Knoller-Betz effect and the Katzmeyer effect induced by the elementary foil it has upstream. So, the raymotion could be considered as a variant of the Schmidt propeller, where the secondary foil pitches in synchrony with the main foil, and with a certain phase angle. Probably a cascade of these wave propellers is even more efficient than just one, but it's not clear whether the mechanical complication is affordable.

I think this kind of propulsion is worth being analysed in depth. Researches like Dr. Jones' have demonstrated that the efficiency of a wing flapping and/or pitching sinusoidally is somehow inferior to that of a propeller, but a train of flapping/pitching foils seems to have (at least conceptually) a greater potential, since each single element may recover part of the energy dissipated in the wake by the element immediately upstream. And what happens if the movement is not sinusoidal, but a trochoidal or saw tooth wave? What happens if the foils are also varying their camber during the cycle? The combinations possible are almost infinite.

What will the future bring?

Some diver has already caught the concept and developed the monofin, which allows people to swim like dolphins. The development seems to be only conceptual (or just marketing?). Check *www.finisinc.com*, under the menu: *products/training equipment/monofins*. I haven't found biometric researches or efficiency studies about this kind of human propulsion. Anyway, I agree with Frank Bailey on the potential of the raymotion as a propulsive method, but the research task seems to be overwhelming for amateurs like us. A systematic research would need at least a wind tunnel and many hours making models to test different combinations of motion laws, frequencies, arrays of elements, etc. And once all the experimental results would be available, the mathematical representation seems to be a mammoth task.

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The *Romy* Sail Rig

Richard E. Tostevin

The following is the basis of an idea for a new sailing rig, based on a lateen sail. The idea came to me about three weeks before Christmas, December 2002. I have called the '*Romy*' sailing rig after my granddaughter.

The Romy rig models sailing at Guernsey

Background

About fifteen years ago I had the pleasure of sailing a 20ft dugout canoe off Mombassa. This rig was very basic. The lateen sail was made of old sacks sewn together. The outrigger was a crooked branch. There was no keel, only the weight of the waterlogged dugout to stop sideways drift, and a paddle for steering. However, to my amazement, this rig still managed to sail upwind even with 4 people aboard. Tacking was another thing. The lateen sail and spar had to be taken down, pulled aft around the mast, then forward again to be raised on the other tack. Not so good!

Boardsailing and windsurfing rigs of today attain speeds of 35 knots and more. Watching them I noticed that the surfer lays back his sail looking not unlike a lateen sail with its laid back profile. The sailboarder is his own mast when sailing to port, just a few quick steps, and then he is his own mast again sailing to starboard.

Then, there it was! To free the lateen sail to perform effectively, two masts side by side are needed. That is the basis of the idea. In all my years around boats I had never seen or heard of a sailing boat with two masts side by side though I have since heard it has been tried out. Was there something fundamental to prevent effective sailing with such a rig?

To answer this last question I acquired a 50 inch model sailing hull with a 10.5 inch beam and 14 inch draft. The keel has about 10lb of weight. Two masts were set at the gunwales with a crosstree member aloft. However the sail fouled on these masts. In place of the two masts I constructed a hollow oval mast joined aloft at right angles.

This design forms a strong pointed egg-shaped oval when viewed from forward or aft; it gives unrestricted deployment of the sail, and the latter does not foul. The oval mast allows the 6ft 6 inch lateen sail spar to be attached to the bowsprit and also held firmly under the apex of the oval mast. The spar lies back at about 45 degrees angle to reach over the stern.

The model's spar is made out of a fishing rod, which spills excess wind with its flexible top end making for smooth and fast sailing.

Conclusions following the Model's Testing

The Romy sail rig's oval mast allows the lateen sail free and unrestricted deployment from the bowsprit to the stern operating within the oval mast and stays without fouling.

The wind passes unrestricted along the full length of the sail, which extends the full length of the vessel. With modern methods and materials the oval mast could be made strong and light, and would suit any sailing hull.

Our two 50 inch radio controlled models have shown the Romy sail rig to perform efficiently in deploying a lateen sail, sailing into the wind between 30 and 35 degrees off the wind, across and down wind.

To a sailor's eye the oval mast looks a little odd at first but the scimitar look of the lateen sail more than makes up for this with its aesthetic and visual good looks.

However, would this rig work on a full size manned sailing boat?

Full Size testing

To answer this question I acquired the use of a 19ft Squib Class daysailer from John Cluet's boatyard in Guernsey. I made up the 30 ft spar with board sail masts. That was easy. I constructed the 10 ft high hoop with 2 inch Alkathene tubing. To give extra strength a 1.5 inch tube was slipped inside making a tight fit.

Besides the fore and aft stays I added two strong stays to the side of the hoop. The sail was cut and altered a few times before we settled on about 165 sq ft.

The 19 foot Squib is a very sturdy craft and therefore I felt a good choice as a platform to try out the Romy sail rig concept. The 4 to 5 NE winds off St. Peter Port never worried the Squib. It was felt the Squib would have carried another 60+ sq ft.

This rig was just to test the concept, and a prototype made hoop and spar of carbon fibre should be easy to construct. The Squib was easy and enjoyable to handle.

Suitable for Beginners and Expert Sailors

The ease of control ensures that the rig is ideal for beginners and people who simply want uncomplicated sailing. It makes holiday sailing easy for most people and is very suitable for disabled persons. Experts will enjoy the opportunity to attack the wind since the Romy rig will sail comfortably 30 to 35 degrees off the wind.

Advantages of the 'Romy' Sail Rig

- Except to handle the tiller, there is no handling of the sail when manoeuvring in any point of wind direction – fine adjustments can be made from the steering position making it ideal for beginners and/or disabled persons.
- There is no boom to contend with at deck level.
- The oval mast allows the lateen type sail free and unrestricted deployment, from the bowsprit to the stern, operating within the oval mast and stays without fouling, making for swift and easy tacking.
- The wind passes unrestricted the full length of the vessel – this is not possible with a center fitted mast.
- With modern materials, the oval mast could be made strong and light – and to suit any sailing hull.
- The oval mast could be made watertight to prevent total capsize with small sailing vessels using dagger boards.
- The scimitar look of the lateen sail is very graceful and pleasing to the eye – the ovoid shape of the Romy hoop compliments the sail.
- The main spar holding the sail has a flexible top end which will spill excess wind, therefore more sail can be carried with the knowledge that excessive gusts will not trouble the vessel.
- With smaller vessels which are in the main 3 to 1 in length to beam ratio, the oval mast will not be a problem when coming alongside.

Disadvantages of the 'Romy' Sail Rig

- Traditional sailors may have a problem with the simplicity of the 'Romy' rig.
- With larger vessels of 4 to 1 or 5 to 1 length to beam ratio the oval mast could be a problem coming alongside a wall – this requires the need to feather the oval mast on possibly a center swivel point and is being considered further. This is not a problem coming alongside a pontoon.
- Other disadvantages and/or problems, if any, have yet to be identified.
- The length of the spar can be a handful – however I managed the 30 ft spar on my own in Force 4 to 5 winds. Reefing on larger rigs needs more research*. On small craft one would adapt the sail to suit the conditions.

Manufacturing Aims and Considerations

The Romy rig could be fitted to a very wide range of hulls from small dinghies to much larger sailing boats. However, the choice of hull to be used for mass production purposes at this stage is a most important consideration.

Stress levels have been considered and tested during the sea trials but have not yet been calculated accurately. Using modern materials, further work on this is planned and a contact has been identified if manufacturers do not arrange this themselves as part of their involvement in the project.

A patent (GB2395932) has been obtained.

Richard E. Tostevin

Squib with a Romy rig

** Editor's Note: Traditionally, lateen sails are slab-reefed up to the yard, on smaller boats by lowering the yard to the deck, on larger craft by sending a man (or men) aloft. I see no reason however why a modern in-spar reefing system could not be used. Whether, on smaller craft, the yard could be supported in a reefing claw and the sail reefed by wrapping it around the outside of the yard remains to be seen.*

The 50 Knot Barrier - Can it be Conquered?

Peter Jefferson

Introduction

The World Sailing Speed record is currently held by *Yellow Pages Endeavour* at 46.52 knots. This record has remained unbeaten for over ten years, in spite of numerous challenges. There is a growing perception that some fundamental limit has been reached and that to exceed 50 knots, over a 500 meter course, is virtually impossible.

In this article, I hope to show that it is theoretically and practically possible to design and build a relatively simple sailing craft capable of exceeding 50 knots in reasonable wind conditions. The proposed craft is a small, single-handed tri-foiler with a wing sail.

The Theoretical Barrier

The ultimate speed of a sailing craft depends on the balance of two opposing forces: the drive force of the sail or wing, and the drag force on the hull or underwater parts of the craft. In order that the craft can accelerate, the drive force must exceed the drag force. In general, as the speed increases the drive force will diminish and the drag force will rise until they reach equilibrium and the craft can go no faster. The challenge is therefore to design the wing so that the drive force is maintained at maximum speed, and to design the hydrofoil suspension system for minimum drag at this speed. In practice, minimising the hydrofoil drag is more difficult than maintaining the wing drive force.

Hydrofoil Suspension

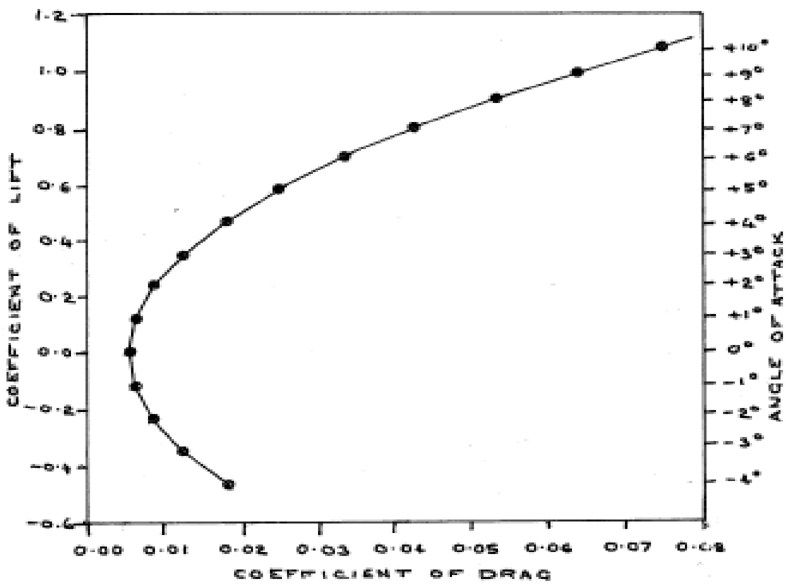
The configuration of the three inverted-T hydrofoils is similar to that of George Chapman's *Ceres* described in Catalyst No 10, October 2002. The calculations of the expected drag of the hydrofoil suspension system are based on information gleaned from his excellent article.

The definitive formula for calculating the drag force is:

$$F_d = ½ \rho C_d A V^2$$

If the unit are in feet, pounds and seconds, and the medium is water, ½ ρ / g approximates to ½.64/32 = 1, so a quick estimate of the force can be got from: $F_d = C_d A V^2$. Similarly the lift force is estimated by: $F_l = C_l A V^2$.

The same formulae apply to aerofoils, except that the force must be divided by 880 to reflect the lower density of air relative to water.



Cl and *Cd* are the Coefficients of Lift and Drag. These are values that apply to a hydrofoil of a particular shape and cannot be readily calculated. They are usually determined empirically from test data. The graph in Fig 1, derived from George Chapman's article, is an example of the lift / drag function of a typical hydrofoil.

