Catalyst

Journal of the Amateur Yacht Research Society

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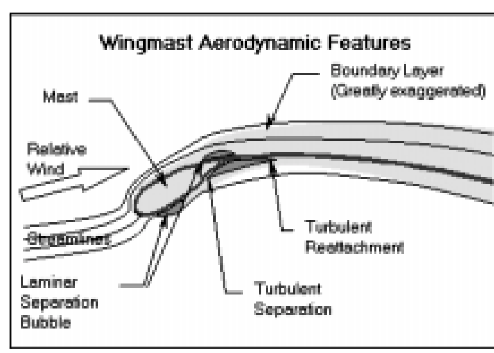
Features



On the Cover –
Windrush *at the International Moth Worlds*

Brett Burvill's Foiled Moth takes to the air at the 2000 Moth Worlds in Perth, W.A. He won two heats aboard this admittedly quirky foiler, the first time such a thing has happened. This was only Brett's 4th outing with the new foils. Can't wait to see what he does next time!

Photo: John Hilton, Leeming 6149, W. Australia

Catalyst

Journal of the
Amateur Yacht Research Society

Catalyst is a quarterly journal of yacht research, design, and technology published by the Amateur Yacht Research Society, BCM AYRS, London WC1N 3XX, UK. Opinions expressed are the author's, and not those of AYRS. AYRS also publishes a series of related booklets.

Contributions are welcome from all, both members and non-members of the Society. Electronic submissions are preferred, emailed to Catalyst@fishwick.demon.co.uk, but disks or typed copy with illustrations may be mailed to the Society's office at the sender's risk. AYRS can take no resposibility for loss or damage.

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To Fly is Divine

Mankind has dreamed of flying ever since they first saw the birds. Sailors have dreamed of flying ever since the first boat buried its bow in a wave and soaked its crew. Swooping along above the wave-tops is an ever-present dream.

Now the dream is becoming a practical reality – not just for those with bottomless pockets or commercial sponsorship, but for anybody. One-design hydrofoil craft are commercial products and now the ides are spreading into more popular classes of boat.

In this issue we present two hydrofoil boats, both, by the standards of some of the boats of the past, relatively conventional, a International Moth, and a daysailing catamaran. Both however represent a significant step forward in the history of hydrofoil boats. To see Joddy or George Chapman wheel their boat down to the beach, launch it into shallow water, sail out and, pausing only for an instant to drop the foils, rise smoothly into the air, is to make hydrofoiling seem commonplace.

Brett Burvill's Moth, on the other hand, is the first time that hydrofoils have been used with conspicuous success on an International Class monohull dinghy (although his is not in fact the first Moth to carry them). So conspicuous has been his success, however, that he has been awarded the accolade of a proposal to ban their future use. It is to be hoped that the proposal fails. The Moths have a long-time reputation for innovation and development, and it is to be hoped that they will not turn their backs on this one.

However, lifting hydrofoils are, it seems, not confined to small light boats. Robert Bussard's paper suggests that they can be (and have been) applied to heavier monohulls. The idea that by raising a keelboat a few inches in the water, with the potential for increased drag and loss of sail-carrying power, a performance increase can be obtained may seem far-fetched to some, but Dr Bussard's predictions, made well before the event, of the outcome of the *America's* Cup , have proven to be chillingly accurate, not only in qualitative terms, but also in terms of the winning margins. Hydrofoils have indeed come of age. — *SF*

Double issue?

Catalyst is meant to be a quarterly publication. Sometimes, however, earning one's living has to take precedence. But although we have skipped the April edition date, this current edition has at least twice as much in it as the last. We hope you enjoy it, and please keep the contributions coming in.

— *The Editor*

Seen at the Shows

This collection of jottings represents the things that caught our eyes (with a little help from our friends, thank you) at the London International Boat Show and at Sailboat 2000 this year.

Bow-Rudder Dinghy

The Escape dinghy is a bright yellow plastic duck of a boat designed I suspect for unskilled sailors on small boating lakes. Its one claim to fame is that the crew sit within it, facing forwards, and steer using an aft facing tiller connected to a rudder mounted beneath the bow. On its own, this might not seem much, but the decision to use a bow-rudder introduces an interesting design choice - should such a design be trimmed to carry weather or lee helm?

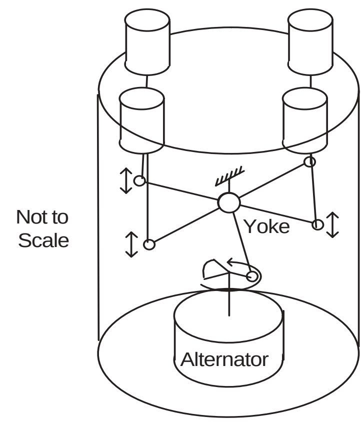
Weather helm, where, when the tiller is released, the boat turns up into the wind and stops, is normally reckoned to be safer than lee helm. However, putting weather helm on a boat with a bow-rudder means that under normal conditions, the rudder is pushing the bow to leeward, and thus acting in opposition to the keel. A bow-rudder that was trimmed to aid the keel in lifting the boat to windward would give lee helm, and releasing the tiller would allow the boat to bear away and (maybe) gybe uncontrollably. The dilemma of efficiency versus safety is always the problem with a bow rudder, effective though they be.

In the Escape, the designers I believe (from a visual assessment - the sales staff did not know) have chosen to favour safety over efficiency, and have given the boat weather helm. For a "pond-boat" this is probably fair enough. I don't expect the customers will notice the reduced efficiency.

Stirling Generator

Now for something completely different. The London Boat Show this year had on display the first Stirling cycle engine I have seen used in a commercial product. The Victron Energie electrical generator (manufactured in the Netherlands) is a sealed package containing an alternator powered by a four cylinder Stirling engine. The heat source, because of course Stirling cycle engines, like steam engines, are external rather than internal combustion engines, is a diesel fuelled heater, which heats the one end of the cylinders. The other end is kept cool by radiant fins. Stirling cycle engines move their working fluid (nitrogen in this case) from the hot end of the cylinder, where it expands, to the cold end, where it contracts, moving the piston behind it. Then the fluid is pumped back to the hot end, and the whole cycle repeats.

The Victron Energie engine has a couple of unusual features. Not only is the whole package sealed against moisture ingress, it is pressurised with the working fluid (nitrogen) at the average cylinder pressure to prevent leakage of the gas out of the cylinders along the piston rods. Pressurising the crankcases of Stirling cycle engines in this way I am told is a relatively standard practice, however the difficulty is always to prevent leaks through the drive shaft seals to the outside world. By combining the engine with an alternator within the crankcase, Victron Energie's designers have avoided the problem altogether. As a result the company are claiming the unit requires no routine maintenance – indeed I do not see how it could receive any without the equipment to re-pressurise the crankcase. This might go some way to offset its relatively high initial price.



Victron Energie Stirling-cycle Generator - Schematic

Apart from its use of the Stirling cycle, its other novelty to me was its use of axial cylinders (cylinders arranged around, and parallel with, the rotating shaft). This allows it to be contained within a compact housing, and also allows even heating of the hot ends of the cylinders with a single heat source. The reciprocating forces of its four axial cylinders are converted into rotational energy by a five-armed yoke – four arms in a cruciform, attached one to each piston rod – the fifth driving a balanced crank on the end of the alternator shaft (see diagram).

Altogether this is an ingenious package, which deserves some success.

Victron Energie BV, De Pal 35, NL1351 JG Almere-Haven, Netherlands

Kiteboarding anyone?

AYRS members have known for some time that kites are going to power the next significant development in recreational sailing. You only have to watch the way the kiteskiing video clips we show at the London Boat Show stops the crowds walking past the stand to realise this. However despite the efforts of the Roeselers and others on the US West Coast, and of the manufacturers of the Wipika inflatable kite in Europe, kite sailing has not yet taken off in a big way, in part because only a few kites are suitable to water use. Most of them sink, which doesn't help water starting.

Now however, kites have attracted the attention of the bigger names in the sport, and Naish Sails had a major display of kitesailing equipment at the Sailboat exhibition. They are marketing a range of equipment, kiteboards (based on surfboards, not ski-boards), control bars etc, and two families of kites providing "sail" areas from 3.0 to 15.5 square metres. Both are semi-cylindrical kites, single surface, with an inflatable bladder along the leading edge, and along the ribs to provide stiffness. One family is low aspect ratio (3.5) with two-line control, the other, the larger, has an AR of 5, and three control lines, the third being used to depower the kite (reduce the angle of attack by pulling on the leading edge). Lines are 30m long, and are used without a reel. Naish salesmen claim the kite can easily be water started, and will pick itself up from the water merely by tugging on one of the lines. Prices appear to be comparable with sails.

Naish Sails UK Ltd, Calshot, Southampton, UK

Laser Vortex

Tunnel hull dinghy

The most innovative of any of the boats at the London shows this winter was undoubtedly the Laser Vortex. Laser UK describe it as a tunnel-hull, and trace its ancestry back to certain Australian Moths of the late 1960s; others might call it a narrow-beam catamaran.

Its length, as best I could tell, is about 14 feet (4.2m) and overall beam is about 5½ feet (1.6m), with a sail area of about 105 sqft (10 sq.m). It is sailed single-handed from a trapeze. The hull is in effect twin-hulls, each of about 2 feet (60cm) beam, connected by a very low bridge-deck (see photograph). This gives it catamaran-like stability and performance and also, claim Laser, allows the bow-wave to create a vortex under the tunnel giving lift and extra stability in pitch (another resurrected idea from the 1960s!) It has twin daggerboards, canted inwards and swept forwards. Laser claim that the canting inwards allows the lee board to give more lift to the hull, and that the sweep-forward forces the board to twist under load, alter the force distribution, and improve manoeuvrability.

Early comments from sailors was that whilst it was a relatively easy boat to sail fast, it would repay careful study to get the best from it under racing conditions.

Laser Centre, Banbury, UK. Photo of the Laser Vortex by Hamo Thorneycroft, published courtesy of Laser UK

Personal Mobile Radios

Although they have been available in USA for a year or two, lightweight short-range personal radios have only recently been made legal in Europe. Operating on UHF frequencies just above 446MHz, they are about the size, and cost, of a mobile telephone, which means they are significantly smaller and cheaper than even handheld marine band VHF radios. For the cost of renting a VHF set for a couple of weeks, you can buy one of these. They do not even need a license (in EEC countries).

The current generation sets have an output power of 500mW, which gives them a range of two miles or so, no good for serious ship-shore use, but perhaps perfect for instructing and coaching, for co-ordinating race and rescue boats or even linking between them and a near shoreside base. They can take an external signal too, which means they could be adapted to data use, though they are not primarily intended for this. (one might have to experiment a little with modem signal levels to avoid distortion and to remain within the regulations)

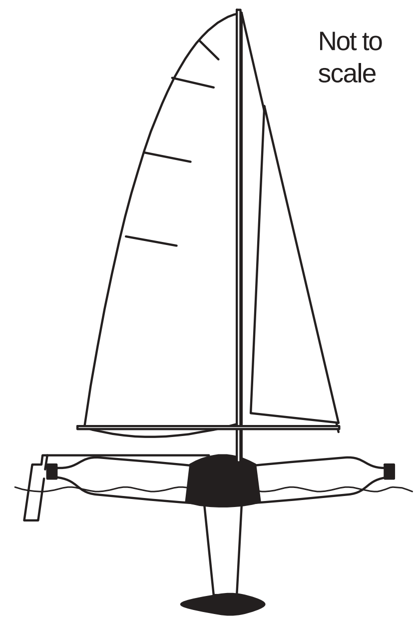
(Various manufacturers and suppliers)

(PS – I note that in the duty-free shops at Heathrow Airport one can now buy two of these radios for under £100.)

Bottle Boat

Finally for those of us who believe that the smaller and cheaper the boat, the more the fun, comes this Millennium Award winning offering from the London Sailboat 2000 Show — a boat made from two recycled plastic drinks bottles, and a plastic bag!

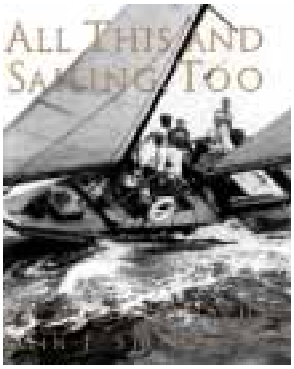
Needless to say, this is not a full size design, but a radio controlled model. The main buoyancy comes from the two 2-litre fizzy drink bottles, joined at their bases by a short purpose-made moulding that supports the rig and the keel and also contains the radio receiver and the two cheap servos. The rudder is screwed onto the neck of the after bottle, and is operated by a pushrod. The sail – a swing (ballestron) rig – is cut from a plastic bag, and mounted on reject carbon-fibre spars. The whole thing can pack away into a briefcase – perfect for taking to the park pond during the lunch break?



Roger Stollery's Bottle Boat

Details from the designer - Roger Stollery, tel: +44 (1483) 421 801 - or from the UK Model Yachting Association, call Mike Hounsell on +44 (1275) 858 528.

— *SF*



All This and Sailing Too
An Autobiography

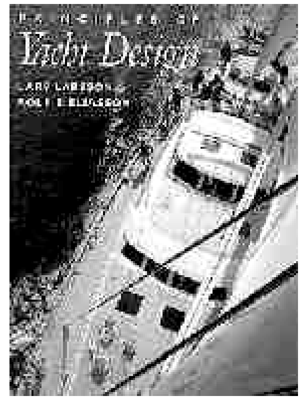
by Olin J. Stephens II

Mystic Seaport Museum,
Mystic, Connecticut USA
ISBN 0-913372-89-7

I was lucky: I had a goal. As far back as I can remember, I wanted to design fast boats. With those words, Olin Stephens launches the account of his long and remarkable career of designing fast sailing boats.

Fast sailing boats from *Dorade* in 1930 through J-Boats and Six Meters to Twelve Meter America's Cup designs, with a fleet of cruising and racing yachts throughout, are an important part of the story. His observations on the Rating Rules' effect on yacht design and the America's Cup's future are worthy to consider. And his reflections on his youth, family, and retirement are a lesson to us all.

All This and Sailing Too is a valuable study for serious students of yacht design.



Principles of
Yacht Design

by Lars Larsson & Rolf Eliasson

International Marine
Camden, Maine USA
ISBN 0-07-036492-3

Larsson & Eliasson's *Principles of Yacht Design* should be a reference work for every yacht designer, amateur and professional. Not since *Skene's Elements of Yacht Design*, revised and updated many times by Francis Kinney, have we had such a comprehensive and current book on the subject. The authors' stated pupose was:

• It must cover all aspects of yacht design.