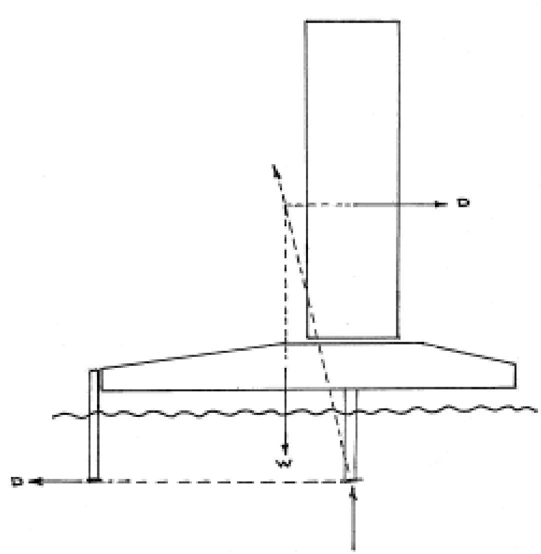
The graph indicates that the coefficient of lift is roughly proportional to the angle of attack, at least in the range -4° to +10°. This curve is for a symmetrical foil with a 6:1 aspect ratio. The coefficient of drag consists of two parts: the incidental drag, approximately proportional to the square of the angle of attack, and the form drag which is a constant equal to about 0.005 in this example.

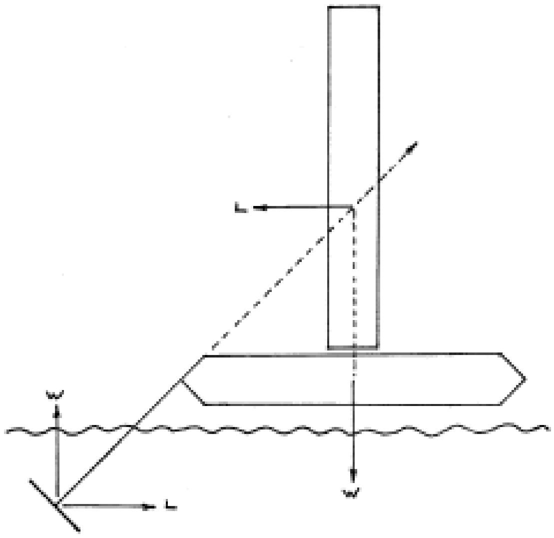
At low speeds, most of the drag is the incidental drag; so increasing the area will reduce the angle of attack, which will result in a net reduction of drag force. At high speeds however, the angle of attack required to provide the lift becomes very small so the coefficient of drag is close to the constant form drag and is almost independent of the coefficient of lift. The form drag seems to be mainly a function of the span and the thickness of the foil. This suggests that, at high speed, a low aspect ratio foil would have a lower coefficient of drag. However, in calculating the drag of the whole suspension system, the form drag of the hydrofoil struts and the rudder must be included even though they may be exerting very little lift.

The critical design challenge is to find a hydrofoil size and shape which has the lowest possible coefficient of drag at maximum speed while having a sufficiently high coefficient of lift to support the craft at lift-off speed.

Longitudinal Forces and Pitch Moments

Referring to Fig 2 below, at any steady speed, the drive force *D* must equal the drag force. However, the drive force acts at the height of the centre of effort of the wing, whereas the drag force is at the level of the hydrofoils. There is, therefore, a forward pitching moment tending to drive the bow down. To balance this moment, the centre of lift of the main hydrofoils is located forward of the centre of gravity of the craft. If, for example, the drive force is one quarter of the weight, then the horizontal displacement of the centre of lift from the centre of gravity must be one quarter of the vertical displacement of the drive force from the drag force. These displacements may not be variable, so either the drive force has to be adjusted to maintain pitch balance or the pitch of the tail hydrofoil must be trimmed to exert a correcting moment.





square of the velocity. It can be shown that, when the aerodynamic parameters are fixed, the drive force varies *inversely* as the square of the velocity. The various parameters must be chosen so that, at maximum velocity, any variation of one parameter would result in a net reduction of drive force relative to drag force. Otherwise, the velocity could be increased and the assumed "maximum" would not be valid. Without knowing the maximum velocity in advance, it is difficult to choose the optimum design parameters. However, many of the trade-offs are ratios such as lift/drag or lateral/drive. It is reasonable to assume that optimum performance will be achieved when none of the factors is significantly worse than the others. It will therefore be assumed that there is one target factor that applies to several of the critical design choices. This target factor, which I will call the Jefferson Factor, is the basis of the design of the proposed speedsailer. It is approximately equal to the ratio of maximum craft speed to true wind speed.

Lateral Forces and Roll Moments

When the craft is sailing faster than the true wind speed, the lateral force on the wing is greater than the forward drive force. This lateral force *L* must be opposed by an equal horizontal force on the hydrofoil system. The hydrofoils must, therefore, not only provide a lift force equal to the weight of the craft *W*, but also a horizontal force *L*. It can be shown that, for optimum efficiency, L and *W* should be about equal. In Figure 3, the hydrofoil system is represented by a single hydrofoil inclined at 45°. It is mounted so that a line drawn perpendicular to the foil through its centre passes through the centre of effort of the wing. In this simplified configuration, it is clear that, if the lateral force is adjusted to equal the weight, then there will be no net heeling moment. In practice, the lateral force is variable so either the centre of gravity must be shifted inboard or outboard, or the effective inclination of the hydrofoil must be adjusted.

Development of Design Parameters

The ultimate speed of a speedsailer depends on the choice of several parameters: the lift/drag ratio of the hydrofoils, the area of the hydrofoils relative to the weight, the lateral force relative to the weight, the drive force of the wing relative to the lateral force, the area of the wing relative to the lateral force, and so on. All these parameters are functions of the speed of the craft. When the hydrodynamic parameters are fixed, the drag force rises as the

The Jefferson Factor

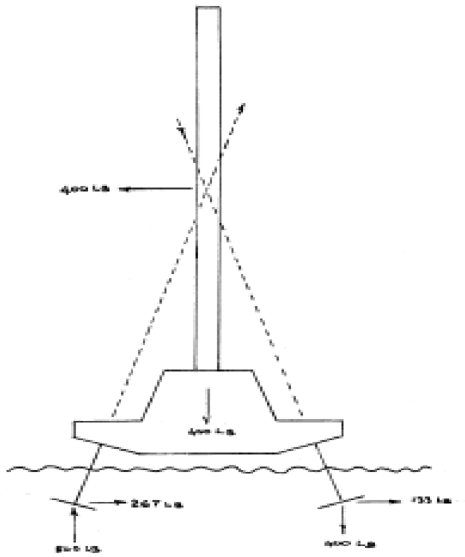
The parameter which is probably the most difficult to improve is the coefficient of drag of the hydrofoil system. If this is the most critical parameter, it would be useful to know how the Jefferson Factor *J* is related to the coefficient of lift. My intuitive hypothesis is that:

$$J = Cd^{-4}$$

This seems to make sense when applied to a practical design. I leave it as a challenge to better mathematicians than I to prove this hypothesis.

The first step in developing the design parameters is to decide on the lowest reasonable Coefficient of Drag. In figure 1, the minimum *Cd* is about 0.005. Assuming that this can be improved somewhat by, for example, reducing the aspect ratio, we will chose a value of 0.004. The fourth root of this is 0.25, hence the $J = 4$.

If the design is based on this factor it follows that the Coefficient of Drag of the hydrofoil system must not exceed 0.004. If the parameters are optimized for a 20 knot true wind speed, and the



craft speed/wind speed ratio is equal to *J* then it follows that the design craft speed will be 20 x 4 = 80 knots (135 ft/sec). If the craft is assumed to weigh 400 lb and the lift/drag ratio of the hydrofoils is equal to the *J* then the drag force *D* is 400 / 4 = 100 lb. If this drag force equals Cd $A\ V^2$, then A = 100 / 0.004 x 135 x 135 = 1.37 sq ft. This area is the effective area of all the drag inducing surfaces including hydrofoils, struts and rudder.

Dihedral

If the lateral force on the wing is four times the drive force and the drive force equals the drag force of 100 lb, it follows that the lateral force must be 400 lb. In figure 3, we showed a single foil inclined at 45°, which would ensure that the lateral and weight forces were equal. However, this is not a very practical configuration. In practice, the craft will have oppositely inclined hydrofoils on either sides, (Fig 4) similar to aircraft wings with dihedral. These hydrofoils each have a vertical and horizontal component of their "lift". The sum of the vertical components must equal the 400 lb weight of the craft, and the difference of horizontal components must equal the 400lb lateral force. The optimum dihedral angle seems to be about 18° so that the vertical component is 3 times the lateral component. If the vertical lift of the lee foil is 800 lb the lateral force will be 267 lb. If the windward foil has a vertical downward force of 400 lb, the lateral force (to windward) will be 133 lb. Thus the net lift force is 800 - 400 = 400 lb and the net lateral force is 267 + 133 = 400 lb. This meets the requirement the lateral force equals the weight.

Coefficient of Lift

In the example above, the lee hydrofoil has the highest loading. The lift force is about 800 lb and the area is about 0.5 sq ft. Hence: Cl = 800 / 0.5 x 135^2 = 0.09. According to figure 1, this represents an angle of attack of only about 1°. When the angle of attack is this small, variations in *Cl* have little effect on *Cd*. What this is saying is that the hydrofoils will be very thin and at 80 knots they can provide all the lift needed without significantly increasing the drag.

Wing Area

The lateral "lift" force of the wing at 80 knots is 400 lb. Hence for the wing:

$$Cl\ A = 880 \times 400 / 135^2 = 19.$$

If it is assumed that the optimum value of *Cl* is about 0.3, then the wing area would be 19 / 0.3 = 63 sq ft. The angle of attack is only about 2°. If the drive/lateral factor is equal to *J*, then the angle of the apparent wind is $\tan^{-1}$ 0.25, which is about 14°. The angle of attack is a small proportion of this, so the assumed value of *Cl* is justified. The conclusion is that a wing area of about 60 square feet is reasonable, but it is not too critical.

Summary of Design Parameters

Craft Speed	135 ft / sec (80 knots)
True Wind Speed	34 ft / sec (20 knots)
Gross Weight of Craft	400 lb
Wing Area	60 sq ft
Wing Lift Force	400 lb
Coefficient of Lift (Wing)	0.3
Loading (Wing)	6.7 lb / sq ft
Hydrofoil Area	1.4 sq ft
Coefficient of Drag (Hydrofoils)	0.004
Dihedral Angle	18°
Loading (Lee Hydrofoil)	1600 lb / sq ft

A Practical Design

Based on the design parameters established above, a practical speedsailer can be designed. The aerodynamic, above surface, part of the craft will resemble a light aircraft except that the wing is mounted vertically above the fuselage. At high speeds, the wing is fixed on the centreline of the fuselage so the angle of attack is controlled by steering the whole craft almost into the apparent wind. To set the craft to follow the desired track, that is, to go in the right direction, the craft makes the appropriate angle of sideslip or "leeway". This may seem strange to conventional dinghy sailors who are used to the idea that, relative to the hull, the centreboard is fixed and the sail angle varies. In a speedsailer, sailing at many times the true wind speed, it makes more sense to keep the wing fixed and, in effect, vary the centreboard angle. The fuselage is, after all, part of the aerodynamic system, not the hydrodynamic system. In fact, the wing and the fuselage together form an aerofoil, which may be called a "Sailing Wing" analogous to a "Flying Wing" aircraft.