• Although it must be comprehensible for amateurs, it must be advanced enough to be of interest also to professional designers.

From "Design Methodology" to "Design Evaluation", the authors have achieved their goals.

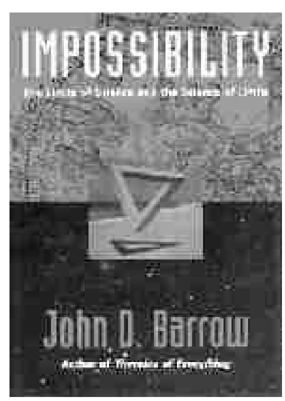
The Simple Science of Flight
from Insects to Jumbo Jets

by Henk Tennekes

MIT Press
Cambridge, Massachusetts
USA
ISBN 0-262-20105-4

From the smallest gnat to the jumbo jet, all things that fly obey the same aerodynamic principles. This book is an introduction to the mechanics of flight and the scientific attitude that finds wonder in simple calculations.

The wonder of it all for the reader is that the book is understandable and enjoyable without the reader being a physicist, engineer, or mathematician. The concepts are simple and vivid and the mathematics hardly venture beyond arithmetic. For the reader interested in flight, in the air or on the water, *The Simple Science of Flight* is a remarkable beginning.



Impossibility
The Limits of Science
and
The Science of Limits

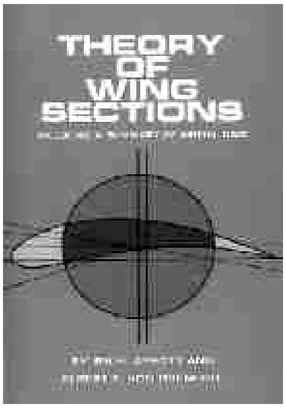
by John D. Barrow

Oxford University Press
Oxford UK
ISBN 0-19-851890-0

What can we never do? What are the limits to human discovery and what might we find, ultimately, to be unknowable, undoable, and unthinkable? What we cannot know defines reality as surely as what we can know. Impossibility is a two-edged sword: It threatens the completeness of the scientific enterprise yet without it there would be no Laws of Nature, no science, and no scientists.

With simple explanations, Barrow shows that any Universe complex enough to contain conscious beings will limit what they can know about their Universe.

It gives us pause for thought.



Theory of Wing Sections
Including a Summary of Airfoil Data

by Ira Abbott
& Albert Von Doenhoff

Dover Publications, Inc.
New York, USA
ISBN 0-486-60586-8

First published in 1949, *Theory of Wing Sections* is a standard reference work with over 300 pages devoted to theoretical and experimental considerations. It progresses from elementary considerations to methods used for the design of NACA low-drag airfoils. Chapters on the theory of thin wings and airfoils are particularly valuable, as is the complete summary of NACA's experimental observations. The 350 page appendix contains: Basic Thickness Forms, Mean Lines, Airfoil Ordinates, and Aerodynamic Characteristics of Wing Sections.

Theory of Wing Sections is an invaluable reference and resource for the amateur yacht designer.

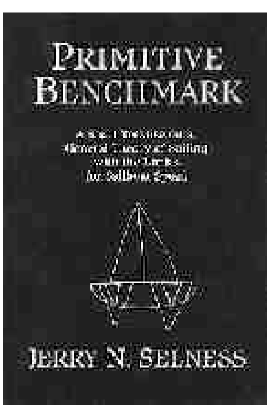
GA Airfoils
A Catalog of Airfoils for General Aviation Use

by Harry C. Riblett

Homebuilt Book Supply
Scottsdale, Arizona, USA

Harry Riblett presents 72 "GA-Universal" airfoils with computer derived performance prediction data for the General Aviation homebuilder and designer. This family of airfoils feature 12%, 15%, and 18% thicknesses for flow conditions in the range of Reynolds numbers from 1 to 10 million, a level suitable for the yacht designer. Figures include polar diagrams, wind tunnel data, stall performance, and printouts of typical airfoil performance analyses.

For the untrained amateur, the author's discussions of the historical development of GA Airfoils, their performance, and their selection, plus the List of References are quite a useful and informative introduction to airfoil design, a beginner's alternative to *Theory of Wing Sections.*



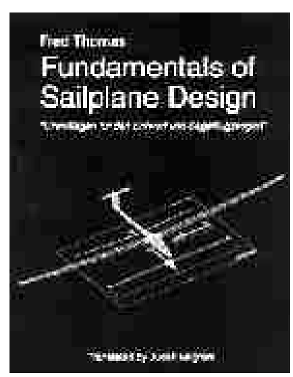
Primitive Benchmark
A Short Treatise on a General Theory of Sailing with the Limits for Sailboat Speed

by Jerry N. Selness

WEGT Publishing
San Diego, California, USA
ISBN 0-9671566-0-2

"The theory and its results, while partly based on traditional concepts, are non-traditional, non-conventional. A sailboat's motion is the result of various forces acting upon it in a kind of yin and yang balance that defines the equilibrium motion of a sailboat. Recent research and writings on naval architecture emphasize the yang part of a sailboat's motion, the responding and resisting forces. The general theory and its results emphasize the yin of sailboat motion, the air's driving and heeling forces that push and pull a sailboat to speed." (from the Introduction)

An unconventional book written for the "sailing physicist" and mathematically inclined.



Fundamentals of Sailplane Design
Grundlagen für den Entwurf von Segelflugzeugen

by Fred Thomas

College Park Press
College Park, Maryland, USA
ISBN 0-9669553-0-7

Sailplane design? — A bit far fetched for yacht designers, isn't it? Not far fetched if you are interested in fluid dynamics, or air and hydro- foil theory and performance, or static and dynamic aeroelasticity, or drag polars and wind tunnels. Sailplanes are closer to sailboats than you can imagine.

What you will see and understand about sails and keels from Fred Thomas's book, recently translated from German, will surprise you. Then go take some glider flying lessons; you'll become a better sailor and designer.

Fred Thomas is a professor at the Technical University of Braunschweig and former Director of DLR, the German Aerospace Research and Test Establishment.

Your Letters

Forward-facing Rowing

Yesterday, I had a call from Fred Barter of Cruising magazine. At the London Boat Show he had seen the F'oarward feature in the AYRS Newsletter [Oct 1999]. He wanted to reproduce details from the feature in his magazine, so I sent him some stuff, including some photos.

It's a start, and I do thank AYRS for your help, especially the long article.

The system works well enough, but can be improved.

There was, contrary to expectations, some friction on the return stroke. This can be eliminated by using some plastic as a rubbing strake. But I am at the moment in the process of having a set made from bicycle bits (see drawing). This will totally eliminate any friction as the moving parts are a self-sealed bearing.

I'll keep you informed as to how things go.

David Chinery

Sailing Documentary

I am currently planning a TV-series on sailing in general, especially on performance sailboats or extreme projects, such as navigating in arctic or tropic waters or racing. The report will be a feature like documentation and is planned to start preferably from the very beginning.

Any of your serious proposals are highly welcome, The project is planned to start in very near future. Strict confidence, if required, is guaranteed.

About us: We are an independent full service TV film and editing team, supplying German and European TV and electronic media. As a journalist, I specialized on multihull sailing (and will of course vote for the multihulled project ...)

Thanks for your esteemed help,

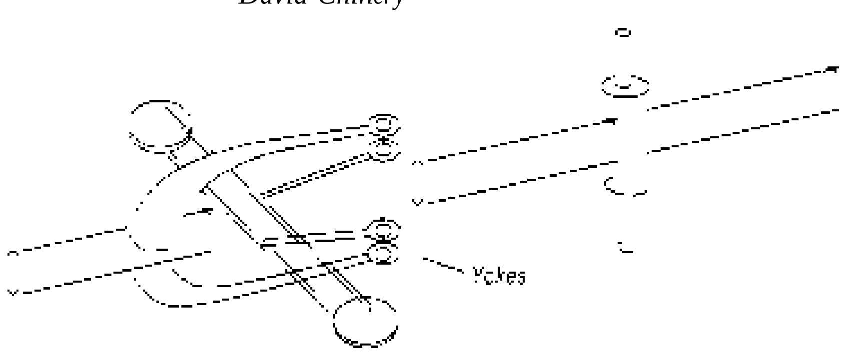
Claus-C. Plaass
plaass@ki.comcity.de.
Tel+fax: +49-431-36 800

Proas: Help Wanted

I am collecting information on short handed offshore Proa's from 1968 (Cheers) to mid-eighties with a mind to perhaps publishing a book on the subject!

As you can appreaciate it is now some fifteen years since the last of these boats were seen in action and the trail is growing cold. So far only two seem to have survived (Cheers and Anglian Pipedream) out of nine. I am eager to track down any survivors – boats, designers and skippers – and any photos, drawings, magazine reports of the period. Can you or any of your readers help? I feel that the Proa despite never reaching its full potential was an important milestone in modern yacht design, and it would be a pity if the wealth of information gathered by the pioneers of modern Proa design were not to be recorded in some way.

Iain Hutchison.
hutch@weirwolf.freeserve.co.uk



See letter from David Chinery

Catalyst No 1

I just got my copy [of Catalyst], and I think it's great. Just what AYRS has been needing. I hope it encourages individuals to write more technical papers and to write up their design process and results in more detail so that others can reproduce and add to what they've done.

Tom Speer
tspeer@gte.net

Letters to Catalyst should be emailed to Catalyst@fishwick.demon.co.uk, or posted to Catalyst, BCM AYRS, London WC1N 3XX, UK
AYRS reserves the right to edit letters for space or other reasons.

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Moths Take to the Wing

by Mark Pivac

The breeze gradually increases from three to five knots. As it rises to six or eight, Windrush lifts onto her foils and glides past the opposition like they are standing still. There is no wake, there is no spray, just smooth speed like skating on ice. This is the stuff dreams are made of and the dream has come true.

Moths have always been an evolutionary class. Radical innovations appear and are subsequently refined and honed into world-beating breakthroughs. The turn of the millennium was a pretty big event and the Moth class has just seen it pass with a pretty big innovation. *Windrush* and Brett Burvill didn't win the world championships outright, but they sure opened some eyes and won a few heats in a highspeed foil borne boat that still has a long way to go. Although it has some vices, *Windrush* is competitive in all conditions, from drifting to gale. I have made a small contribution to the evolution of *Windrush*, and it feels great to be part of the project.

photo: John Hilton

Hydrofoils and Moths are not a new match and hydrofoil sail craft have been around for decades. As an example, Hobie makes the Trifoiler, which can do in excess of 30 knots out of the box. The Rave is another production sailing hydrofoil. To avoid confusion I'll call the lifting foils on *Windrush*, Piv Foils. A few Moth class stalwarts have been experimenting with lifting hydrofoils for years. So what is so unique about *Windrush* and its Piv Foils? It's the first fully flying hydrofoil Moth to be competitive in all wind strengths, on all points of sail. It's the first and only hydrofoil Moth to finish a world championship race and it's the first to have won a heat (*Windrush* won two). To give an idea of how fast it can be, in one race Burvill ended up on the wrong side of a light wind beat. The wind was a land breeze whispering at around three to eight knots, so it was pretty important to be in the right place at all times. Burvill rounded the top mark 35th whilst the leaders were in a pack down past the wing mark. On the first reach he passed 20 boats as *Windrush* popped onto the foils in less than eight knots of breeze. His opponents were cheering at being passed. He rounded the bottom mark in 5th place. It was like watching a 49er passing a fleet of Manly Juniors. In another heat in about 18 knots of breeze he crossed a few transoms at the start and by pointing as high but footing faster on the foils, led around the first windward mark by a minute. Moths are so competitive, this sort of thing only happens rarely. It was happening in Perth in every race this championship.

So why didn't Windrush win overall? The answer is simple. It takes more than crack sailing on a boat with blinding boat speed. To give credit where credit is due, the new world champion sailed a brilliant series on Mark Thorpe's Moth design. Thorpe boats placed first, second and third overall. Brett Burvill is also a brilliant sailor, Windrush is a brilliant concept, but the synergy that links mind, body and boat were missing in the early races. In some conditions *Windrush* is as tame as a pussycat, but her nemesis is flying downwind in a breeze with chop. Occasionally the surface piercing foils will lift too high, pass through a wave trough, ventilate, and then *Windrush* turns into a tiger and bites. It looks hilarious as *Windrush* instantly bears off and simultaneously capsizes to windward. Fortunately this isn't frequent and to his credit, Brett is learning to control this tendency.

In the early races, Brett was probably struggling with the fear of capsize and psyching himself out. Towards the end of the series he probably had to think less about staying upright and could concentrate on winning races. By sailing conservatively and heading all over the show downwind to avoid the worst waves, Brett managed to keep *Windrush* on her feet (that should be foils!). He won two of the last three heats. He came close to winning another 5, but that's sailboat racing. It's the close ones that win or lose a series. This steep learning curve came about because the Piv Foils had only been sailed 4 times before the worlds. Brett and I had been discussing hydrofoils for a few years as part of our normal business. I work for By Design Group and routinely design centre boards and rudders that we then shape using a three axis CNC router. Burvill then completes the vacuum bag composite laminates and finishing of these foils through his company Windrush. Although Windrush builds a lot of boats, Burvill has had six years off from competitive sailing to race Formula Ford. The 2000 Moth World Championships in Perth provided the impetus to get back into it. He initially built *Windrush* to his own design as a fairly conservative but narrow skiff Moth. The rig and wing bars are all state of the art carbon fibre, an incremental improvement on current Moth best practice. The foil idea was resparked when By Design Group received a brief to do a set of inclined foils for an 8.5 trimaran (White Wave) that was being modified. In early September Burvill and I started talking about how to get a set of foils to really work on the Moth class. It was decided that if By Design Group would design and machine the foils, Burvill would finish, fit and sail them. We agreed that the foils had to be simple, strong, easy to fit with minimal modification and FAST.

Photo: AYRS

I have been interested in high speed sailing and racing for decades. Along the way I managed to do my Aeronautical Engineering Degree thesis on "Performance Improvement and Stability Analysis of High Speed Sailboards" (RMIT, 1989) and this contributed to me being awarded RMIT's Tom Shelton Memorial Prize. By Design Group has expertise in the design and development of new equipment and products, especially those with an aeronautical slant such as fans, composite structures and aircraft. I have keenly followed sailing speed record development and hydrofoil design and this marriage of design skills and sailing interest proved invaluable in developing *Windrush*. Our centreboard and rudder designs are currently widely successful in the dinghy, cat and skiff classes. In designing the Piv Foils, we were acutely aware of the need for simplicity and stability. We pared the design down to its essential elements. We got rid of everything we could and took the simplest path. We carefully worked out foil geometry and sizing so the boat would sail to windward foilborne in light airs. It's a tough job to balance low speed lift off and high speed stability. Although we started seriously thinking about it in September, this was the busiest time of the year for both of our businesses and the foil project had to fit in after everything else. Really you need a lot of time with new ideas if you want to win races. Burvill nearly didn't use the Piv Foils because he was only barely comfortable with them. Quite a few people suggested he wait until the next worlds to avoid the danger of them being copied. We feel that this is against the spirit of a development class and wanted to see the concept advance as rapidly as possible. Additionally we really wanted to get the foils further forward on the boat but there wasn't enough time to do it. This has certainly compromised down wind controllability, but the challenge of design is to use what you've got. The boat takes off exactly as predicted and performs well in an overall sense. This was our first attempt at Hydrofoils and to see it work so well and win some heats was a real thrill. Together we are confident that the next boat will solve the few problems that *Windrush* has.

The keys to a successful sailing hydrofoil design are always to think of stability and drag. Although it looks so simple and has only the rudder as a moving part, *Windrush* has a naturally stable arrangement in pitch and ride height, has reasonable yaw damping and she has improved roll stability compared to a standard skiff moth. The hydrofoils on *Windrush* are an advanced design. The main lifting surfaces are the forward hydrofoils mounted from the hiking out wing tips. These foils are inclined at around 45 degrees to the horizontal so that they provide both lift and side force. The toe in/toe out angles and the incidence angle of the rudder foil are critical and confidential. We also use a special hydrofoil section shape and planform shape that blends a range of features to minimise drag, spray and the tendency to ventilate or cavitate. The horizontal aft or rudder foil is used primarily for stability. It utilises an elliptical plan form and a symmetrical low drag section shape. The rudder uses a section shape that is very tolerant to operating close to the surface. It has a fairly sharp leading edge to reduce spray and it can also generate significant side force. As boat speed increases the inclined foils ride higher on the water to maintain the optimum lift coefficient and in doing so their area decreases. The T foil on the bottom of the rudder is essential for stability and will lift up or down, depending on the pitch angle and pitch rate of the boat. To minimize drag it is essential to have as few foil intersections and water surface penetrations as possible. We use very efficient low drag laminar flow hydrofoils with very smooth surfaces so the parasitic drag of corner joints and spray making surface penetrations is a substantial part of the total drag. When you look at *Windrush* sailing there is almost no spray and no visible wake. She just glides past very smoothly at a really impressive speed. Burvill says, "In an eighteen knot breeze on a choppy course the ride up wind is quite smooth, you do bounce around as the foils flex through waves but the hull never slams, on a normal boat you often pound

Photo: John Hilton

quite a bit going up wind. By keeping the support strut intersections above the waterline and by only having three foils (two inclined foils and a T rudder, collectively termed the Piv Foils) we have really minimized the drag. If we could get away with one foil we would to do it, but we need three for stability. It really is a case of "less is more". The boat does not have a centreboard. The angled "Piv Foils" off the wing tips are asymmetrical so that the leeward foil produces most of the lift. It actually lifts the boat to windward. The rudder is around 300mm deeper than a standard Moth rudder to keep the rudder foil in the water. Each main foil is similar in size to a standard Moth centreboard. Although the total wetted area has been increased by slightly more than the area of a centreboard, this is offset by the hull wetted area reduction that occurs as the boat starts lifting out of the water. The hull rides noticeably higher even at speeds of only a few knots.

For very high speed sailing, hydrofoils may not be the answer. Above 45 knots it is very difficult to control ventilation with the side loads and waves that sail craft encounter. Really high speed craft are likely to continue to be planing craft like sailboards or the *Edge*. However the International Moth is not in that league. Beam, length and sail area restrictions place limits on power to weight ratios that make hydrofoils the perfect solution to improving Moth performance.

To improve the Piv Foil layout on *Windrush*, the main or forward foils will be moved further forward. We will also be experimenting with incidence controlled main foils using surface sensing 'feeler' skis. Neither of us is convinced yet that these will be better all round. Surface sensing will be good at high speed to maintain a constant foil depth and help to avoid ventilation by keeping the lifting surface deep, but it will be difficult to maintain low drag at low speed without adding complication. More likely to work is some on the course angle adjustment to the rudder foil or all three Piv Foils. The basic arrangement is stable, however the handling and geometry changes with speed. This is quite similar to aircraft where it is necessary to trim them to fly at different speeds. The Ketterman Trifoiler uses incidence control but it is fairly complex. We are after a simpler solution.

The concept is not limited to Moths. By Design Group and Windrush are both keen on a production version. The Windrush company has produced thousands of "Windrush 14" cats but production levels are now far below the heydays of the seventies and eighties. A simple to build, relatively cheap and easy to sail hydrofoil could be a fantastic boost to the popularity of sailing. If all goes well we can look forward to a one or two person off the beach boat with kick up folding foils and a smooth and fantastically fast ride. Enthusiasts have been predicting such a craft since the fifties but we are now realistically close to achieving a boat as suitable for the masses as a "Hobie Cat" or "Windrush 14". On a grander scale By Design Group has plans for an unlimited offshore racer. We would love to discuss this in detail with someone serious about taking on the big budget, big boat teams in "The Race" around the world. Our vision encompasses a sailing hydrofoil about 11m (35 feet) long, doing 45 knots. With hydrofoils, size hardly matters, the boat need only be big enough to carry the crew and supplies for the duration of the race.

Windrush is a simple concept that is already reviving the Moth class. With further development it is very likely that the next world championships will be won on hydrofoils. With hydrofoil production boats in the wind, it is already shaping up to be an exciting century.

Mark Pivac ran his own engineering design consultancy before joining By Design Group, a Western Australian aerospace, marine and industrial design firm, as its Director. He has been interested in high speed sailing and racing for many years. he can be contacted by email at mark@bdg.com.au.

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The Design and Development of a 4.9m Hydrofoil Catamaran

E.J.C. (Joddy) & G.C. (George) Chapman

Calliope is a round bilge wide beam single handed 4.9m catamaran designed to investigate the versatility of a hybrid displacement/hydrofoil sailing boat. Horizontal lifting foils under the dagger boards are controlled by surface sensors via a unique clutch mechanism, permitting three operating modes – displacement, one hull flight and two hull flight.

The background to the design was greatly influenced by the authors' experiences and observations at Weymouth (UK) "Speed Weeks" held from 1972 onwards. However, this design is intended for recreational sailing operating from the confines of a particular boatyard and slipway, rather than speed record attempts. Recognising the need for good low speed displacement performance, incidence-controlled fully submerged lifting surfaces were chosen over fixed incidence surfacing piercing or ladder foil options. Trailing height sensor arms are used in preference to forward reaching 'Hook' sensors.

Dagger board or strut profile was initially based on some inappropriate received knowledge for surface piercing foils, causing severe ventilation when sailing close hauled. The solution to both this problem and one of heave instability were aided by modelling in a low speed flume.

Calliope

Because she is not a race boat, sailing performance is measured by on-board logging of apparent wind speed, direction and boat speed. Data is presented in both time series and true (relative) wind polar form for comparative purposes and to verify VPP modelling. The latter, using data from wind tunnel and towing tests, has been used in the design of a larger craft currently under construction.

Introduction

The authors, father and son (George and Joddy), have been designing, building and sailing unconventional small craft since 1971. We took part in the first Weymouth (UK) Speed sailing competition in 1972 and from 1974 competed in the 10 sq. m. sail area class until sailboards dominated the event from 1979. For us, the quest for speed was replaced with one for stability and improved all round performance. In 1991 we decided to apply the lessons we had learned from the early speed sailing competitions to the design of a recreational hydrofoil catamaran for single handed operation from our local boatyard. The aim was to produce a boat that was stable, fast and fun in sufficient wind for foiling, but would also have good performance to windward and at low speed in light winds.

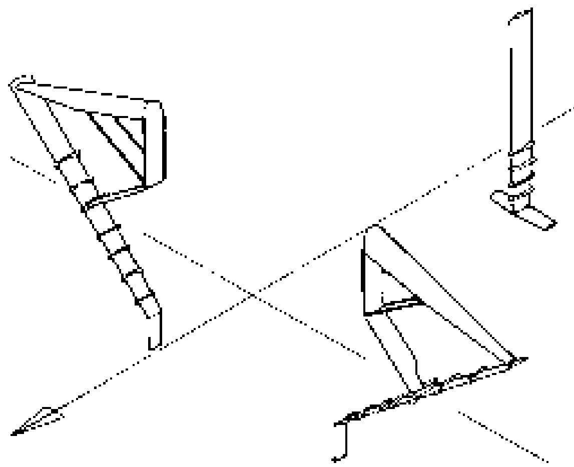


Figure 1. Surface piercing Mayfly *foil configuration. Vertical tips were added to improve yaw stability (from Pattison and Wynne, 1980).*

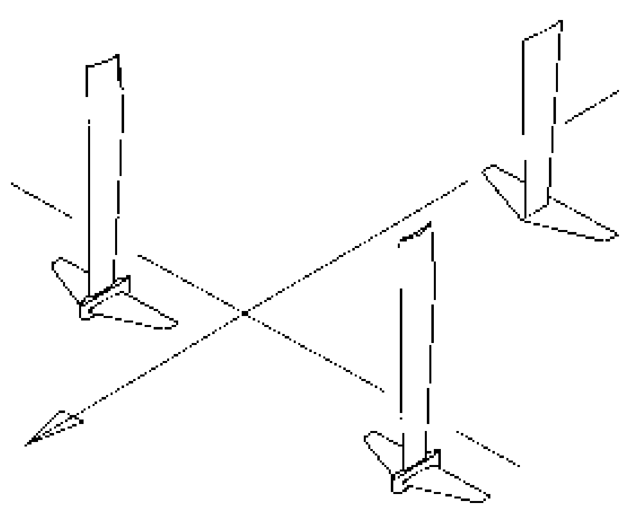
Background

While many competitors' craft at Weymouth displayed short bursts of speed, few managed to traverse the 500m course without a "crash" of some kind. Of the small craft, the best results were from those who adopted the classic aeroplane surface piercing hydrofoil system shown in Figure 1. Attributable to Philip Hansford in 1971 (Alexander et al, 1972) the use of surface piercing main foils supporting most of the weight of the craft plus a fully submerged inverted "T" rudder for pitch stabilisation became known as the *Mayfly* configuration after the small catamaran to which it was fitted. Copied by others, most notably James Grogono and the *Icarus* syndicate, this arrangement yielded a string of world records for both boats throughout the 1970's (Grogono, 1987). Unfortunately, this system suffers from the close coupling between lift and side force on the main foils as a consequence of their dihedral. G Chapman (1985) showed that any change in the division of side force between the rudder and main foils, as occurs during an alteration of course, shift in sail centre of effort or wave action, alters the lift on the main foils. Often exacerbated by the helmsman attempting to compensate, the ensuing motion of skying and diving may lead to a "crash" – a dramatic reduction in velocity as one or more hulls hit the water – and a reduction in average speed. To physically isolate the lift and side force producing functions of the appendages necessitates geometrically orthogonal hydrofoil surfaces. With the absence of the inherent passive height control of the surface piercer, either a ladder foil arrangement or an actively controlled incidence fully submerged lifting surface is required. Active control held the promise of greater potential, particularly in waves.

A general arrangement of an aeroplane submerged foil system is shown in Figure 2, while Figure 3 shows three different methods of controlling the angle of attack, or in the case of a fixed foil with a trailing edge flap, the flap angle, of the submerged lifting surface. The first of these was devised by Christopher Hook as the "Hydrofin" for powered craft. Applied to sailing craft including briefly Hansford's *Mayfly* in 1974, Figure 4, structural deficiencies put back its development and it was not until 1976 that the system was successfully adopted for use on the sailing trimaran *Force8* (Pattison and Wynne, 1980). It comprised of a forward reaching arm with a small planing shoe at its front end working a fully moving foil via crank arms and push-pull wires. A change in boat height above the water caused the arm to rise or fall relative to the boat, which in turn changed the incidence of the foil such that the lift it developed opposed the initial disturbance from equilibrium. As such it is a simple proportional system, but Pattison also incorporated a manual input for roll control, similar in function to the ailerons on an aircraft.

To us, any forward reaching arm of this type appears unsatisfactory, for example if the planing shoe digs into the back of a wave or patch of floating weed. Although this was not reported to be a problem, the spray thrown up by these surface sensors was. *Force8*'s main shortcoming was with the

Figure 2. Submerged, incidence controlled foil configuration (from Pattison and Wynne, 1980)



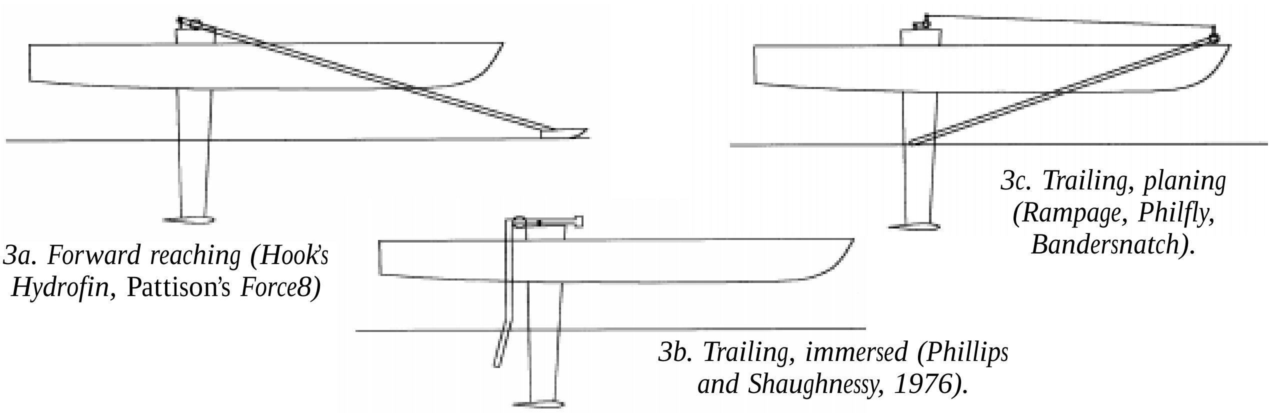


Figure 3. Submerged foil control mechanisms

foils sticking, having used acetyl journal bearings rather than balls or rollers, resulting in occasional broaching and crashing. *Force8* was the inspiration for Greg Ketterman's "trifoiler" *Longshot* (Ketterman, 1994), which persisted with forward reaching sensors but used a flexible structure rather than crank arms and bearings to break the dominance of sailboards in speed sailing in the 1990s

The second control arrangement in Figure 3b is that proposed by Phillips and Shaughnessy (1976) and consisted of an almost vertical "wand" pivoted about a point on the hull. Connected via a crank arm and push rod to a trailing edge flap, the variation in drag on the wand with depth of immersion provided the feedback needed for level flight. Initially believing that a bob-weight mounted in such a way as to cause the flap to rise with upward acceleration of the boat would dampen out the rigid body motions of the boat in waves, their analysis showed this to be incorrect. They suggested that a more practical arrangement would be to have a planing device on the end of the wand to follow the water surface. The steep wand angle and aft-of-foil location is a feature of Dr Sam Bradfield's series of incidence controlled hydrofoil sailing boats, including the *Windrider Rave* (Guillaumin, 1998)

The third arrangement is that due to Simmonds (G.C.Chapman, 1977), with a trailing, planing height sensor arm working a flap via linkages. In the case of Mark Simmonds' A-Class catamaran *Rampage*, only one such foil was fitted to the Port hull, and it was not until Hansford adopted the system on both sides of his trimaran *Dot* (later *Philfly*) in 1985 that truly stable, level flight on a variety of headings was seen.