Two inverted-T hydrofoil assemblies are mounted below the fuselage on either side. They are set with a dihedral angle of about 18° and placed far enough apart so that lines extended from the struts intersect at the height of the centre of effort of the wing. This ensures that there is no net heeling moment and the pilot can sit in the centre of the fuselage.

To keep the craft level, at the right altitude and flying in the right direction, the pilot must simultaneously control the angle of attack of the three hydrofoils and the three struts. A simple and efficient system of accomplishing this has been designed. The pilot flies the craft in much the same way as flying a light aircraft. He steers the craft with a rudder bar connected to the tail inverted-T hydrofoil. The vertical strut of this assembly forms a conventional rudder. He would use a control column to keep the craft flying level at correct altitude, with the fuselage just touching the wave tops.

The Prototype

A simplified prototype of the design has been under construction for some time, and is now almost complete. Its purpose is to serve as a test bed to prove the principles described above. However, although it is not expected to beat any speedsailing records, it probably will beat other comparable sailcraft. It would also be economical to build and simple to transport, launch and fly. The prototype has the following features:

Length	10 ft
Gross Weight	300 lb
Wing Area	20 sq ft
Hydrofoil Area	3.5 sq ft

The craft was designed to lift-off in a 15 knot (25 ft/sec) wind. If we assume that the wing is set abeam and the wind is about 20° abaft of the beam, the coefficient of lift of the wing is about 2.1 and the wing drive force, acting directly ahead, is: $2.1 \times 20 \times 25^2 / 880 = 30$ lb.

If the target lift-off speed is 5.5 knots (9.3 ft/sec), and the hydrofoil lift equals the craft weight, then the coefficient of lift of the hydrofoils must be: $300 / 3.5 \times 9.3^2 = 1.0$. At this coefficient of lift, the lift to drag ratio will be about 12, so the drag will be about $300 / 12 = 25$ lb. Thus the drive exceeds the drag and the craft should take off under these conditions.

The prototype is pitch balanced for a drive force of 30 lb at all speeds. There is no control over the tail foil pitch angle. At 30 knots (50 ft/sec), if the drag has risen to 30 lb, the coefficient of drag is: $30 / 3.5 \times 50^2 = 0.0034$. This is probably the limiting factor. The lowest value of *Cd* shown on figure 1 is about 0.005 but this is for a foil with an aspect ratio of 6. The prototype foils have an aspect ratio of about 2 which should give a lower value of *Cd*.

If the craft is flying at 30 knots in a 15 knot true wind abeam, it is flying at twice the wind speed. The wing will be trimmed to an angle of about 27° so the lateral component of the wing lift is twice the forward drive component. Hence, the lateral force will be about 60 lb. If the centre of effort of the wing is 7.5 feet above the lateral centre of effort of the hydrofoil struts, then the heeling moment is 450 lb ft. The pilot, weighing 150 lb, can counteract this heeling moment by sitting 3.0 ft to windward.

The wing is about 7.5 ft high by 2.7 ft wide and pivots on a tabernacle so that it can easily be stepped or un-stepped. The clew of the wing is conveniently close to the pilot's hand so that he can control the wing by a short "main sheet" connected directly to the clew. The wing is balanced so that there is not too much tension on the main sheet.

The hydrofoil assemblies are mounted in trunks so that they can easily be retracted. When retracted, they are above the lowest part of the hull so the craft can be beached without damaging the foils. When in deep enough water, about three feet, they are simply pushed down and locked in the deployed position.

Conclusions

The design of a speedsailer involves several trade-offs. The hydrofoil area must be large enough to keep the incidental drag low, but small enough to minimize the form drag. The area of the wing must be large to give the maximum drive, but not at the expense of excessive lateral force which would increase the foil drag. These are related to the choice of weight/drag ratio and lateral/drive ratio.

In juggling these parameters, the optimum is achieved when all the factors become critical at the maximum speed. It seems that, for a practical design, this occurs at a speed of about 80 knots. Any attempt to improve one factor has an adverse effect on other factors, so there is little or no advantage.

There is some scope for optimizing the design of the hydrofoils for low drag at 80 knots but this is ultimately limited by the drag of the struts, which cannot be eliminated. Even if the coefficient drag could be substantially reduced, it would only gain a few knots since other factors such as the drive force are also reduced at the higher speed. However, in competing for the World Sailing Speed Record, a few knots may make all the difference.

The prototype design represents a simple economical craft which will be relatively easy to transport, launch and fly. It will perform well in a moderate wind and should reach speeds of about 30 knots which, if not record beating, will be very exciting. It is expected that craft of this type would compete at speedsailing events, racing against the clock over a 500 meter course. Round-the-buoys racing would probably be too dangerous.

The hull or "platform" would be standardized but the owners could design their own hydrofoil assemblies which would fit the standard trunks. The owners could also design their own wings, which would mount on the standard pivot.

The development of this prototype could lead to popularization of the sport of speedsailing, with the formation of speedsailing clubs and an increase in the popularity of speedsailing events such as Weymouth Speedweek.

Peter Jefferson
May 2004

An Autonomous Wing-Sailed Catamaran - Construction of the Wingsail

Gabriel H. Elkaim
Ph.D.Thesis

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

This presentation details [some of the work on] 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 wing-sail mounted vertically on bearings, mass balanced to 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.

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. [The analysis carried out for the Atlantis project showed that this was not necessarily so, and that adequate performance could be achieved by a symmetrical wingsail.] The design choices for the wingsail were presented in a previous article. This article describes the sail construction.

STRUCTURAL DESIGN

The structural analysis presented in the previous section has already demonstrated the type of structure modelled. The actual structural design is very close to that of the design analyzed. The stub mast is secured to the cross-beam through a ball and socket joint, thus rendering the idealized version more complex than the actual one. This was done in order to simplify the attachment process of the mast onto the boat since no welding would be required.

The cable stays were replaced by 6061 aluminum straps that are 2.5 centimeters wide by 9 millimeters thick. This is excessive in terms of strict structural requirements, but they have been repeatedly used as step ladders and hand-holds to maneuver the catamaran while on land and have a very small weight penalty.

The stub mast is standard 6061 aluminum pipe, 11.36 centimeters in diameter with a 9 millimeter wall thickness. Again, this is unnecessarily robust, but the difference in weight was small and since a structural failure would likely have brought all progress to a halt, the decision was made to be conservative. The lower bearing is a simple press fit onto the stub mast; even though the internal diameter of the bearing is the same as the outer diameter of the stub mast, the bearing race required a strong press to slide it into place due to the eccentricity of the stub mast.

Atop the stub mast are the two spherical roller bearings placed to cage the wing onto the stub mast. Also, the Mercotac slip ring is there with four conductors (power, ground, and the two differential signaling wires) coming out of the stub-mast and looping down into the structure of the lower wing section. The wing section has a pod containing the batteries, ballast, and electronics. This forward pod is used to bring the mass of the entire wing sail and tail assembly in line with the wing quarter chord and bearings. The wing is built in three sections, each connected by two aluminum tongue and groove joints and secured with stainless steel bolts on either side of the spar caps. While these are sufficiently strong in bending loads across the thickness of the wing, they proved to act as hinges for the in-plane fore and aft loads of the wing. While the prototype was able to sail even with this handicap, future versions will require a better method for joining the wing sections in order to make the entire structure more robust.

The wing and tail are made entirely out of plywood, blue foam, and polyester covering. The wing ribs, spar sheer webs, spar caps, and leading and trailing edge sections of the wing are made out of wood, and the whole thing is covered with polyester cloth that is heat shrunk for a tight fit. The total weight of the complete wing and tail section is 70 kilograms without the ballast weight. The stub-mast and wing spar were tested with a dummy load of 72 kilograms as a point load at the end of the wing and found to withstand that bending load with no damage.

CONSTRUCTION

Essentially, this section is a pictorial representation of some of the steps taken while constructing the wing. The wing was built by Cris Hawkins Consulting in Santa Rosa, California, over a time period of approximately nine months. This construction included the attachment of the stub mast to the cross beam, creation of the wing sections and tail sections, and the fabrication and installation of the actuators and pushrods.

Figure 5-40 shows the lower bearing surface and the attachment plate for the top of the 6061 aluminum stringers that replace the stainless steel guy wires on the original construction. These stringers, attached to the mounting plate using stainless steel bolts, are bolted onto hard points of the hulls. The stub mast is shown with the inner part of the needle roller bearing pressed into position above the stub mast collar to which the aluminum straps (spider) attach.

Figure 5-43 shows the stub mast load test, using a dummy point load of 72 kilograms. The stub mast is secured to a replacement cross beam and has two of the six spider legs attached to the collar. Careful analysis of the load test video showed that the deflection of the stub mast under load test was, in fact, caused by deflection of the wooden building column that was used to secure the cross beam in place. Both of the spherical roller bearings are secured in position on top of the stub mast. This can be seen next to the dummy load's hands. The dummy load was increased to a 153 kilogram point load on the end and the deflection remained undetectable after the deflection of the wooden column was accounted for in the measurements. This did, however, cause some concern about the stability of the building during the load test, but the roof remained in the appropriate position.

Figure 5-40 Stub mast, inner bearing surface for needle roller bearing, and stub mast collar for attachment of the aluminum spider. The lower needle roller bearings roll on the surface just above the collar. The collar is used to secure the 6061 aluminum straps (instead of stainless steel guy wires) that support the stub-mast and wing.

Figure 5-44 shows the master wing rib jig. This is milled from a high density plastic using a computer controlled milling machine that is programmed from the points generated from the XFOIL program. This pattern is used to route out all of the main wing ribs and ensure dimensional accuracies are kept throughout the construction. The main wing ribs were cut from marine grade plywood. There are several interesting features of the jig that can be noted in the picture. Circular holes in the front and back of the rib are used to assemble cut ribs onto a jig made from electrical conduit. The eleven smaller holes are for threaded rods to hold the stack of plywood sheets together, thus ensuring uniformity of fabrication. The notches in the top and bottom are for the spar caps, and the lightening holes in the forward and rear center are to reduce weight.

Figure 5-43 Stub mast, two spider legs, and cross beam load tested with a 72 kilogram static dummy load. The stub-mast is attached to a replacement crossbeam that is secured to a wooden column supporting the building. The two spider legs are secured to the crossbeam. Close inspection of the figure shows the two spherical roller bearings at the end of the stub-mast. No deflection occurred in the stub-mast, though the wooden column was deflected under the test load.

Figure 5-45 shows the ribs aligned on the jig, with the spar caps glued in place; the large front doubler ribs are for the electronics pod and counter weights, the use of PVC pipe spacers is to ensure the uniform spacing of the wing ribs. In the foreground is the lower wing section. In the back, the center section of the wing can be seen, also with the spar caps gluing in place. All joints are glued with epoxy to ensure maximum joint strength. Epoxy has the added advantage that it will not spontaneously disassemble due to increased moisture or direct immersion in water. Close inspection of Figure 5-45 reveals a hole pattern at the top of the lower wing section spar cap. This is where the two 6061 aluminum 3/8” thick plates will be attached to either side of the spar cap and be used as the slot for a mortise and tenon joint. This joint uses a 5/8” thick 6061 aluminum tongue attached to the bottom of the center section spar caps. This functions not as a draw bar mortise and tenon joint, but rather a plain mortise and tenon in which the wedge is replaced by two stainless steel bolts on either side of the wing. The inside 6061 aluminum plate is tapped for the

Figure 5-44 Master main wing rib template used to fabricate all wing ribs from marine grade plywood. The large holes are to lighten the ribs. The two medium sized holes forward and back are for a assembly onto a jib made of electrical conduit. The eleven small holes are for threaded rods that secure the stack of plywood together to ensure uniform fabrication.

right threads. Though overtightening is an issue, as long as the bolts are tightened to the right torque, they will hold the sections together easily.

Figure 5-46 shows the leading edge skin being glued onto the ribs to form the front "D" tube assembly. This "D" tube resists the torsional loads imposed by the lift and flap on the wing section and keeps it from twisting. Severe problems with cracking of the leading edge wing skins were encountered while attempting to secure the leading edge skins. Soaking in water only resulted in the outer layers of the marine plywood absorbing water and proved unsuccessful. The solution is to thin the leading edge to half its original thickness at the location of the maximum curvature, and then soak the plywood in water. In retrospect, it would have been wise to reinforce this thinned leading edge with fiberglass and epoxy from the inside before the shear webs were glued between the spar caps. The leading edge proved to be an extremely delicate area of the finished wing. Great care had to be taken to avoid cracking the leading edge and the wing sections could never be allowed to support their weight on the leading edge.

Figure 5-45 Main wing ribs on jib, spar caps, and pod ribs extending forward on lower wing section. The forward pod ribs are double thickness plywood, and the PVC pipe spacers ensure uniformity in the rib spacing. The spar caps are glued in place with epoxy. The top of the spar caps has been drilled for the aluminum mortise and tenon joint that holds the wing sections together. The three sections will be held together with stainless steel bolts at the joints.

Figure 5-47 shows the sheer webs, looking inside the wing. The sheer webs are made out of the same marine plywood as that of the wing ribs. Lightening holes can be seen cut out of the sheer webs as well as the gap between the spar caps and the sheer web. The gap is required only on the lower section in order to clear the lower bearing and stub mast, which rises up through the center of the hole cut out of the main wing ribs. In order to make up for the distance between the spar caps and the sheer web, the spar cap on the lower wing section is extended back to butt up against the sheer web, and is glued with epoxy and fiberglass to the ribs, sheer web, and wing ribs. This is necessary because the sheer webs were found to buckle, with the center narrowed section of the sheer web twisting into a potato-chip-like shape when the entire wing assembly was subjected to a 72 kilogram dummy point load on the end. The shear webs on the lower section were made solid (no lightening holes) and were increased to 5/8" thickness from the nominal 1/4" plywood that was used on the rest of the sheer webs.

Figure 5-46 Plywood leading edge skin glued to wing ribs. The wing skins suffered severe cracking problems when bent around the leading edge. In order to accommodate the sharp radius of curvature, the wing skins were thinned and soaked in water before gluing them on to the ribs to form the forward "D" tube. This area remained weak and prone to damage in the finished wing structure.

Figure 5-48 shows the three sections of the wing assembled for the final load test before covering. The ladder in the foreground is not actually supporting the wing at all, but is there to prevent the trailing edge from rotating downwards, as the connection between the stub mast and the wing spar is through bearings, and is designed to allow the wing to rotate freely about the axis down the center of the wing spar. At the front of the lower section is the pod for the electronics and counter weight ballast, with the lid removed. The upper flap actuator is visible on the fifth rib down from the top of the wing. The load test was conducted by placing the same 72 kilogram dummy load on the end of the wing, and resulted in the reinforcement of the bottom section sheer webs. Following the reinforcement, a 72 kilogram dummy load was again placed on the end of the wing, simulating 70% of the maximum loading scenario. This resulted in a 15 centimeter deflection at the end of the wing, though most of this was due to the wooden column support of the building deflecting as well as the cross beam pulling off its mounting. The residual deflection was about 5 centimeters.

Figure 5-47 Plywood sheer webs join the leading edge skin and upper and lower spar caps. Lightening holes are cut in the sheer webs. Note the distance between the rear of the spar cap and the sheer web. This is because this is the lower section, and the stub-mast will fit just inside the circular opening in the rib. After the load test, the spar cap was extended back to the sheer web and the sheer web reinforced with thicker plywood.

The anti-drag bracing can be seen diagonally bracing the top to third rib. These anti-drag braces give the wing strength when bending in the plane of the wing (in this picture, pulling the top of the wing to the right horizontally). The three sections are pinned together using the mortise and tenon joints, as previously explained. There is no connection of the three sections at the trailing edge. This later proved to be a weakness in the design, as the mortise and tenon joints act as hinges during high velocity pitch motions of the wing (as when crossing through waves). These effectively allow the three sections to open up like a fan and then come crashing back together, damaging the lower trailing edge structure. A simple method of joining the trailing edge together would mitigate this problem and cause the entire wing to behave in a rigid fashion when pitching front to back. The wing is covered with "Coverite," a thick polyester fabric normally used for model airplanes. The fabric is coated on one side with a heat activated glue and with chemical

Figure 5-48 The final wing assembly setup for load testing, before covering. The ladder is only supporting the rear edge of the wing from rotating downwards (as the wing is attached to the stubmast via bearings). The diagonal internal brace just above the ladder is the anti-drag bracing. A 72 kg load was suspended from the end of the wing, and the deflection was recorded to be approximately 15 cm. After corrections were made, the residual deflection was 5 cm.

resistant paint on the other. The covering is resistant to water, salt water, oil, alcohol and gasoline.

Figure 5-49 shows Cris Hawkins of Cris Hawkins Consulting shrinking the covering onto the upper wing section. The concavity of the main wing section requires that the covering be firmly glued onto each rib cap before the final shrinking can take place. Furthermore, great care has to be taken in order to keep the hot, pliable polyester fabric from detaching from the rib cap while the covering cools into position. This is accomplished by the use of cooling pads that keep the sections of the covering directly above the rib cap from reaching a temperature sufficient to allow the glue bond to lose its strength. The same covering is used to make the hinges for the trailing edge flaps. These are so called figure eight fabric hinges which allow the flap to deflect through a 180 degree arc without imposing any moment on the surface itself. Another benefit of these hinges is that they effectively seal the gap between the trailing edge of the main wing section and the flap itself. Figure 5-50 shows the lower section trailing edge flap.

Figure 5-49 Coverite polyester fabric is used to cover the wooden wing structure. Cris Hawkins of Cris Hawkins consulting applies heat to shrink the fabric onto the ribs. The covering is oil, gasoline, and salt-water resistant. In order to prevent the fabric from pulling off the ribs on the rear section of the airfoil, the fabric was glued down to the ribs during the shrinking process through a process of applying pressure while the coverite was allowed to cool.

With the wing sections built, and covered, the next task is to install all of the electronics and wiring, as well as some extra sealed flotation balloons in case of a capsize. With this accomplished, the entire wing sail and tail assembly is very tail heavy. This is to be expected as the entirety of the mass of the booms and tail are very far behind the main wing quarter chord line. In order to bring the center of mass of the entire wing sail and tail assembly in line with the quarter chord, each section is weighed, and the center of gravity position noted relative to a reference at the quarter chord center. This allows the correct ballast position to be computed and the ballast to be added to the electronics pod. In order to correctly balance the wing on the quarter chord, a 25 kilogram battery is placed into the pod, as well as a 12.7 kilogram lead brick. Figure 5-51 shows the interior of the pod.

The breakdown for the weight and balance of the wing sections is summarized in Table 5-1 below:

Figure 5-50 main wing trailing edge flap with pushrod, control horn, and fabric hinge. The figure 8 hinge is made from the same covering material that covers the wing. The advantage of this kind of hinge is that there is very little hinge friction. Additionally, the hinge seals the gap between the flap and main section, while at the same time allowing a large range of motion.

This leads to a total weight for the wing of 108.61 kilograms and a nominal offset of -2.0 centimeters, slightly nose heavy. This configuration allows the wing to point away from the wind in an upwind heel, reducing lift and stabilizing the sailboat. With the construction of the wing complete, the propulsion system of the Atlantis has been described in detail.

The wing, spider, and hulls can be seen in Figure 5-52 which shows the entire system during a final system check. This is a composite image, and there are no sharp discontinuities in either the wing or the hulls

Figure 5-51 Electronics pod, showing the battery and ballast weight. Inside the pod is the main battery, secured by two threaded stainless steel rods. The black material is neoprene for cushioning the electronics. Forward of the battery is a 12.7 kg lead brick that is used to mass balance the wing. The wires lead to the main bus breaker on the side of the electronics pod. The ribbon cable joins the can bus and the anemometer microcontroller which is secured to the underside of the pod lid.

Future Work: Experimental Measurement of the Wing Sail Performance

Given the amount of analysis that went into designing the wing sail section, verifying the performance under sail would validate the CFD codes and design methodology. There are a number of ways in which this could be accomplished, either by using strain gauges or by generating high accuracy drag polars of the hulls from towing tests.

Obviously, the entire wing could be placed in a wind tunnel as well, though the costs would most likely be prohibitive. Several methods have been published on how to generate accurate drag polars of the hulls using towing tests [28]. Note that several other attempts to measure the performance of an actual sailing wing have met with much difficulty and little success [8]. Both of these methods required that the measurements of a strain gauge or scale be estimated on-the-fly by a human observer. Modern electronic recording equipment eliminates these obstacles, and better estimation techniques should be able to generate a high confidence estimate of the parameters in question.

Future Ocean Crossing

With the improvements to the control system, user interface, wing structural robustness, and on board power generation, the Atlantis becomes capable of self-sufficient crossings of large bodies of water. After several shakedown cruises of longer and longer lengths, it becomes conceivable to attempt a very long crossing, such as the trip between San Francisco and Honolulu. With that crossing, the viability of the concept will truly be established.

Dr Gabriel Elkaim
<http://www.soe.ucsc.edu/~elkaim/>

Section	Mass (kg)	Distance aft (cm)
Lower wing section	26.81	1.3
Center wing and tail	29.10	53.6
Upper wing	14.55	15.9
Battery	25.00	-42.6
Ballast	12.70	-59.7
All Sections	108.61	-2.0

Table 5-1: The breakdown for weight and balance of the wingsail sections. The mass of each section was measured with a spring scale and the distances using a two-point suspension method to mark the center of gravity. The net result is a very nearly mass balanced wingsail that exhibits no tendencies to rotate when pitched or rolled.

References

[8] Baker, R.M., *Tests of a Rigid-Airfoil Sails using a shore-based test stand*, The Ancient Interface IX, Proceedings of the Ninth AIAA Symposium on the Aer/Hydronautics of Sailing, AIAA Lecture Series, Vol. 23, AIAA Pamona, 1979. Pages 25-60.

[[28] Bradfield, W. S., *Predicted and Measured Performance of a Daysailing Catamaran*, Marine Technology, January 1970. Pages 21-37.

Figure 5-52 Final Atlantis wing, with spider below and electronics pod. This is a composite image made up of several photographs of the Atlantis taken inside the HEPL high bay entrance. The entire system was assembled inside of a hangar in order to perform a final system check before performing the water trials. The clearance between the top of the wingsail and the roof of the hangar is approximately 12 cm

The Application of Soft Wing Sails to Large Racing Yachts to Improve Upwind Performance.

Philip R. Eltringham

Abstract

Conventional single layer sails have developed greatly in recent years and now are able to get around many of the problems they once encountered, but, is it still possible to produce a two layer sail that will be overall more efficient than the new breed of single layer sails? The idea of a two layer sail is to remove the turbulent flow around the leading edge and produce a section nearer that of an aircraft's wing, which has less drag and more thrust for a given size of airfoil. Previously it has been believed that the increase in mass involved with these sails would negate the increase in performance they offer. This dissertation will hope to prove that two-layer sails still offer superior performance over existing technology.