The authors' own *Bandersnatch*, a 14' ultra-light catamaran (G.C.Chapman, 1991) served as a test platform for a variety of configurations, finally converging on the trailing, planing wand/trailing edge flap system, Figures 5 and 6. As such, this craft demonstrated excellent stability foilborne. However, with low displacement hulls of almost zero rocker and large surface piercing additional lifting surfaces, low speed manoeuvrability and displacement windward performance was poor.

Figure 4. Christopher Hook and Philip Hansford discuss Mayfly's *fully submerged foils. Castle Cove (Weymouth UK), September 1974.*
Photo - G.C.Chapman

Figure 5. George Chapman on Bandersnatch, *13 August 1989. Photo – E.J.C.Chapman*

Design Aim

The requirements for a new boat were:
(i) Retain the excellent flying characteristics of *Bandersnatch*
(ii) Improve windward performance, displacement and/or flying
(iii)Reduce time to deploy and stow lifting foils
(iv) Be operable single handed from our favourite boatyard in Plymouth, UK.

Design Realisation

To meet these objectives we chose to retain a catamaran configuration but switched to vertical struts sliding through the hulls, as on a conventional cat, and adopted fuller, semi-circular underwater hull lines with modest rocker, Figure 7. The boat was to be called *Calliope* after an RN ship of that name whose Captain lived at the authors' address in the 1800s.

The beam of the craft was limited by the width of the boatyard gate, and the length by the size of our garage! Although a wider foil base was desirable it would have probably been necessary to choose a trimaran platform, which in turn would need to be dismantled to get to and from the water. The ability to adjust trim through moving crew weight fore-and-aft and athwartships was considered desirable, and this could not be done if restrained in a central cockpit.

By operating the foil control system on the windward side only, it was envisaged that in light winds the windward hull only would fly, overcoming the disadvantage that a wide beam cat has in those conditions.

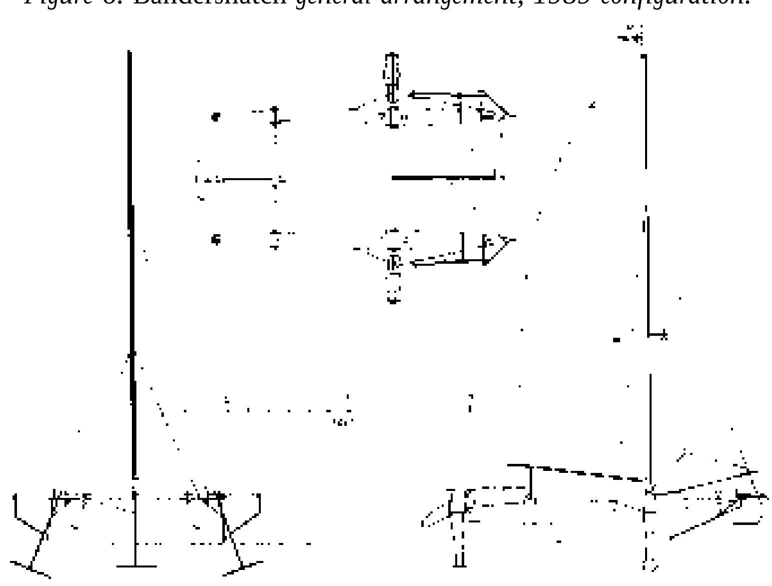
Structure

The hulls were built from 3mm tortured ply bonded with glass tape and epoxy resin. Simple 3" diameter 16swg aluminium tubes formed the main beams and a 2" 16swg tube the rudder beam. The hulls have three watertight compartments each, the centre one containing the centre-board or strut case. Each bow is a separate structure, originally concealing the linkage from the height sensor to a crank arm at deck level. These foam/GRP bow units are detachable so the reduced hull length fits in the garage.

Foils

Initially, the struts and foils from *Bandersnatch* were used. These have a lifting section approximately NACA 0012 with the last 25% forming the trailing edge flap, Figure 8a.

Figure 6. Bandersnatch *general arrangement, 1989 configuration.*



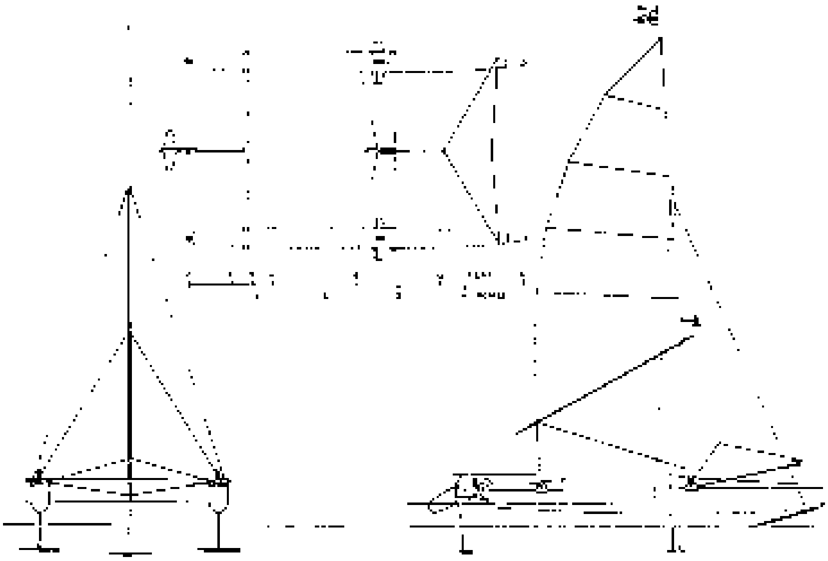
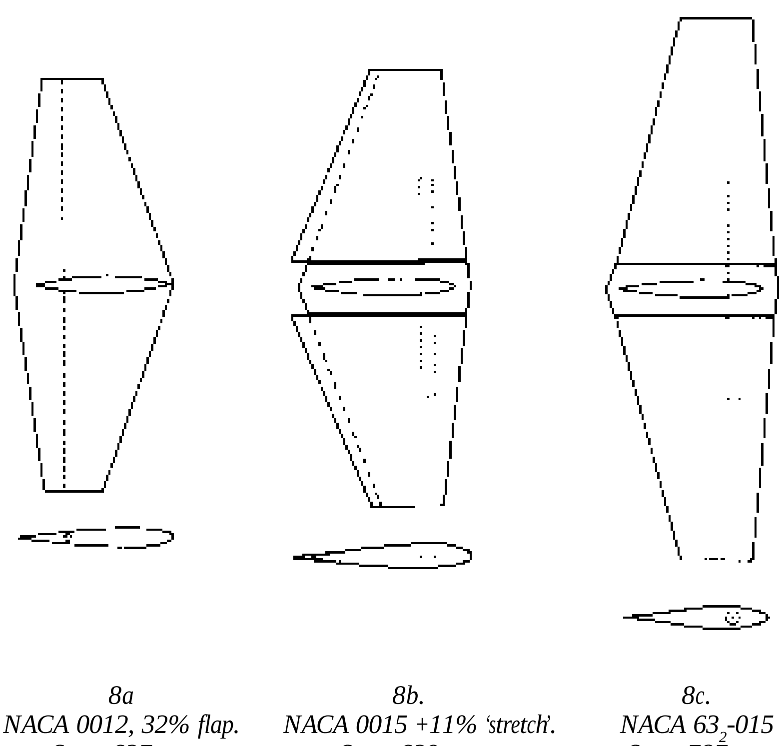


Figure 7. Calliope *general arrangement, initial configuration, 1992*

The struts remained of bi-ogival section but were stripped of their anti-ventilation fences so that they could be retracted through the centre-board cases.

Two rudder blades are carried and deployed from a single, central rudder stock. A spring loaded 'hack' blade is used during launch and recovery – it does not matter if it hits the ground – and an inverted 'T' foil that can be locked down once in sufficiently deep water. The horizontal incidence of the rudder foil can be pre-set by rotating the rudder stock around the rudder beam and securing it with a pin. It is set to zero degrees and is not usually adjusted afloat. The lifting and strut sections were originally 0012 and bi-ogive respectively.

The height sensing wands (or 'feelers') were pivoted from within the bow pods and shaped to fit snugly under the hulls' centre lines when not in use. Small triangular planing surfaces at their tips provided enough force through the crank and wire linkage to pull the foil flaps to rise (i.e. flaps down) if the boat was too low. A powerful elastic pulled the flaps to dive (i.e. flaps up) if the boat rose too high, the wand having to overcome this as well as the flap moment when boat height low.



8a	8b.	8c.
NACA 0012, 32% flap.	*NACA 0015 +11% 'stretch'.*	*NACA 63_2-015*
Span 627mm	*Span 629mm*	*Span 787mm*
Area 0.1036 sq.m.	*Area 0.1155 sq.m.*	*Area 01374sq.m.*
AR 3.8	*AR 3.42*	*AR 4.5*

Figure 8. Evolution of Calliope's *lifting foils.*

Foil Structure

The initial *Bandersnatch* struts, foils and rudder were made from a glass fibre/polyester hand lay-up on a softwood core. Carbon reinforcement was included in the high stress areas. The trailing edge flaps were made of carbon in a two part mould, core material being high density filler.

The shells of the later fully moving foils, described below, were made in two part moulds similarly to the flaps. After laying up the shells the tube to accommodate a stainless stub shaft and a continuing wooden spar were firmly glassed in. After reinforcing the edges of the shells and filling each half with polyurethane foam the two halves were glued together. This proved to be inadequate. On two successive outings first the Port inner, and then the Starboard inner foils shed their top shells. In both cases they were the lee foils. Surprisingly the boat

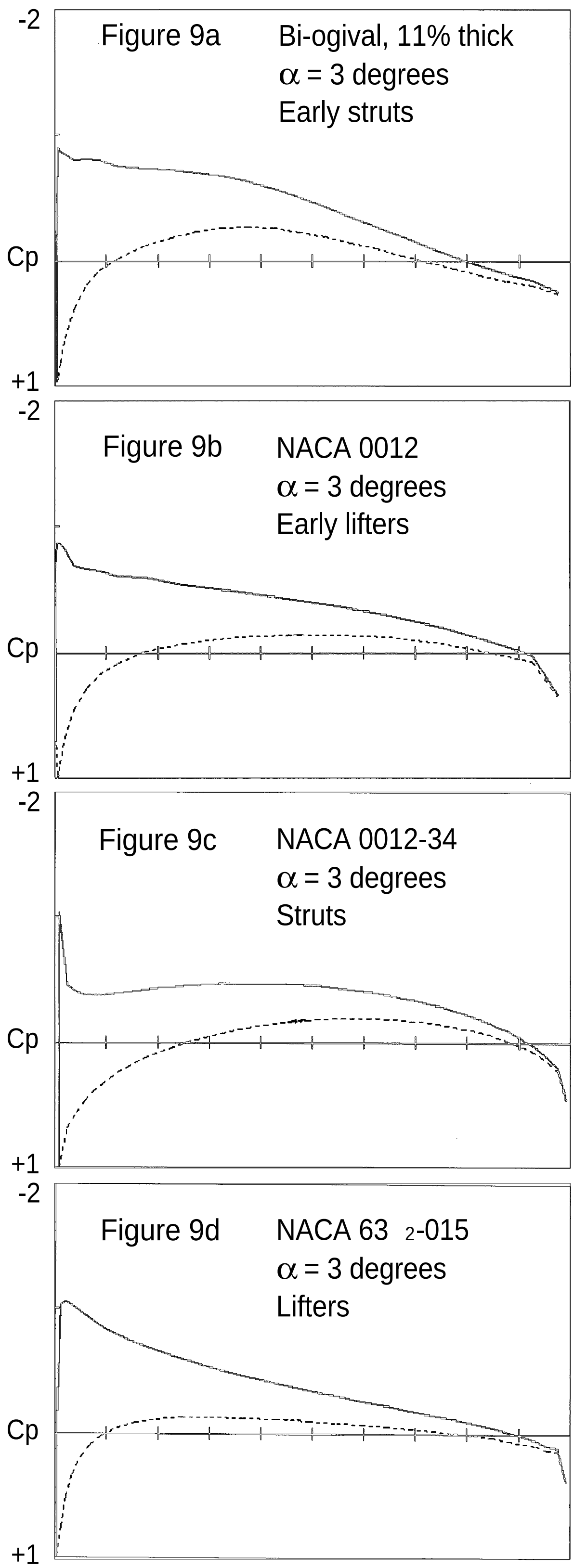


Figure 9. Pressure distributions for foil sections used on Calliope

went on flying, though at reduced speed. These two had been 'up-side-down', with the tube and spar glassed to the lower shell. Replacements, and later models, have been carefully handed to make sure the major strength of the shell-to-tube join is upwards.

Clutch and Lost Motion Mechanism

A unique feature of *Calliope*'s foil control system is the clutch at the top of each strut. Controlled by two strings they permit remote engage/disengage of the wand-to-foil connection, locking the foil in neutral and allowing the wand to trail freely for minimum drag when de-clutched.