Introduction

Sails are airfoils, like aircraft wings, they work in the same way and obey the same rules of fluid dynamics. Therefore the same sorts of designs that work for aircraft wings should work for sails. However sails have one additional problem, in that they must be reversible, in that they need to produce lift with either side 'to windward'.

Until the middle of last century this had only been achieved by way of a single panel of sail material that could fill with either side to windward. This is fairly efficient (especially in light winds) but has high drag especially around the leading edge. During the 1960's with the advent of the windsurfer and thus sailing at substantially faster speeds, ways were found to reduce the drag of sails and increase efficiency. One idea was to find a way of making the sail's cross section more like that of an aircraft's wing, with two layers of material separated so that the sail had an airfoil section. Windsurfers experimented with this but found that because the all up weight of the craft was so small the increase in weight due to the more complex sail was not countered by the increase in performance. The reason for this was that the main component of drag on a windsurfer was the helm's body and at the high wind speeds at which windsurfers operated a single layer sail was found to be efficient enough. This makes sense, as extensive research in the aeronautics industry has found that as flow over a foil increases in speed, the most efficient section is one that has a smaller thickness in relation to its chord length. So at the speeds the windsurfers were reaching a cambered single surface sail was close enough to the most efficient section and once weight was taken into account it became the most efficient solution and so research in the area of 'wing sails' was abandoned.

Meanwhile the idea of airfoil-sectioned sails was also being trialled on small boats. The best example of this is the rigs used in the Little Americas Cup competition racing C-Class catamarans in the 70's and 80's. These used rigid wing sails extensively and some research was done into design of such rigs, however they proved very difficult to control and now the competition is sailed in the Formula 18HT class of catamaran.

The next step was to find a way of making the sail have an asymmetric section on both tacks so that maximum efficiency would be available all the time. This could be achieved by having two parallel panels of sail material, in essence a 'soft wing sail'. This was tried briefly on the C-Class cats and some development has been done in development dinghy classes but as many rules forbid the use of 'double luff' sails this has never been very serious. Having spoken to class associations about that point it turns out that the reason for the banning of such sails is that they have been perceived to be prohibitively expensive and as such were prevented as a way of keeping costs down. The only dinghy class that I know of which has not yet prevented the use of wing sails is the 11 foot International Moth class, but here the current avenue of development is the use of hydrofoils. This could either provide the perfect platform for the use of wing sails or the death of them if the same problems are encountered here as with windsurfers using this technology.

The last 15 to 20 years have seen soft wing sails being tested on dinghies and yachts up to around 25' in length, but nothing much larger. Also the use of wing masts has become popular as a way of reducing drag at the join of sail and mast; however these cannot be 'turned off' and are dangerous in high winds. A 'wing sail' allows for a more conventional mast section and as such less 'windage' when the sail is removed, thus making for a safer situation in strong conditions.

I believe that larger vessels have the biggest potential for the application of the soft wing sail. This is because larger vessels are less sensitive to mass increases and also the larger sail area involved should allow for even greater gains.

Existing Knowledge

Single Layer Sails

Before any work is begun on trying to improve something it is necessary to understand existing technology and why things are as they are. To this end some of the important details in the design and use of single surface sails will be discussed here.

Sails are lifting surfaces that operate at low speeds and high Reynolds's numbers; they also operate at high angles of attack. The lift they produce is a result of the pressure difference across the sail. This is due to the different speeds of the flow on each side of the sail. On the windward side the flow is slower, giving high pressure, and on the leeward side the flow is faster; this gives a lower pressure. Contrary to popular belief the majority of the force produced is actually due to the suction force of the leeward side of the sail rather than the high pressure on the windward side. In reality the pressure increase on the windward side is almost zero, except for very close to the leading edge (stagnation point). The resulting difference in pressure gives a lift force from the sail. On a yacht rig upwind there are usually two sails, the main and the foresail; they work together as a single lifting body to propel the yacht. This can be best illustrated by looking at the sheeting angle of mainsails on single- and two-sailed boats upwind. On single-sail boats the main is sheeted at an angle of around 15-20º to the centreline, whereas on a two-sail boat the mainsail is sheeted to the centreline of the boat due to the way the flow of air on it is changed by the presence of the foresail.

There are many different types of foresail depending on wind strength and the angle that will be sailed to the wind. These arrange from reaching headsails and Code 0's (which tend to be used in lighter winds and at broader angles) to storm jibs (for the heaviest conditions). Cruising yachts tend to save effort by having a single sail which roller-reefs around the forestay. Racing yachts, on the other hand, have different sails for different conditions, so that the sail that is set always has the correct shape. It is unlikely that a wing sail such as I am proposing will be easy to roller-reef, to that end I will be concentrating on a sail that does not reef, as it removes one problem from the list.

Mainsails in comparison tend not to have as much variety, it is more usual simply to allow the main to be reefed as opposed to carrying several different sails. The effect of the foresail is to make the airflow from its trailing edge try to go around the windward side of the main, resulting in a vastly different angle of the air flow on to the main. This means that the main is now sheeted a lot closer to the centreline of the boat than if it were alone.

Below are some images of the flow around single layer sails. These show where the inefficiencies occur with this type of sail and thus where improvements to the design can be placed to make the biggest gain in performance.

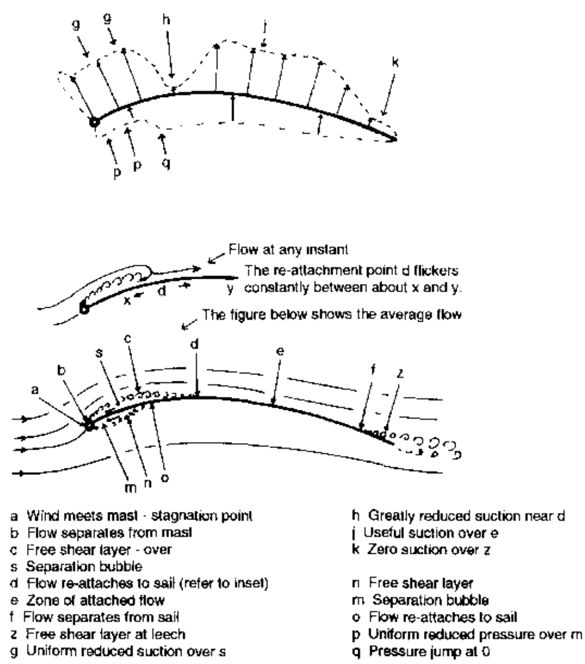


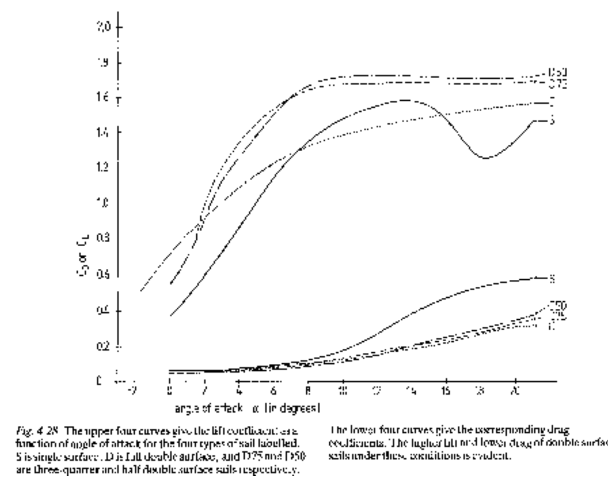
Illustration of flow around a conventional mast and sail, taken from Bethwaite Page 192

Wing Sails

The first step towards the wing sail from the conventional rig was to use a wing mast. Here the conventional circular tube section for the mast is replaced with a tube that had a symmetrical airfoil section. This had some improvement to the airflow around the leading edge of the sail. In essence it filled in the gap between the mast and sail and so there was less of a 'step' in the section and so less drag from eddies and turbulent flow. This clean up in the airflow made the sail more efficient and also 'smoother', in that it reacted better and more predictably to changing conditions Wing masts were trialled with varying sizes up to around 20% of the chord of the sail. As the percentage chord of the sail and mast that the mast made up increased so too did the efficiency, however the added mass of the rig that resulted meant that the optimum size for the mast was around 5-8% of the sail's chord. This type of arrangement was found to work best on multihull rigs, as these tended to sail at higher speeds.

The next line of research was to use a pocket luff on the sail instead of the standard boltrope configuration. This involved having a tube of material for the luff of the sail, into which the mast was slid. If this tube, or pocket, was larger than just the circumference of the mast then the extra material would form a similar section shape to that achieved with a wing mast. This is obviously much lighter, but the section is not as rigid and so not as stable. The natural progression of this was to see what percentage of the chord this pocket could be stretched to, to find its optimum.

This lead to people experimenting with the whole sail as this pocket, thus the soft wing sail was born. This design had several advantages; firstly it was substantially lighter than solid wing sails of the same size. Also as the sails were made out of conventional soft materials, they were able to have an asymmetrical section of both tacks. Solid wing sails had had symmetrical sections with the trailing edge as a trim tab, similar to those on aircraft wings, these were found to be very difficult to control and also the hinge of the tab was found to create a lot of drag. Another advantage of the soft sails was that they could be raised and lowered in a similar way to conventional sails; the solid sails could not be, and so in extreme conditions were not viable.



Graph of wind tunnel experiments into wing sail designs, taken from Garrett Page 115.

The new wing sails were found to be very efficient, with around twice the lift to drag ratio of comparable conventional sails, 1:40+ rather than 1:20. However there was still the problem of the increase in mass of these new sails. The next line of research was to see if a partial wing sail would be more efficient from a power to weight point of view. In his book, Garrett details some experiments he did to compare sections with the two layers stretching over 0, 50%, 75% and 100% of the chord of the sail [Garrett 1996]. In his experiments he found that the lift from the 50% and 75% wing sails was greater, and the drag was only marginally higher, than that of the 100% wing. The tests were done in a wind tunnel on sections where the leading edge diameter was around 7% of the chord. To ensure 2D flow, plates were placed at either end of the foil. The foil surfaces were made using 1.23 oz woven nylon cloth wrapped around the leading edge tube. The section was inflated by way of a vent on the leading edge, and the stagnation pressure within the sail envelope maintained the section. Garrett notes that, as the angle of attack increased, the section would become thinner. This he puts down to the minimal difference in pressure between the two sides of the windward layer of material.

Garrett notes that tests with less porous sailcloth materials improved the performance of all the sections. He also mentions that the substantially later stall angle of the wing sails would prove highly advantageous in light wind conditions.

One of the main drawbacks to wingsails that has constantly come up has been the increased mass of the sails. Although this could prove a problem on dinghies, it should not be as much of a worry for yachts. This is for two reasons: firstly, yachts are less sensitive to weight increases than dinghies, and, secondly, wing sails have a larger operating range of wind speeds. This could prove to be the saving point of wing sails if they are to make inroads into commercial markets. Because each sail is able to work in a far wider wind range, fewer sails need be carried on board a yacht; hence the total mass of the wing sail inventory carried by a yacht will at worst be similar, and possibly even smaller.

People who sail yachts have expressed worry about the effect of raising the centre of gravity of the yacht as a result of using heavier sails. Although this is a concern, as the static stability may be slightly worse, the vast decrease in heeling force from the sails, as a result of their shape, will more than make up for this. Boats would sail more upright with wing sails. This result could be used to increase performance in one of three ways. Firstly leaving the yacht unchanged with a straight swap to wing sails would allow it to sail with less heel, and so faster. Secondly the sails could be increased in size, if less heeling moment is being produced, which would increase performance further. The third and final change is the most radical: if less heeling moment is produced by the sails than before, a lighter keel would be needed. This decrease in the mass the sails have to propel would allow the boat to sail quicker and accelerate faster.

One final obstacle to the use of wing sails on yachts is the way in which they are handled on board. Wing sails have tended to be less flexible and so their storage has been be an issue. Secondly, wing sails for the main sail traditionally have involved wrapping material around the mast. On a rig with stays, as on a yacht, this is not easy to do. On dinghies this is not a problem as they can be capsized easily on shore to hoist the sail and attach the sail around the mast above the spreaders. On a yacht however, this is not possible, and so this leaves one of three solutions if a wing sail is to be used. The first is to hoist someone up the mast with the sail to make the attachments above the spreaders. This is not a safe option in high winds, and is not possible on some yachts. The second is to have a rig with no stays. Some research has been done into this and with new materials this is possible but success with unstayed rigs has been somewhat hit-and-miss. The final option is to try and find a way that does not need to wrap material around the mast. This has some potential, possibly by having separate outhauls for each layer of the sail. It does however create problems smoothing the join of mast and sail and of keeping a sharp trailing edge.

The other line of research, and the one which will be explored in this project, will remove the problems with the mainsail illustrated above. If the foresail is studied instead, there in no need to worry about spreaders and other rigging as all that is needed is the forestay off which the sail is hung. The other reason for concentrating on the foresail is that at the 'leading edge' of the whole rig is subject to smoother airflow (easier for modelling), and also it has a far greater effect on performance than the main. Usually around 45% of the driving forces of the rig come from the foresail, when it is usually less than 40% of the total sail area.

As the title of this project is to look at increasing performance when sailing windward a baseline is needed of a foresail designed specifically for the best possible speed to windward. The chosen baseline comes from the Americas Cup Class (A.C.C.). Here boats sail on windward/leeward courses and the foresails are only used on the windward legs. This means ideas can be tested against some of the most developed contemporary upwind foresails. Unfortunately the current A.C.C. rules ban the use of 'double luff sails', but, as a marker to work against, ACC boats provide the best option. If a sail is designed that would be significantly better than these existing sails, one could assume that the design would be an improvement over current sails for other boats as well.

Experimental Procedure & Reasoning

Basis Data

The first part of the experiments is to collect data on the existing sail so that there is something against which to compare later results. The first step towards this is to work out how big the existing sails are, and to get some idea of their shape. Here 'GBR Challenge' was very helpful. They sent a DXF file of the sail plan of the yacht from which it was able to obtain the sizes of the sails, thus allowing the models to be the correct size. They also sent a file describing the shape of the main sail when in use. This could prove useful; however it is unlikely much work will be carried out on the main as it has already determined that this research will be of more use applied to the foresail. Unfortunately a similar file was not available for the foresail, due to problems with file conversion from the software used by GBR Challenge to model the sails when in use.

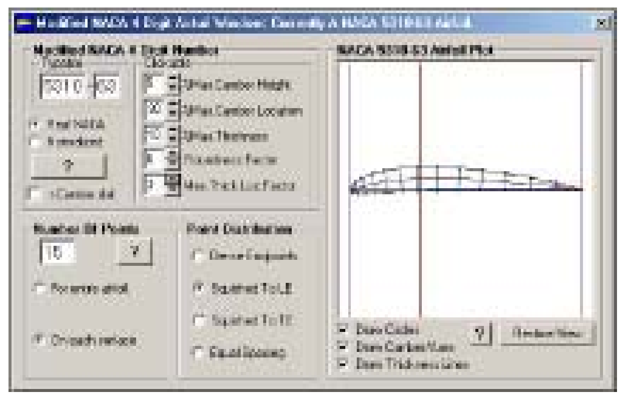
This shortage did not prove to be as much of a problem as first thought, as unfortunately it was not possible to model single layer sails successfully in the Hess & Smith software. There was however a starting point, as GBR Challenge was able to send overall data on the rig to use as a start point. They had recorded that at a boat speed of 10 knots, with apparent wind at 21°, and an angle of heel of around 30°, the rig was producing a thrust of 545Kg and a heeling force of 2000Kg. Although this does not seem like much data, these are the main parameters, and the more specific data that is needed can be derived from them.

With this data, development can begin of a new sail design that will out-perform the current one.

Producing Section Shape for Sail

Using the Designfoil software it was possible to create a section shape for the wing sail. The plan was to produce a shape which it was felt could be fabricated accurately in real life, and which would still perform well. In the end a shape was derived with a section described by a modified four digit NACA section number. The section that was chosen is 5310-63. The numbers describe different attributes of the section: the first describes the maximum height of the camber line from the chord as a percentage of the chord length, the second digit describes the point along the chord at which the maximum camber occurs, in multiples of 10%, and the last two digits give the maximum thickness of the section in percent. The two extra digits describe the radius of the leading edge and the position of maximum thickness respectively. So for the section chosen: the maximum distance of the camber line from the chord is 5% of the chord length; this occurs at 30% of the chord from the leading edge; the maximum foil thickness is 10% of the chord length; it has a leading edge roundness factor of 6; and finally the maximum thickness of the section is at 30% of the chord. (Incidentally the last two digits being 63 make the section almost identical to the 4 digit '5310' NACA section).

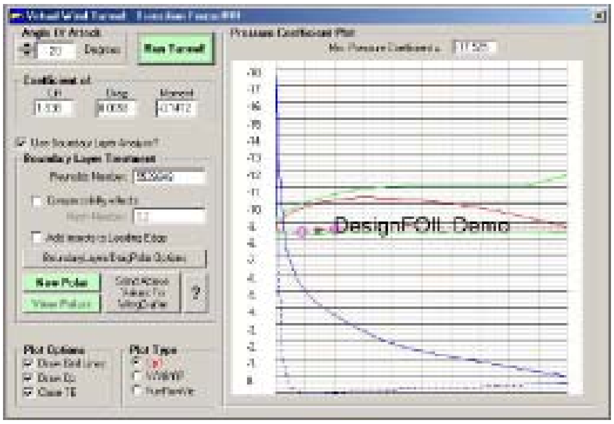
The reason for choosing this section is that it was



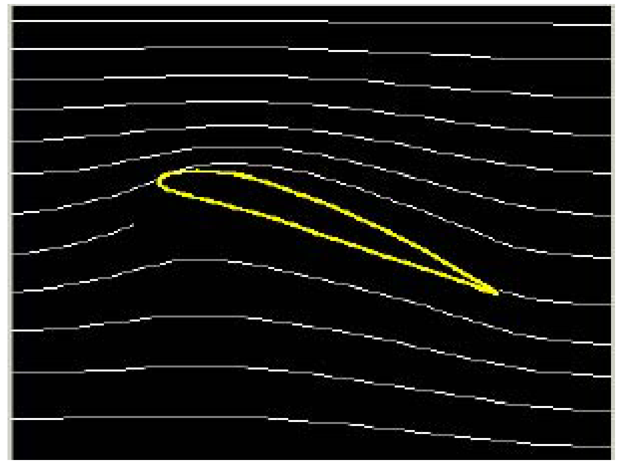
Screen shot from Designfoil software of foil section generator

felt to be realistic to produce and maintain this shape whilst sailing. It has a relatively flat windward surface with some camber to leeward, which is realistic in light airs at least, and deformation from this in stronger breeze is not that detrimental, as explained above in Section 5.2. Also the leading edge is quite sharp. This is good as it will require less shaping added to the forestay to create, as if the leading edge was blunt it would require something larger to 'pack out' the shape there.

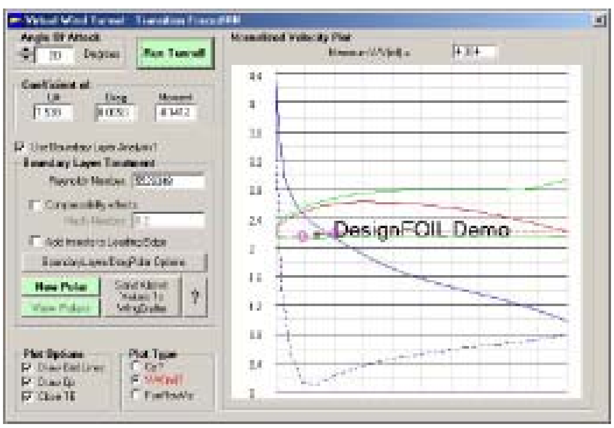
In Designfoil it is possible to test the section to get an idea of how it would perform. The program produces plots of the pressure co-efficient (pressure at that point on the surface with respect to the free stream pressure), and air speed V/V_{inf} (speed of flow compared to free stream velocity). These plots for the chosen section are shown below. The dotted lines are for the windward surface, the solid for the leeward.



Screen shot from Designfoil software of pressure coefficient plot



Screen shot from Designfoil software of flow around foil



Screen shot from Designfoil software of normalised velocity plot

The Reynolds number used by the program was set for the section operating at about half the height of the sail (about 13 meters (40 ft) above sea level) and at an apparent wind speed of 20 knots. The window says that the transition is forced. This refers to the point at which flow over the surfaces becomes turbulent. I set this manually at 4% of the chord, because that is where I believe the transition will occur. I came to this value because of the design I will be looking at.

The program was also able to generate a plot of the streamlines around the foil, this is shown this below. It is for an angle of attack of 20° as with the graphs above. It is not very accurate but does give a rough idea of the flow around the section, clearly illustrating the compression of the streamlines above the section and the downwash from the trailing edge.

Creating 3D Model in the Hess & Smith Software

The final step was to create the 3D model in Hess & Smith from the 2D section in Designfoil. Designfoil is able to export the section shape in a number of formats, the most useful for me however was as a series of co-ordinate points with the origin at the leading edge and the values of the co-ordinates given in terms of the section having unit chord length (i.e. chord=1). Designfoil was made to describe the section with 15 points per side and the majority near the leading edge.

The next step was to make a series of these sections to describe the sail. Here Phil Fisher helped immensely; he took the section points and had a piece of software that could scale them to the correct size given the chord length at a particular height of the sail. The software also compiled these values into the format that the Hess & Smith software required to read. The way Hess & Smith works is to produce a series of sections through the wing (sail) called 'N' lines. A pair of these is used to make up a strip of the sail, formed by elements between each of the points on the 'N' line. The series of strips is then put together for the whole section. It is possible within the program to have a series of sections with different shapes, but where two sections join they must have a common 'N' line, and all sections are trapezoidal. For this project's model there was only one section for the sail and the origin was set at the tack point of the sail, so the values of forces and moments will be in relation to that.

Choosing Which Simulations to Run

With the sail described in a way Hess & Smith can understand, all that remained was to set the flow conditions and run the program. The onset flow described is for infinity up to the foil in the three planes, X, Y & Z. The first tests were done for the sail vertical (this compares to around 5 degrees of heel) at varying angles of attack between 5 and 50 degrees. It was felt that this gave a good range of results covering the sail's potential range of operation from hard on the wind round to reaching. The tests were conducted with an onset flow velocity of 7m/s (14 knots), which represents the bottom of the apparent wind range in which the sail would be operating. It was thought that this would be where the biggest gains could be made; as wind speed increases the section shape will thin out, but at this lower speed it is more likely that the section shape described in the model can be maintained in the real world.