A fixed incidence surface piercing foiler would take around a minute to change from displacement to foiling mode by stopping and lowering the cumbersome foils, or put up with sluggish performance from dragging a considerable wetted area, at incidence, through the water. With clutch operated foils the switch from displacement to flying takes only a second and can be done while moving. This offers a huge advantage when sailing in light winds marginal for foiling.

A lost-motion linkage at the top of the main foil strut was intended to prevent excess loads developing in the control system, the wand-to-stow or fully up position exceeded the corresponding flap-to-rise.

Sail Rig

For the rig we chose a fully battened main/rotating mast with a wishboom sheeted to the mid-point of the aft beam. *Bandersnatch* had suffered from an undesirable bow-down twist of the leeward hull due to the high sheeting load applied via a track to leeward of the centreline, which we wished to avoid. A small jib was retained from the previous boat as an aid to tacking and helm balance, its tack carried on a light bowsprit.

To begin with, a circular section mast was used, later replaced with a D section Z-Spars Z-170.

Instruments

Initially, Smiths Instruments apparent wind speed, pitot log and a Speedwatch log all ex-*Bandersnatch* were carried. The wind speed cup anemometer was mounted on a forward reaching strut on the mast and the orifice for the pitot log built into the leading edge of the rudder foil strut. The Speedwatch impeller was mounted on one side of the rudder strut, with its pick-up coil above the water on the stock.

Figure 10. 10 August 1992 -the second time afloat. A hang-up of the lost motion device leaves the lee flap fully to rise with the resulting 'skying'. Weather hull behaving perfectly. Photo – EJC Chapman

Preliminary Results

The first few sessions afloat were disappointing. Although the boat sailed well enough displacement and flying one hull, excessive ventilation down the leeward main foil strut as soon as the leeward hull cleared the surface prevented two-hull flight. Increasing the chord of the struts to the maximum within the constraint of the centre-board cases did little to improve matters. Only when the lost motion control linkage 'locked-up', jamming the wand in its up position (foil-to rise) did the boat get both hulls off the water, and then only transiently, Figure 9.

Reasoning that the disturbance created on the surface of the water by the wand tip was in some way initiating ventilation, a simple experiment was set up in a low speed flume to investigate. A section of old foil strut was held at an angle to the flow whilst a kitchen whisk agitated the surface just upstream. Ventilation was immediate. On the boat, the leeward wand was secured in its stowed position and the foil flap angle locked to a mid-to-rise position, reproducing the two hull unstable flight experienced 'by accident'. The in-line under hull wand location was abandoned in favour of a deck mounted, inboard arrangement.

The ability to fly both hulls, although now possible, could only be done when sailing well off the true wind. What the true wind angle actually was was uncertain, so as a parallel exercise an improved instrument system was developed (outlined below).

With inboard wands, flapped foils and bi-ogive struts *Calliope* was entered in a privately run time trial event at Weymouth in October 1993, recording a best 500m average of 15 knots.

Foil Sections and Pressure Distributions

Our choice of strut section had been greatly influenced by Alexander et al (1972) and the success of ogival surface piercing foils. Although we were aware that ventilation might be a problem without fences, we were so wedded to the received idea that a sharp leading edge was necessary to 'cut' the water surface, and that an ogive or bi-ogival section would have the required un-peaky pressure distribution that our progress was delayed.

Bethwaite (1993) had conducted experiments on 10 surface piercing rudder blades at speeds up to 25 knots, albeit transom hung. He concluded that the best compromise for low and high speed performance, in terms of lift/drag and anti-ventilation properties, was for a section with a fine but highly polished parabolic leading edge. Describing 18' skiff development, he reported that a 0.5% of chord radius leading edge proved optimum in moderate winds, falling to 0.4% at boat speeds up to 28 knots. This information came to our attention at an appropriate time!

To overcome the deficiencies with *Calliope* we adopted a NACA 0012-34 section with a 0.4% nose radius for the struts of a new set of foils. We also chose to use a balanced, fully moving foil instead of a fixed foil plus flap, initially of 0015 section but subsequently of NACA 63_2-015. To ensure the foil would not stick at one incidence, as had plagued *Force8*, needle roller bearings were used in the hub at the foot of the strut. Sections, plans and computed pressure distributions of all the sections used are shown in Figures 8 and 9.

The lifting surfaces have the appearance of being swept forward In fact they are straight but tapered about their quarter chord point. Theoretically, for a 2-D symmetrical section both the centre of pressure and the aerodynamic centre lie at the quarter chord point. In practice our initial 0015 foils exhibited a tendency to pitch the 'wrong' way, and we were forced to extend the trailing edge aft, reducing the aspect ratio. Following their structural failure the opportunity was taken to use the NACA 63_2-015 section whose experimental $Cm_{(c/4)}$ versus angle of attack curve (Abbot and von Doenhoff, 1959) indicates that the aerodynamic centre is at 27% chord. When pivoted about the 25% chord line, a small restoring moment is created when at incidence, tending to feather the foil. The Cd versus Cl curve shows a modest laminar flow 'bucket', and the pressure distribution a less steep adverse pressure gradient towards the trailing edge than the other sections.

The graphs of pressure distribution were computed using a 2-D complex variable boundary element method assuming inviscid, incompressible flow (Chiu and Zino, 1996). They are included here to show the 'peaky' negative pressure coefficient at the leading edge of the bi-ogive section, which would cause separation and ventilation on a surface piercing strut. Also, note that both the upper and lower surfaces of all these sections are subjected to a negative Cp. Too often the authors of texts, who should know better, perpetuate the mis-understanding that the lower surface of a foil at incidence is subjected to a positive Cp (for example Larsson et al, 1994). As with the ogive struts, this 'received knowledge', instilled from kindergarten, took an embarrassingly long time to overcome when faced with a problem of air being sucked out through the drain hole at the foot of the struts.

The new foil assemblies, with the 0015 lifters, were available for the 1994 season. Although leading edge ventilation had been banished, we encountered a stability problem.

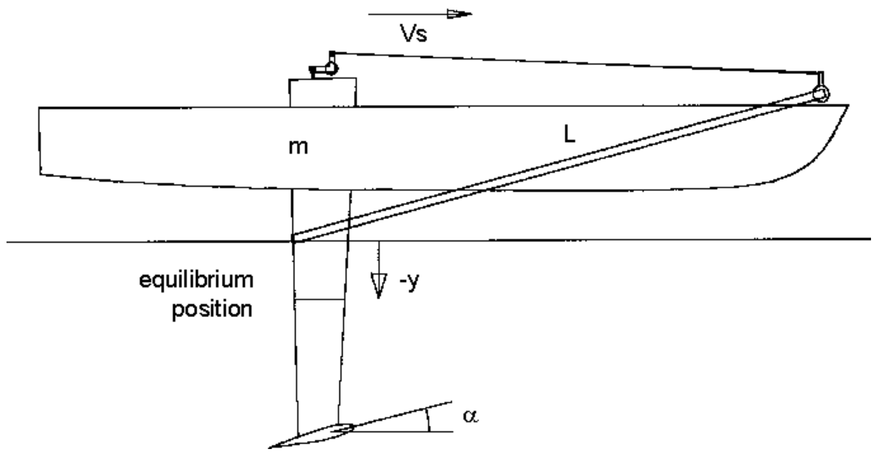


Figure 11. Schematic for 2nd order linear model of hull-foil system

Dynamic Response and Longitudinal Stability

On occasions, usually when sailed by EJC (of less weight than GC), at the point where the leeward hull would clear the water when accelerating from rest, the windward hull would start to heave up and down with increasing amplitude at a frequency of about 1 Hz. Increasing crew weight by sailing two-up eliminated this problem, but this was not a useful solution.

A full treatment of the dynamic stability of this craft would require a six degree of freedom analysis and is beyond the scope of this paper. Instead a very simplified model of the main foil system is developed as a one degree of freedom linear second order system, leading to estimations of natural frequency and damping coefficient.

Figure 11 shows the elements of the model. The mass of the hull, crew and strut is supported by the foil at an incidence set by the trailing wand to be proportional to the difference between the flying height at equilibrium and the actual height. The constant of proportionality is an equivalent wand length. The inertia and rotational damping of the wand/foil system is assumed to be negligible, the various crank arms of all the same length, the forward velocity constant and motion constrained in heave only. Heave velocity, dy/dt, positive upwards, is assumed small compared to the forward boat speed such that the instantaneous effective incidence at the foil is reduced by (dy/dt)/Vs. The lift force associated with this angle corresponds to the damping of a dashpot in a mass-spring-damper system. The delayed build up of circulation around the foil, added mass and other unsteady fluid dynamic effects are ignored.

Applying Newton's second law:

$$m\frac{d^2y}{dt^2} + \tfrac{1}{2}\rho Vs^2 ACl_a\left(\frac{1}{Vs}\cdot\frac{dy}{dt} + \frac{y}{L}\right) = 0 \quad \text{........... (1)}$$

where ρ is the water density. Setting k = ½rACla and rearranging gives

$$\frac{Lm}{kVs^2}\frac{d^2y}{dt^2} + \frac{L}{Vs}\frac{dy}{dt} + y = 0 \quad \text{............................. (2)}$$

from which it can be shown that the undamped natural frequency is

$$\omega_n = Vs\sqrt{k/Lm} \quad \text{... (3)}$$

and the damping factor

$$c = L\omega_n/2Vs = \frac{1}{2}\sqrt{\frac{kL}{m}} \quad \text{.................................. (4)}$$

For *Calliope*, typical values are known or estimated as

Vs = 5m/s (10 knots, typical take-off speed)

L = 0.44m, representing an angular 'gain' of 3 from wand to foil, the wand length actually being 1.33m.

m = 118 kg (half boat weight plus 1 crew)

A = 0.1 m^2

Cla = 3.0 rad^{-1}

k = 150

from which

ω_n = 8.5 rad/s or 1.35 Hz, and

c = 0.37

The resonant frequency for such as system is given by $\omega_{res} = \omega_n.(1 - 2c^2)^{½}$, giving a value of 1.15Hz, in good agreement to that experienced. The value of c would be regarded as low, resulting in a decaying oscillatory response to a step input. As can be seen from (3) and (4), increasing the mass by carrying an extra crew would reduce both the natural frequency and the damping factor, while increasing the effective length of the wand (by reducing the gain) reduces the natural frequency and increases the damping.

Nomenclature

A	foil area
a	angle of attack
b	apparent wind angle to course through water
c	damping factor
Cl	lift coefficient
Cla	lift slope, dCl/da
Cd	drag coefficient
L	equivalent trailing height sensor length
λ	leeway angle
m	mass
TWA	true wind angle
Va	apparent wind speed
Vs	boat speed
Vt	true wind speed
VPP	velocity prediction program
ω_n	undamped natural frequency
ω_{res}	resonant frequency

Although highly simplistic, this model illustrated the sensitivity of the system to gain. As shown above, damping is reduced by increasing the system mass, but in reality the oscillatory behaviour is eliminated when sailing two-up. This suggests that a better description is required which should include pitching as a second degree of freedom, the rudder foil and fluid dynamic effects left out here.

A scale physical model, initially built as a constructional pattern, had briefly been fitted with an electronic height control system. This had demonstrated a tendency to oscillate if the gain was set too high.

On *Calliope* the gain was substantially reduced to 1:1 between the rotation of the wand and the foil, giving (from above) a damping factor of 0.65 and a resonant frequency of 0.3 Hz. This permitted the removal of the lost motion link and simplification of the clutch mechanism. No further stability problems have been encountered, and we were able to record a 500m average of 19.01 knots at the 1994 Weymouth event, winning the prize for fastest non-sailboard by more than 3 knots from a standard Hurricane 5.9m catamaran.

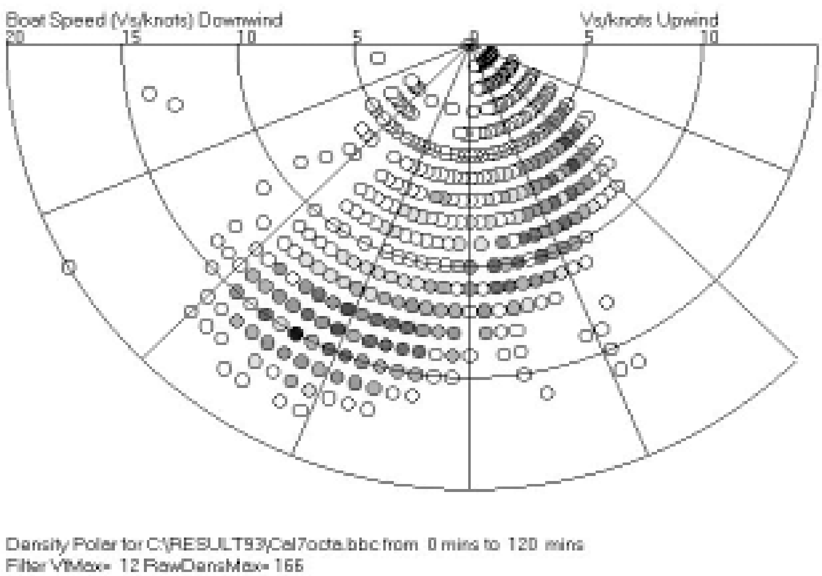
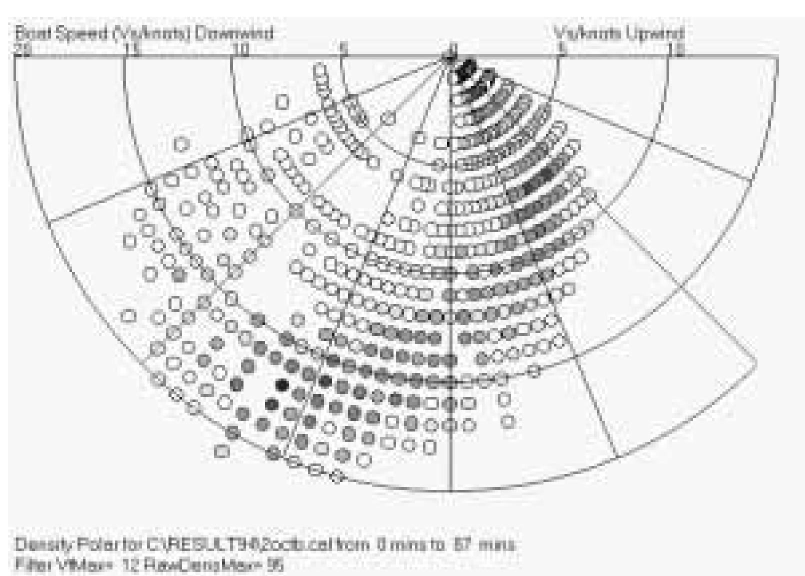


Figure 12. Frequency density true-relative wind, boat speed polars of raw 1Hz logged data from Calliope *at Weymouth on 7 October 1993 (top) and 2 October 1994 (bottom). Points where the calculated true wind is more than 12 knots omitted. The modal values (darkest) represent 166 and 95 occurrences respectively*

Instrumentation and Performance Measurement

To answer the question “what is the true wind angle” an instrument to display this and other quantities was designed and built, (E J C Chapman, 1993). Accepting data from sensors for apparent wind speed and direction and boat speed, a look-up table containing calculated values of true wind speed, velocity made good (sailing upwind) and true wind angle (sailing downwind) is addressed and the result displayed. Leeway is not measured and is assumed to be small. The size of eprom memory dictated a coarse 5 bit resolution for the measured parameters - 0 to 31 knots in 1 knot steps for Va and Vs, 5.625° steps for b.