Also, at angles of attack of 20° and 45°, a series of simulations were run at different onset flow velocities from 1, through to 10 metres per second (≈ 2-20 knots) apparent wind speed. This allowed me to see how the forces from the sail changed as the wind speed increased. This is slightly idealised as no account has been made for any change in the section shape as the wind speed changes. However this data still makes a good basis for future development, which is the main aim of this project. 20° and 45° were chosen as these represent sailing at close hauled and on a fine reach, as this is where this sail would have the majority of its use. At wind angles much higher than 45° or 50° on a racing yacht it is likely that a different sail would be carried. This is not to say that this sail would not work at higher angles, but it is likely that a least a different design of wing sail would be more efficient than the one used for sailing to windward. For much deeper angles, such as VMG (Velocity Made Good) downwind a spinnaker would be far faster than any genoa.

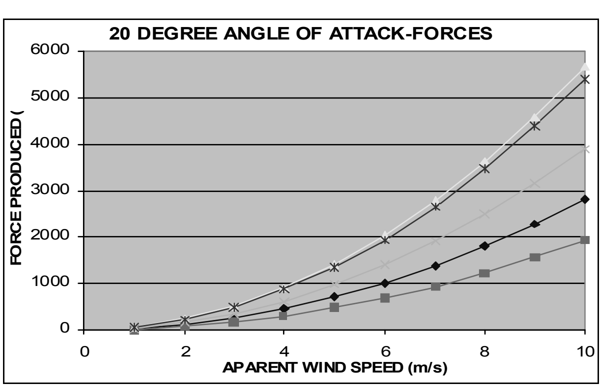
These simulations were run for both the airfoil and for thin sections to allow for direct comparison. The results from all of these are detailed and plotted in the next section.

Results

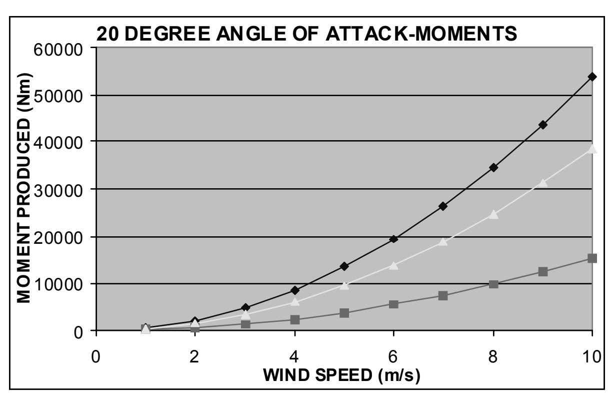
In all the graphs of forces: 'X' is the thrust force parallel to the chord of the sail, 'Y' is the vertical force (upwards), and 'Z' is the heeling force. For the moments: 'X' is the heeling moment, 'Y' is the moment turning the boat away from the wind, and 'Z' is the moment pushing the bow of the boat down. Onset conditions are as at an infinite distance upstream.

Onset Flow 20° to Chord

Airfoil section sail results alone.

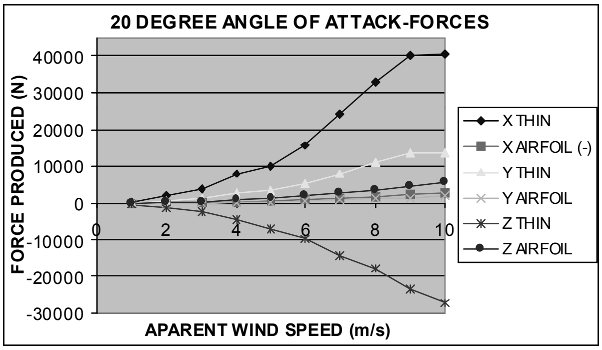


Graph of forces from wing sail operating at 20° to apparent wind

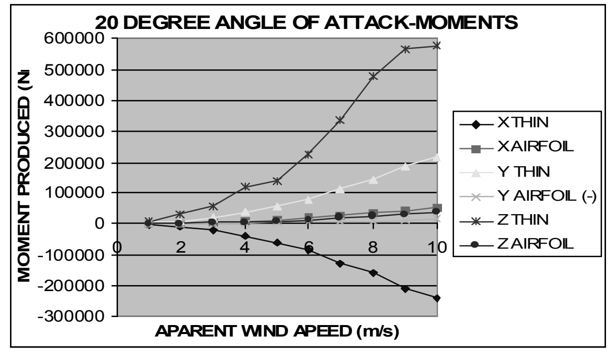


Graph of moments from wing sail operating at 20° to apparent wind

Airfoil and thin sections plotted together.



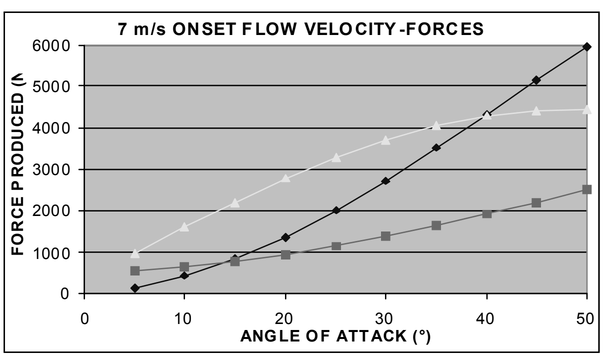
Graph of forces from wing and thin sails operating at 20° to apparent wind



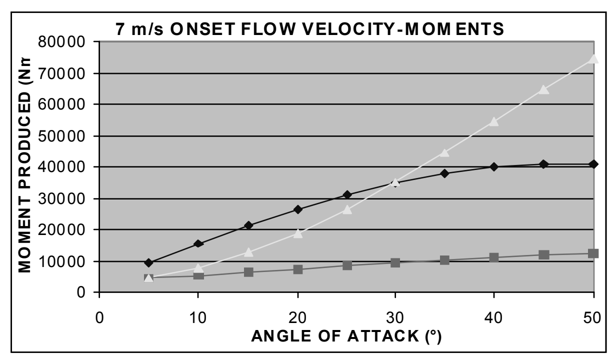
Graph of moments from wing and thin sails operating at 20° to apparent wind

Here it is obvious that there has been an error with the model of the thin section as the force values are some 20 times the size of those of the airfoil. This is nothing like the real world, and although the results have been plotted here, they cannot be used for any serious comparison and are omitted from further consideration.

Onset Flow 7 m/s

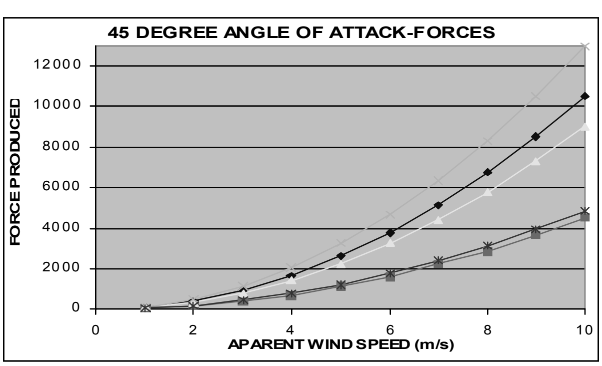


Graph of forces from wing operating at 7 m/s apparent wind

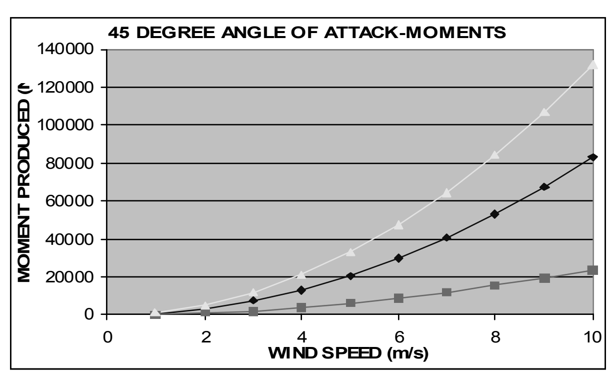


Graph of moments from wing operating at 7 m/s apparent wind

Onset Flow 45° to Chord



Graph of forces from wing sail operating at 45° to apparent wind



Graph of moments from wing sail operating at 45° to apparent wind

Analysis of Results

Simulations Run at 20° Angle of Attack

The first simulations were the most important, as they were testing the sail when being used to windward. As far as the America's Cup would be concerned, only the top end of the results would be of any relevance as the yachts sail in a very specific wind range. However it was decided that it would be important to get results over a far larger wind range to prove that the sail design would be applicable for more that just this specialist environment.

The results from the wing sail are about as good as could have been hoped for. It shows clearly the exponential growth of the forces produced in each plane, by the sail. For the entire range of results the thrust force is just under half that of the heeling force. This is a brilliant result for the wing sail, as for the conventional sail the heeling force is between three and four times the thrust force. The original data that was supplied on the forces produced by the rig was that the whole rig produced 545Kg of thrust and 2000kg of heel force when sailing at 10 knots upwind. This represents an apparent wind speed of around 24 knots. It is assumed that around 45% of the thrust and 40% of the heel force are produced by the genoa. These percentages are standard 'rules of thumb' used across every level of sail design. This means that it is required that the new sail design must be better than 245kg thrust and 800kg heel force at 24 knots (thrust to heel force ratio of 0.3).

From the results it can be seen that, in as little as 16 knots apparent wind speed, the new sail is already producing 253kg of total thrust, but is producing only 352kg of heel force. This result was reached assuming that the chord of the sail is at about 10° to the centreline of the hull. It includes the forces in all three planes, and assumes an angle of heel of 30°. It has also been assumed that the sail's span (height) is at 5° to the mast, meaning the sail is heeled at 25° to the horizontal. This gives a total thrust:heel ratio for the wing sail of 0.72. This is more than twice the efficiency of the original sail, and at a lower wind speed as well. This is a massive improvement in performance.

It is likely however that in the real world the gains would not be this large, due to the instability of the air flow, some deflection of the sail from the design shape, and losses due to friction on the sail surfaces. However it is believed that all these combined will still not outweigh the huge increase in performance from this design. Another point in the wingsail's favour is that the angle of 30° used above is in actual fact very pessimistic. The heel force I have calculated is less than half of that of the original sail for the same thrust and so the yacht would be sailing significantly more upright (about 15-20º). This would greatly reduce the drag from the hull form allowing the boat to sail faster for the given thrust force produced. To calculate the true increase in performance as a result of this change in forces a complete analysis would be required. This would require data on the entire yacht, something to which there was not access. It is felt however that there is great deal of potential for far greater performance with this sail than compared with conventional designs.

The moment diagrams, as expected, mirror these results perfectly. The curves produced are also very impressive with respect to how well the results fit. On the graphs the points are connected only by straight lines but the curve in the results can be seen, and is very fair.

The results from running the same tests on the thin section to try and make a more direct comparison to the existing sail are something of a disappointment. It is believed that what has happened is that with such a thin section, there has been a division by a number close to zero somewhere in the calculation used by the program. This has meant that the results have become wildly too large. It is felt that in reality the section used would never produce forces some 20 times that of the airfoil section, and as such all the results for this section will have reluctantly to be ignored. They have been shown graphed out for these simulations in comparison to the wing sail to show just how wildly wrong they are.

This is unfortunate but it does give something to work on in future work on the subject. It is also known that the GBR Challenge sail design team have very accurate simulation and experimental data on the actual forces their rig and sail produce. So annoying as the errors are, in the grand scheme of things they are not a huge problem. Had there been access to a different piece of software, which was known to be able to handle single layer sails, and which used a similar method of calculation, I could have used that and then it would be possible to make a direct comparison.