With the addition of a battery backed memory card, the device can log up to 120 minutes of data at a rate of 1 Hz from the Speedwatch sensors. No running averages or damping is applied to the data. The anemometer and wind vane are mounted at the front of the bowsprit, the rotating mast being unsuitable for this purpose.



For improved sensitivity at low speed the log impeller pick-up coil was embedded within the rudder strut. The original Smiths masthead anemometer was retained, which together with the bowsprit unit enabled some wind speed gradient information to be collected.

Analysis of sailing performance is carried out off-line. Both time series and polar diagrams can be displayed for any section of a record. The polars shown in Figure 12 present the raw, 1 Hz data plotted as a histogram or frequency density of boat speed against true wind angle. The darker the colour the more time the boat was being sailed at a particular speed and heading.

The turbulent nature of the wind and the unsteady, non-linear behaviour of a sailing boat mean that the generation of ideal, steady state ‘smooth-line’ polars, with any degree of statistical significance, is a challenging goal. Initially, we ran a peak average search routine over the data to find the fastest average, over typically 10secs, for each 10° bracket of true wind angle, (GC and EJC Chapman, 1995). More recently, by searching for short pieces of sailing where the variance of the three recorded parameters is within preset limits it was hoped to get a more

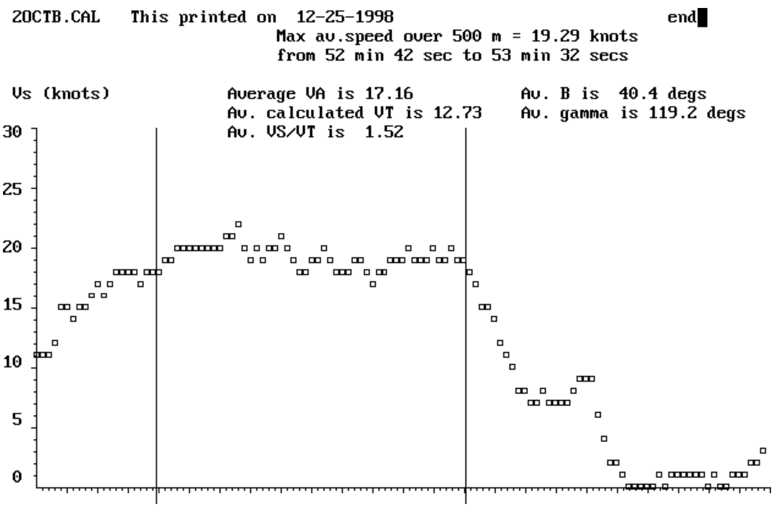


Figure 13. Maximum 500m speed for Calliope *on 2 October 1994. 'B' is the apparent wind angle, 'gamma' is the true wind angle*

reliable, reproducible measure of performance. The drawback with this method is the apparent wastage of data - it is rare for all three variables to be sufficiently steady for a 10secs average to be valid. Higher sampling rates and resolution may permit shorter sample periods to be considered, but until then it is felt necessary to return to the raw data and present it in form shown here. It must be remembered, however, that the true wind fluctuates in direction as well as speed, a factor which cannot be accounted for without logging compass heading. For this reason, we call these diagrams true-relative-wind, boat speed polars.

The results plotted in Figure 12b show the improved performance in October 1994 over that 12 months earlier. Both sets of data were recorded on Portland harbour during the Weymouth events in similar weather conditions.

As an aide to assessing the probability of success in a 500m timed trial, the record of Vs can be searched for the fastest 500m or any other distance, Figure 13

Velocity Prediction

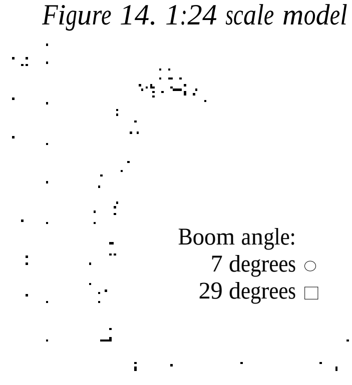
As well as analysing performance as above, an early exercise was to take the data from a fast run at Weymouth and attempt to put numbers to the whole set of steady state forces acting on the foils, sail and hulls. This developed into a velocity prediction program (VPP) for the three modes of operation — displacement, one hull and two hull flying — and proved useful in determining how best to sail the boat as well as a design tool for successor projects.

Data for the VPP is largely empirical, but includes the results of full size towing and 1:21 scale wind tunnel tests, previously unpublished and presented in Figures 14 and 15.

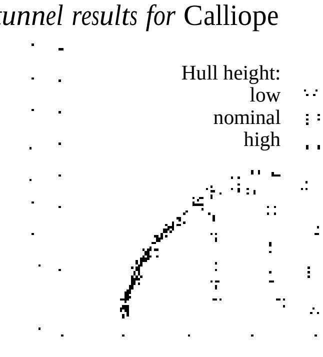
The towing test was conducted on a flat calm day in Portland Harbour. *Calliope*, with a crew of two, was pulled by a RIB from straight ahead by a line connected via a spring balance to the forward main beam. The mast was up but no sail set. Without the forward pitching moment from the sail, the rudder foil had to be set at a high incidence and the both crew had to sit well forward for level flight when flying. Three runs were conducted: displacement, one hull flying and two hulls flying. Maximum speed was 15 knots before the difficulty of steering from such a forward position caused a near shipwreck and the tow was slipped.

The model used for the wind tunnel tests is shown in Figure 16. It was tested at two typical sheet settings, and with the hulls alone at three heights. The small model with its brass sails and low wind speed make for incorrect Reynolds scaling, but to the

Figure 14. 1:24 scale model wind tunnel results for Calliope



14a. Model with small main and small jib.
$q = 161.8 N/m^2$
$Re_{0.1} = 108000$
No corrections,
2.5 degree steps.



14b. Hulls and 1 crew only.
$q = 308.9 N/m^2$
$Re_{0.1} = 149000$
No corrections.
0 – 50° in 5° steps
50 – 90° in 10° steps

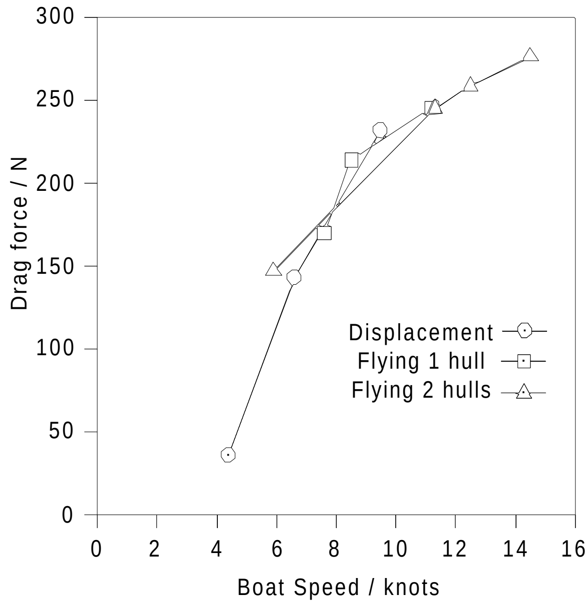


Figure 15. Calliope *full scale towing test, 5 October 1994. Flat calm conditions, straight-ahead pull from mast foot, two crew. Rudder foil at +5° for 2-hull flying to compensate for low height of tow. 63_2-015 lifters*

extent that much of the flow over an object of this kind is separated and 'messy', it could be classed as a non-aerodynamic structure for which correct scaling is less important. The resulting plots of Cl and Cd conform to those produced elsewhere, so we believe they are not so far off the mark. The wind tunnel was the small recirculating teaching tunnel at Exeter University's School of Engineering, with a jet 416mm wide x 455mm high.

What is of interest is the wind tunnel data for the hulls alone (plus 1 crew). The increasing lift and drag with height above the 'sea surface' suggests either an influence from the velocity gradient in the tunnel and/or a change in flow pattern. The low height state was with the hulls touching the surface rather than immersed in it, so the displacement condition was not reproduced.

By combining this data together with that from standard references for the foil sections used, the VPP works by iteration to find a balance between the aero and hydrodynamic forces acting on the boat.

The resulting printout for *Calliope* flying both hulls, Figure 17, differs from usual VPP output since it shows the envelope of performance for the chosen true wind, rather than just maximum speed. Square symbols show where the windward foil will be set to dive, circles where it will be set to rise. There is a blank area in the down wind sector due to lack of down wind sail data, but since the boat tacks down wind this is no hardship. The figure suggests that in this case it is not possible to fly both hulls at less than 8 knots. In reality 9 knots is about the minimum flying speed.

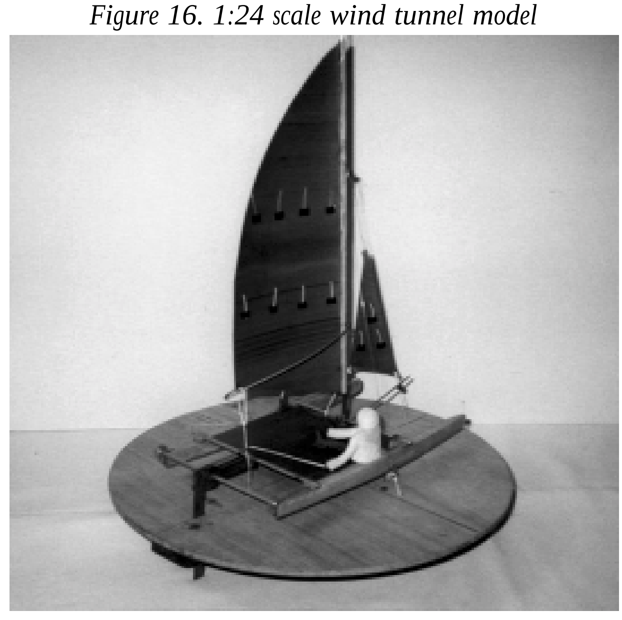
Final Performance and Discussion

By the end of the 1994 season the boat was performing well. She had met if not exceeded our expectations. The polar shown in Figure 12b remains typical of her performance. Figure 18 shows the final general arrangement, with a photomontage in Figure 19.

In 1995 a new, larger sail was fitted which reduced the true wind speed required for two-hull flight by a knot to 10 knots, but did not increase maximum speed when sailed single handed. With two-up, maximum speed in stronger winds is predicted to be greater since the drag penalty incurred through providing righting moment by additional weight is less than that associated with the windward foil developing downforce. Unfortunately, attempting to investigate this has resulted in a number of breakages.

Inevitably in a project of this kind more than one alteration to the boat may occur between outings, and so it is difficult to assess the affect of any one factor. In particular we do not know whether the improvement on changing from 0015 to 63_2-015

Figure 16. 1:24 scale wind tunnel model



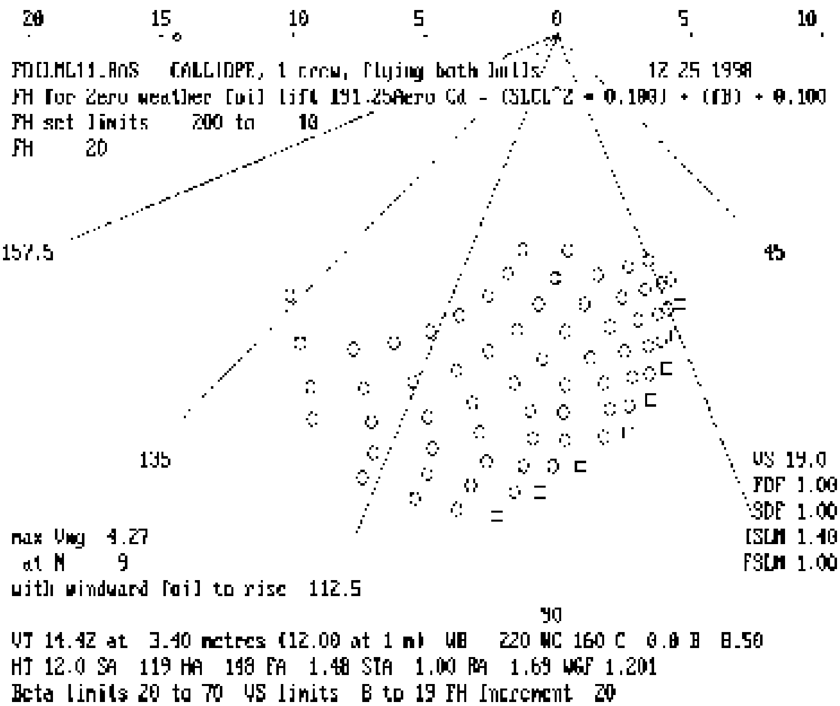


Figure 17. Typical VPP output for Calliope *flying 2 hulls in a nominal 12 knots, small main sail, small jib. Squares indicate windward foil to dive, circles to rise. (The figures relate to various parameters within the program defining sail area, centre of effort height etc, units mostly imperial.)*

foils was due to the increased area and aspect ratio, or from laminar flow. Bethwaite (1993) maintains that when highly polished his blades enjoy laminar flow. Parsons (1998) says “The sure proof that the question of how much laminar flow can be obtained at full scale has not been answered to everyone’s satisfaction is the heat and vehemence that divides the international naval architecture community on this issue. There have been no conclusive experiments carried out and made public that convinces everyone of what is actually going on. Based on full scale measurements carried out on the large K boat for the 1988 [America’s Cup] contest, the New Zealand technical community believes that significant laminar flow can be obtained”.