Simulations Run at 7m/s Onset Flow Speed

The results of the simulations where the angle of attack was changed at constant flow velocity have come out very well again. Firstly it can be seen that, as expected, the 'thrust' force is increasing exponentially as the angle is increased. The interesting thing to note with this is that between 45° and 50° the increase does not follow the curve of the rest of the plot; it is slightly smaller. This is an interesting point but not unexpected. As mentioned in Section 8.4, it was expected that at the highest angles of attack, the sail would not be as efficient when compared to lower angles of attack. In the end it turns out that the wingsail is still performing very well compared to a conventional sail, but the increase is not as great. This may well be because the sail is beginning to stall.

The forces here are not resolved as in Section 9.1 because the angle of heel of the yacht is not known. The results, unresolved however, still indicate the sail's potential and so are still of use in this 'raw' condition.

The heeling force is seen to increase as the angle of attack goes up, but this increase is progressively smaller as the angle of attack increases. It is important to remember that, with the increase in the angle of attack, the total thrust and heeling forces will become a combination of the forces labelled in the results as 'X' and 'Z'. This means that the actual forces in line with the centre of the hull and perpendicular to it will be somewhat different to the 'X', 'Y', and 'Z' forces plotted above.

Also, as expected, the force in the positive 'Y' direction is increasing slowly and exponentially with the angle of attack. In the most part the force 'Y' will not play much part in the heel force produced by the sail; indeed it is not until the sail is heeled that it adds to the total heeling force.

Simulations Run at 45° Angle of Attack

The final group of simulations were done to see how the sail would react when used at a higher angle of attack. This is simulating its use on a reach, although this is not relevant for the windward/ leeward courses of the America's Cup competition, it is however useful because the sail will need to perform in this condition if it is used for the more common 'round the cans' and offshore races.

On the force graph, not only are the results output from the simulation plotted as before but also are included the resolved results of the 'X' and 'Z' forces for the sail at 20° to the centreline of the hull. These then give the actual forces in line with and perpendicular to the hull, i.e. the thrust and heel forces. This condition represents an apparent wind angle to the hull centreline of 65°, which is about average for a fine to beam reach. This is about as far off the wind as an upwind sail would be likely to be used. As expected the heeling force is quite small, and the thrust force is larger than that for 20° angle of attack. The effect of heel has not been taken into account, for two reasons, firstly the angle is not known, and secondly the angle would be very small, and so the actual result should not differ too much.

The magnitude of the thrust force however is quite impressive: 13000 Newtons (1325kg) at 10 m/s apparent wind speed. This force is more than twice the total force of the whole existing rig when sailing to windward, and this from the genoa alone. This could prove to be the best reason for the use of wing sails, fine reaching. Indeed this raises the issue that it could well be faster, in VMG terms, to sail deeper angles on a beat, if the increase in forward force is so large when sailing slightly off the wind. This would require far more detailed research into the possibility, and the use of a full Velocity Prediction Program (VPP) with full data on the yacht and the whole rig.

Analysis of Project

Looking back on the completed project as a whole I feel I can be quite pleased with what I have achieved. I may not have managed to complete everything I wanted to do when I decided on my aims and objectives back in Section 2, but what I have managed to do I feel is of some use beyond this project.

It has been very difficult to find any previous scientific papers on this subject. Although there is a vast amount of data available of the relative merits of different foil sections in different conditions, there has been little done trying to apply wing sections to sails. I have found that what research has been done has been conducted by individuals for their own curiosity, and hence little scientific data is available. I was able to find some data referring to the possible use of sails as an auxiliary power source on trade vessels; this often mentioned the use of wing-sails, but this line of research died out in the late 80's and none of it is particularly relevant to this project. What information I was able to find was from speaking to people in the business of yacht sails. Peter Kay and Richard Pemberton have both been of a huge help in making sure that the results of this project can be of some use in the successful development of this type of sail in the future.

Another problem I had initially with the project was in what form my tests of the new design would take place. I had found the Designfoil software early on and decided that it would be the easiest way for me to choose and develop section shapes, but where I went after that was not as clear-cut. At the start of the year, the Department were in the process of building a wind tunnel, which had the potential for me to do some very detailed and exciting research. However, it became apparent early on that I would not be able to get access to it before the deadline of this project, and so I had to look for other methods of modelling my ideas.

I considered a number of possible software packages, both 2D and 3D. In the first category, FLUENT is a widely used and very powerful piece of software. However its models take a very long time to run, and writing computer code is not one of my strong points. Hence I decided to look elsewhere. The next piece of software I found was called XFOIL. This is a 2D CFD package specialising in solving the flow around NACA sections. This could have given me good results. I would simply have had to run the program for a series of sections through the sail and then integrate them to get answers for the whole. I was ready to start on this when Dr. Downie suggested the Hess & Smith software. He put me in contact with Phil Fisher, who had working knowledge of the program and also had a compiler for generating the element coordinates easily.

The final problem I encountered was with the model of the thin, conventional, sail in Hess & Smith. As I have detailed in Section 9, I believe that the calculation employed by the program inherently cannot deal with a section as thin as this. As such, although a number is produced at the end of calculation it bears no resemblance to the real world figure for what it is trying to model. This is unfortunate, but luckily the sails I am modelling are some of the most highly tested in the world, and as a result there is plenty of data on their performance. The data I have been given has been enough for me to ascertain that my design does indeed offer a significant level of increased performance.

Outline of Possible Future Work

Personally I would like to see future development covering the following areas in more depth with the view to making the technology practical and hopefully even commercially viable in the near future.

For this project I picked one sail shape that I felt could realistically be recreated in the real world (with some research and testing). Given further research into possible section shapes, I would like a way of choosing the best shape for a given sail and condition range to be found.

As I have not been able to put in much development, I would like to see more research done into the actual rigging of the sail and its use on-board. It is vital that the sail be no more complicated to use than existing designs, or any chance of wide commercial appeal for it will disappear.

I would like to see some research done into the use of wing sails for the main sail on yachts as well; also into rigs where both sails have airfoil sections. In this project I have looked at the genoa in isolation, but it is important to know how its change in design affects the mainsail and hence the effectiveness of the rig as a whole.

The final and most important point I feel needs to be researched further is how the increase in mass affects the performance of the yacht. It is important to ensure that the increased performance from the better design of sail is not completely neglected by the increase in mass and hence hull friction. This would have to be checked for each yacht design in turn but I feel that this would just be a matter of working out the exact increase in performance rather than working out if the new sails would be better.

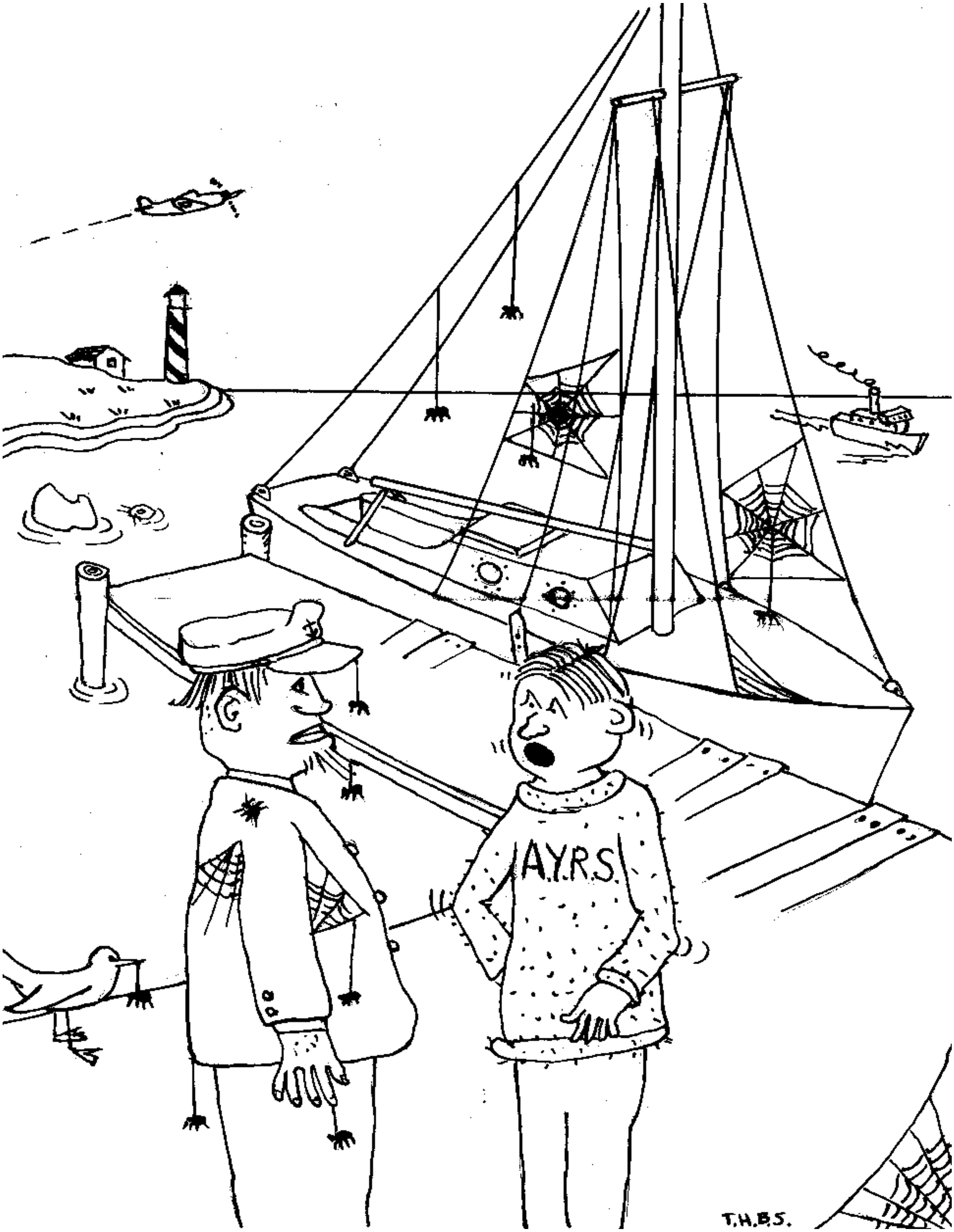
Acknowledgements

I would like to thank my supervisor Dr. Downie for his help and enthusiasm, Peter Kay for the genoa idea, and all at the GBR Challenge America's Cup team, especially Richard Pemberton, for their help, both with technical data and expertise. Given the secrecy that normally accompanies this competition, the data has been made available is much appreciated

A huge "thank you" must go to Phil Fisher for his help and input with the creation of the computer models I have used.

Thanks to my friends for putting up with me moaning about computers and deadlines, and finally thanks to my family for allowing me to take over the PC while I put this all together.

Philip Eltringham



I read where spiders webs are stronger than steel diameter for diameter; so I trained some spiders to do my standing rigging to cut down the windage - but things kinda got out of hand.

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**

July

3rd British Model Multihulls Association 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) tel: +44 (1727) 862 268; email: ayrs@fishwick.demon.co.uk. Items for the Agenda should be notified before December.

February

2nd 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

March

2nd 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

April

6th 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; tel: +44 (1727) 862 268; email: ayrs@fishwick.demon.co.uk

May

2nd-6th AYRS sailing meeting ??
To be confirmed. Somewhere in UK.

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

On the Horizon . . .

Buoyant keel hulls - Newman Darby
Flying Proa - Roberto Rampinelli
Unfinished projects - Roger Strube
More sources and resources: reviews, publications and Internet sites

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