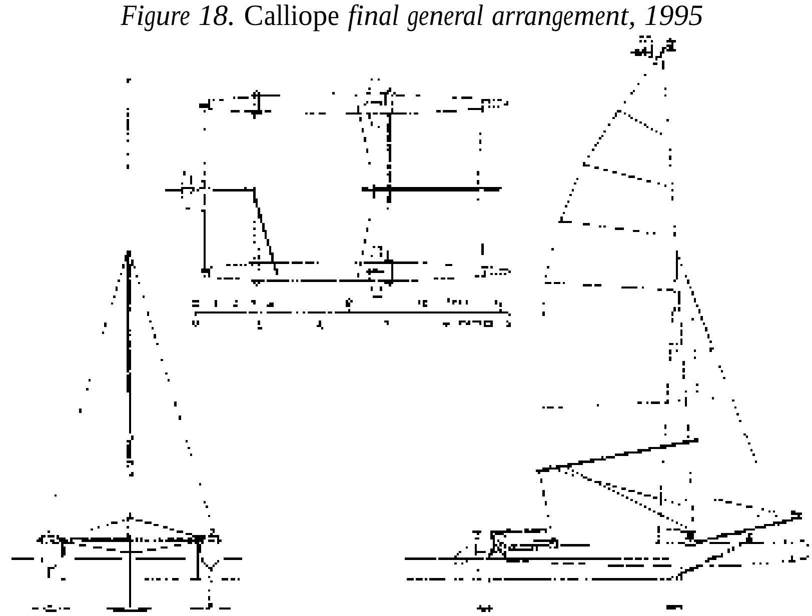
By comparison with America’s Cup standards, our performance measurement and velocity prediction accuracy and resolution are deplorable, but we are seeking improvements in the order of 10% in 10-20 knots rather than 0.1% . For our purposes the VPP is useful and it will doubtless be improved. We believe it may be unique in being applied to a dinghy sized craft and tied to afloat recorded measurement.

There is plenty of scope to model the dynamic behaviour of the craft, a subject we have barely touched on. Measuring performance at a higher sampling rate and resolution to capture the dynamics is an aim for the future.

In the last season *Calliope* was afloat, 1997, we began to explore windward performance with greater care. We had thought she would go to windward better by sailing displacement or flying one hull. The VPP suggested that either flying both hulls or fully displacement would be better than one hull flight. Moving the sheeting point to windward and sailing on the VMG meter appears to confirm this.

Calliope is now in refit and a new and larger sister *Ceres* is under construction. At 5.8m this craft – essentially a scaled up version – is designed for a crew of two, of more robust construction, and intended to see if this design is competitive against similarly sized conventional catamarans.

Figure 18. Calliope *final general arrangement, 1995*



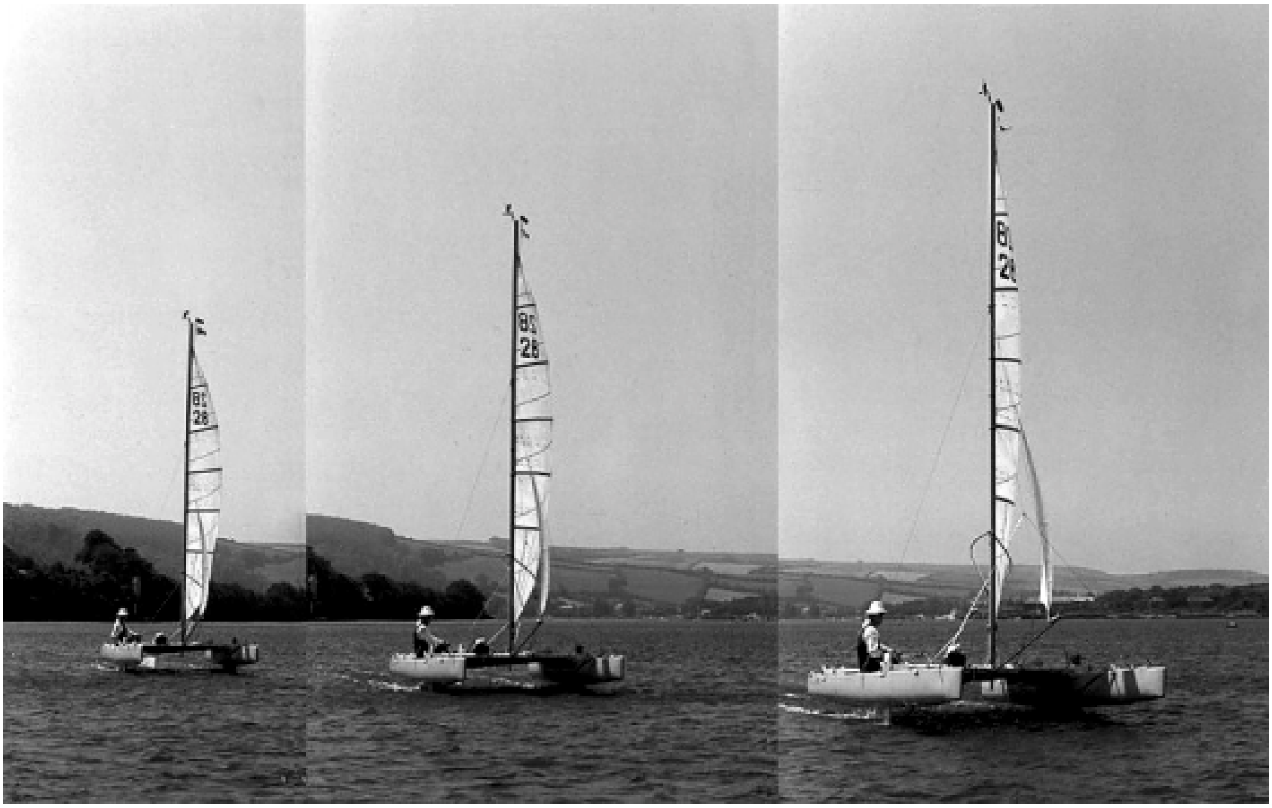


Figure 19. Photomontage of George Chapman sailing Calliope *on 28 June 1994. At this time the 0012 lifters / 0012-34 struts were in use and the wand – foil gain still too high. However, stable flight was possible on flat water.*

Conclusion

The use of incidence-controlled submerged foils has been successfully applied to a 4.9m catamaran that can be operated single handed from a conventional boatyard. Problems of ventilation on the vertical main foil struts were overcome by adopting a section with a fine, highly polished, parabolic leading edge. Balanced lifting foils of moderate laminar flow section have proved satisfactory. A tendency towards heave instability was eliminated by reducing the effective gain between the height sensor and foil.

Logging data from on-board wind and water speed sensors has enabled a record to be kept of sailing performance. Wind tunnel and towing test data enabled a VPP to be written which has helped us to get the best out of this craft and in designing a successor.

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George (G.C.) Chapman has been a member of AYRS for a very long time. In 1965 he was recorded as fitting a wingsail to an RNSA 14ft dinghy. Later records show a progression of interests through wingsails to speedsailing and later to hydrofoils. His son, Joddy (E.J.C) has followed in his footsteps and is now researching into Junk rigs at the University of Exeter, UK, sponsored by the Junk Rig Association.

Figure 20. Joddy Chapman sailing Calliope *on 13 September 1995. Bowsprit wind sensors, instrument pack on Starboard side of main beam and video camera outboard of leeward hull (recording foil behaviour) are visible.*

References

Abbott, I.H., von Doenhoff, A.E. (1959). Theory Of Wing Sections. Dover, New York. pp 524-525.

Alexander, A., Grogono, J., .Nigg, D. (1972). Hydrofoil Sailing. Juanita Kalerghi, London. ISBN 0 903238 004

Bethwaite, F. (1993). High Performance Sailing. Waterline Books, Shrewsbury, England. ISBN 1 85310 337 3. pp 237-243.

Chapman, E.J.C., (1994). Small Craft Performance Measurement, Multihull International vol .27 no. 320, pp 274-275.

Chapman, G.C. (1977). The John Player 1976 World Speed Sailing Record Attempts. AYRS Publication no.87, pp 3-9.

Chapman, G.C. (1985). Why Aren't Hydrofoils Faster. Multihull International, vol.18 no. 206, pp 68-70

Chapman, G.C. (1991). Stable Sailing On Submerged Hydrofoils. AYRS Publication no 108, pp 7-13

Chapman, G C., Chapman, E.J.C. (1995). Instrumented Perofrmance Measurement And Assessment. AYRS Publication no. 119, pp 7-28.

Chiu, T.W., Zino, A.J.P. (1996). Nwing 1.0 For Windows. School of Engineering, Unversity of Exeter.

Grogono, J. (1987). Icarus, The Boat That Flies. Adlard Coles Ltd, London. ISBN 0 229 11803 8.

Guillaumin, J.C. (1998). WindRider Rave Test Report. Multihulls World, no 43, pp 64-67.

Ketterman, G. (1994). Hydrofoils - What Makes Them Work So Well?. Multihulls, vol 20 no. 3, pp 59-61.

Parsons, B.L. (1998). Experimental Techniques For Model Yacht Performance Evaluation – A Review. Ocean Engineering International, vol 2 no 1, pp 1-18.

Pattison, D.R., Wynne, J.B. (1980). Surface Piercing Versus Fully Submerged Foils For Sailing Hydrofoils: The Design And Development Of Two Small Sailing Hydrofoils. High-speed Surface Craft, conference papers. Kalerghi Publications, London. pp 350-365.

Phillips, W.H. and Shaughnessy, J.D. (1976). Investigation Of Longitudinal Control System For A Small Hydrofoil Boat. J. Hydronautics, vol 10 no 2, pp 39-45.

Considering the Future of the America’s Cup

From a talk for the CCA/EYA, 27 April 2000

By Olin Stephens

My feelings on the future of the America’s Cup are split by what it is, what it was and what I wish it could be. I don’t like the course the Cup has taken and would like to see major changes but I have to believe that, for a while, it will continue much as it is.

In the world as it is, we see Seattle as a potentially able challenger. That is a club or area that may well have just what is needed. Aircraft and computer expertise and plenty of money.

I believe that winning the Cup has always had a lot to do with management, but it is now not only “like a business” but it is a business every step of the way, getting the money and seeing that it is spent right. That is management. The search for new possibilities is surely open. One, I will mention.

I have recently seen a suggestion, highly intriguing to me, made to the AYRS, by a Dr. Bussard, who sails in San Diego, that the central wings used by the New Zealanders ballast bulb could have acted as hydrofoils to lift the hull enough to reduce the hull drag more than the added drag of the foils. He believes that they first used this in 1995. My own rough analysis shows the two drag sources a close stand off but careful design seems likely to justify the suggestion, particularly as the greatest benefit would occur at the higher range of windward speeds, a condition in which N.Z. was fast in both matches.

New Zealand had a well organized team in which the design and the sailing were beautifully coordinated. They knew the tricky race area and their boat handling was perfect, but over all else they had a faster boat. They could in the future be vulnerable as, to my knowledge, they have no aircraft industry. Seattle has an advantage there, as well as the whole U.S. in both personnel and facilities. Today’s fast boats need top technology primarily in the area of fluid mechanics. They need that kind of knowledge, supported by full scale sailing data, as well as wind tunnel and towing tank facilities. That seems the way to go and I believe that there are opportunities to do even better in the rig, the sails and appendages. A good VPP could serve as a checklist with every step a point to search for improvement. Use of lift is just one possibility.

The other side is very different. For me the intent of the Cup’s donors has been completely distorted by the extent to which the Cup races have become big business rather than sport. That is the result of commercial sponsorship which has grown into a whole complex of money making effort. It is not a contest between nations represented by clubs and supported by owners driven by sport and pride in their country. The clubs and the commercial sponsors do not mesh well.The sponsors are in it for the advertising dollar and the sailors and designers are only by formality related to the nationality claimed,

My true personal feeling is that the Cup should be withdrawn from competition and a professional World Cup put into play between crews representing whomever but without fake restrictions. I am not against professional sport, which has been successful in many fields, but I am against upsetting a great tradition. Clear of the name “The America’s Cup” the competition could be open and honest, no longer pretending to be something it is not.

I know that the NYYC leadership hoped to be able, if they had won, to go to the New York State court, and to set up a new trustee system to impartially administer future matches. The court was evidently asked about retiring the cup as it told the club that could not be done. The club considers that it would have to be holder of the Cup to take any such step, and so that is not possible now. I would still like to see the N.Y. club enter into discussions with the Italians and the New Zealanders, if only to enforce binding rules on the nationality of designers and sailors. That would help to restore meaning to the America’s Cup.

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Why America Can't Win the Cup: *Foiled Again,* by Better Design

by Dr. Robert Bussard

When Dennis Connor lost the America's Cup in 1983, it was by the narrowest of margins to the Australians, who were driving a new concept IACC boat. On the lecture circuit the following year, Dennis explained the loss with the simple phrase, "The better crew lost to the better boat." While seemingly self-justifying, this explanation was both accurate and technically correct. The Australians *did* have a better boat; they had used wings on the keels for the first time in IACC racing, while the US boat, *Liberty*, had none.

The effect of these fixed horizontal wings, or hydrofoils, was to increase the effective aspect ratio of the vertical keel, thus giving it less induced drag for a given lift, and to reduce leeway by the additional lateral force provided by the tilted wings when the boat was heeled. The margin of performance improvement, though small, was enough to match the performance of Connor's boat in the series, and to beat it in the final race.

After this loss, all US design teams turned to winged keels, and these became a staple of IACC boat design. The first Cup use of this by the US contenders was in the rematch at Perth in 1987, when Connor soundly trounced the Australian defenders, 4-0, with an average margin of about 1.6 minutes per race. This time the boats were equal in inherent performance ability; both had nearly identical winged keels that gave the same performance improvements as seen in 1983.

Having won by copying the Australian design lead and matching boat performance, US designers (and those of other challenger nations) continued on

The 2000 America's Cup—A Short Course

The America's Cup, as it is currently sailed, consists of two separate but related regattas; the Louis Vuitton Cup, where challengers vie for the right to challenge, and the America's Cup itself. The name is a bit of a misnomer, because although the Cup, nicknamed after its first winner, the schooner *America*, has been held by US yacht clubs for an unprecedented 134 years, three of the last five AC regattas, encompassing nearly 20 years, have been won by non-Americans.

All races now are two-boat "match races" sailed between restricted-design boats built to the IACC (International America's Cup Class) Rule. Typical dimensions for an IACC boat are: LOA 23.8 meters, beam 4.3 m, draft 4.0m, SA upwind 364m^2, downwind 730m^2, disp 24,000kg. These boats are thus very powerful, very fast, very expensive monohulls.

This year, the race was run on a 6-leg windward/leeward course, without reaching legs, for a total length of 18.5 miles. Race times varied of course, but averaged a bit over 2 hours.

The Louis Vuitton Cup consists of a large number of round-robin races, leading to a semi-final round, then a two-boat final round. The semi- and final rounds are a best-of-9 race series, in each case. The final round of the 2000 LVC , sailed from 26 Jan through 6 Feb, 2000 pitted Italy's *Prada* against USA's *AmericaOne*. *Prada* won the series 5-4 in a very close match. Her five wins were by an average of 63 seconds, her four losses were by an average of 51 seconds. Call her 10-12 seconds faster than the Americans, per race. This is a bit over one-half second, per mile.

The America's Cup races, sailed between *Prada* and *New Zealand*, were a "walk away." *New Zealand* won in five straight victories, with an average win of 1.6 minutes. Her 5 second per mile advantage was simply too much for the Italian boat to overcome.

NZL 60's legendary keel. Designers Laurie Davidson, Tom Schnackenberg OBE, Nick Holroyd and Mike Drummond pose alongside. —Quokka Sports, Inc.

with the same design philosophy that brought the Cup back to the US in 1987. Thus the AC series sailed in 1995 saw, on the US side, a variety of attempts to modify and improve the basic horizontal winged keel concept, but nothing really new. Wings on keels were thought of as keel extenders and leeway stabilizers, and that was all. The few innovations tried (e.g. curved wings on rudder tips, drooping foils on the keels, etc) seemed to be based more on whimsy than hydrodynamics. The series was run and, in what was almost a reverse mirror of the 1987 Perth races, the New Zealand team swept it 5-0, with a margin of nearly 2.0 min per race, beating Connor again. But, if all the boats were equal, how could this have happened?

Unfortunately for the US, this was—once again—a case where the better boat provided the margin for victory (given that both crews were comparably competent). How so? It was very simple. The Kiwi design team, not content to follow standard thinking on the function of wings/foils on keels, noted that the one thing hydrofoils are really good for is to provide lift. All yacht design books since the early 1980's had discussed keel foils, but none had ever described them as a means for providing lift to the entire boat. This idea was non-existent in the design literature and the design mind, as seen at racing yacht design conferences of that era (e.g. the Chesapeake Yacht Design Symposium, Annapolis, MD, biennial in odd years, et al).

But not in the NZ design team's mind. There, with the team headed by Laurie Davidson, jointly with Doug Peterson, was Tom Schnackenberg, trained as an engineer/physicist, who saw the nature of lifting foils with great clarity. It was obvious, given the limits of the IACC design rules, that the only way to increase boat speed was to reduce total drag, and the only way to reduce total drag was to reduce hull wetted area (friction drag) and effective displacement. Yet reducing true displacement meant reducing structure mass available for load-carrying—which was not a good idea, witness the death of *One Australia* in the contender trials. And reducing wetted area meant making a smaller boat, which was not a good idea, given the need for maximum sail area, lesser heeling moment, and the limits of the Froude equation for wave drag.

Voila, the solution was clear; provide some lift from the keel foils, and thus reduce the effective displacement of the entire boat. This would lift it slightly above its static waterline when underway, and thus reduce wetted area and friction drag, as well as wave drag (which varies as the cube of the speed). The net result would be a faster boat, if the lift/drag ratio (L/D) of the keel foils was larger than the displacement/drag ratio of the original (unlifted) boat configuration.

Analysis of this prospect shows that a foil area of about ten square feet can be used to give approximately 1600 lb of lift (in typical race conditions), and reduce total drag sufficiently to achieve a speed increase of about 1% over its unlifted condition. This gives a margin of about 2 min per race over the San Diego course used for the 1995 America's Cup - and that is just how Connor was beaten in the series. Clever Tom Schnackenberg!

Now we are about to do it again - lose, that is, to the better boat. How and why? Because Tom Schnackenberg and Laurie Davidson are still there. They have had 4+ years to improve and refine their lifting foil concept, to get some of its bugs out of the way, while none of the US designers has yet a clue about this functional advantage of properly designed and mounted keel-foils. The only other contender that has a chance at the Cup is *Prada*, and this is because Doug Peterson - who was part of the Kiwi boat design team for 1995, heads the *Prada* design team (together with German Frers). It is certain that he remembers the advantage of foil lift, and has incorporated it into *Prada*. And *Prada* is leading the contender trials as this is being written.

What bugs can there be? To answer this question it is necessary to describe the keel-foil system in a bit more detail. The equations that describe the overall lifting foil performance show that there is an optimum angle of attack (AOA) for foil use to suit differing wind (and sea state) conditions. The ideal case would be to adjust the foil AOA while racing, to best fit the conditions at that moment. But, of course, that would be illegal as the rules only permit one movable surface (excluding kelp cutters - more about these later) below the waterline on such boats. However, it is evident that the best way to test the foil system is to have a continuous adjustment from above decks so that one can trial sail against another identical boat with fixed foils. It is likely that this was what the NZ team did before the 1995 series.

Their final race boat, *NZ-32* had keel foils mounted at the aft end of the bulb, on a straight through axle, so that foil rotation could be accomplished by turning the axle. This was attached to a moment arm that passed inside the bulb to a vertical adjustment arm by which the AOA could be set. A machined airfoil section flat was on each side of the bulb to reduce local turbulence. Finally, each (straight) foil had a retractable knife edge kelp cutter along its leading edge, which could be motor-driven out and back, as needed. When retracted, the forward edge was closed by a covering membrane, to preserve good aero/hydrodynamics.

When running downwind, under spinnaker, the effect of a fixed AOA set for upwind leg conditions would be considerably reduced. This is because the sail load moments tend to pitch the boat forward and thus reduce the effective AOA, and the leeway reduction upwind would not be seen on the downwind leg. And the Kiwi boat did not win the downwind legs by any significant margins. This can be corrected - and most probably has by now, by Schnackenberg, et al - by moving the foils forward from their position at the aft end of the bulb, and/or by another trick, using the kelp cutter blade. If the kelp cutter blade is designed with a slight curvature, it can act as a leading-edge flap when extended, and thus provide increased lift for any given positive angle of attack. Hence, the allowed kelp cutter can be metamorphosed into an aerodynamic lifting feature of the keel-foils, for use when the basic foil lift is not sufficient, as when running downwind.

The Kiwi foil system design was a closely held secret, to which it is likely that only a few of the NZ design and sailing team members were/are privy. In 1995 I had a chance to examine the bulb/keel system on NZ-32 before it returned to New Zealand, and have since—again by chance —seen details of the design and construction of the foils themselves. The NZ design team has very bright and clever people, who are not afraid of innovation, who have used it to win the Cup once, and who do not think that they already know everything there is to know about yacht design. As Peter Blake has said (Sailing World. Collector's Edition on the America's Cup, Dec. 1999, p. 14), "There may be a better way. As soon as we think we have got it right, we are lost." And the Kiwis are NOT lost, they are most likely to keep the Cup, just because they are better designers with more open minds.

— Dr. Robert W. Bussard ,
27 December 1999

Dr. Bussard is an engineer and physicist, and a member of the AYRS. He is engaged in development of new energy sources as Technical Director of Energy/ Matter Conversion Corp (EMC2). He sails his Olson 40, Uproarious, out of San Diego, California. Email: EMC2QED@compuserve.com

[It is important to note the date of this article. Dr. Bussard waited until late 1999 to write the article in order to avoid having it affect the design of any of this crop of IACC boats. Nevertheless, it was written, and received by AYRS, before the Louis Vuitton Cup finals were begun.—Ed.]

Wingmast Aerodynamics

by Tom Speer

The aerodynamics of sails alone, and the aerodynamics of round masts plus sails have been studied for some time, both in theory and in the lab. Likewise, rigid wing rigs can benefit from the body of knowledge aimed at aircraft high lift configurations; but there's very little information on wingmast-sail combinations. I've used some well known airfoil design programs to calculate the characteristics of wingmast-sail airfoils, and I'm beginning to appreciate just how remarkable this combination is.

Before I get into the aerodynamics, a cautionary note about the limitations of the methods I've used: The theoretical methods I have are strictly two dimensional. That is, they apply to the cross section of a shape that is infinite in length and rigid. A real soft sail is inherently a three dimensional, flexible problem, since we all know that the shape of the sail is affected by the tensions up and down the sail, as well as the tension in the streamwise direction. So you really have to combine the material strains and the aerodynamics of the whole rig to get the true picture; but 2D isn't a bad approximation and it has a lot to say about the cross section shape. The other limitation is that the programs I have cannot really handle separated flow – but they can identify the onset of separation, and they have some empirical methods for indicating whether the surface's stall characteristics will be gradual or sharp. So take things with a grain of salt, and I hope this clears up a some misconceptions.

Flow Features

The basic features of the flow around a wingmast-sail combination are sketched in *Figure 1*. As the wind approaches the leading edge, part of it will pass to leeward, part to windward, and the dividing line between the two will come to a complete stop near the front of the mast. This is what we call the stagnation point, and it's where you'll find the highest pressure on the whole airfoil. Everything else is downhill from here. As the air whips around the leading edge, it speeds up tremendously because of the low pressures needed to make it bend around the sharp curve. So in a short distance, it goes from dead stop to the highest velocities it'll see on the whole airfoil; but it has to slow down to get back to something near ambient pressure by the time it gets back to the trailing edge.

A computed velocity distribution for a typical wingmast-sail combination is shown in *Figure 2*. The velocities are generally faster on the leeward side,

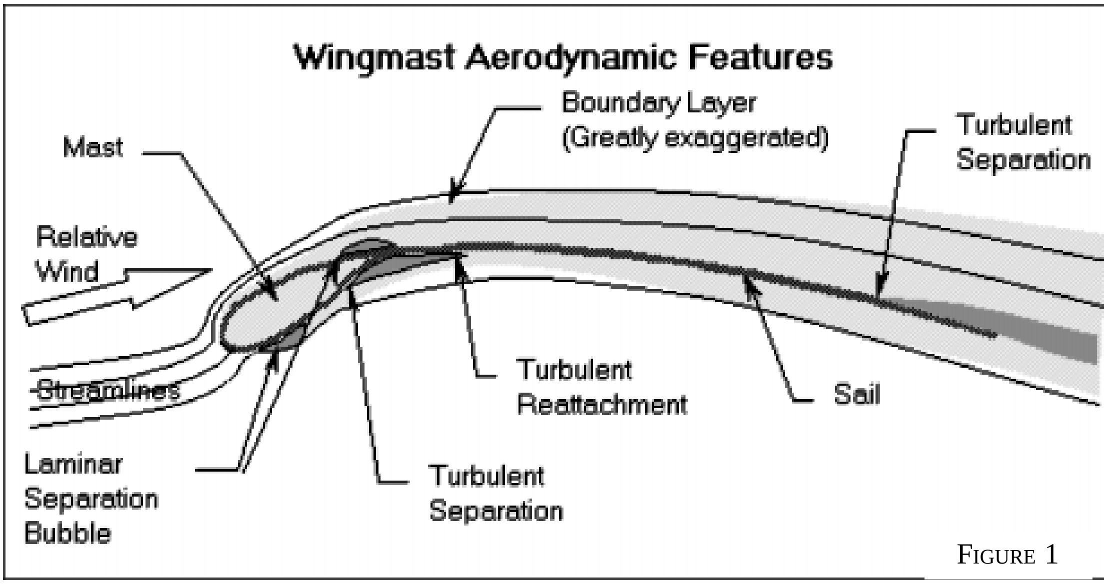

FIGURE 1

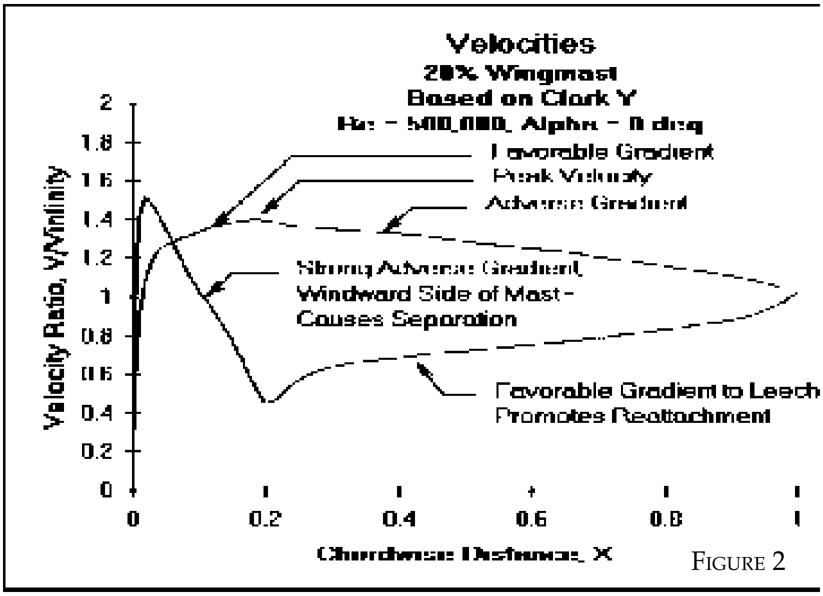

FIGURE 2

determined by the boundary layer, because without it, the pressures would add up in such a way that there'd be no net force. To get good performance, you have to stress the boundary layer hard. But push it too far, and it'll let go and your rig stalls. So the art of airfoil design turns out to consist of manipulating the pressure distribution in order to manage what's going on in the boundary layer.

At first, near the stagnation point, this boundary layer is very thin, but as you trace the flow downstream, the boundary layer gets thicker because the air slowed by the upstream surface continues to drag on the air farther out, and the air next to the surface is slowed down some more. So the effect of the surface diffuses outward into the flow.

At some point, the boundary layer can't maintain this smooth state of affairs, and eddies start to appear. This is known as the transition from laminar (the smooth flow) to turbulent flow. A turbulent boundary layer is much thicker than a laminar flow, because the eddies are taking big chunks of low velocity air from near the surface, and throwing them some distance away from the surface. They are also bringing some of the higher velocity air from outside down closer to the surface. This higher velocity air gets slowed down, naturally, so this causes the "skin friction" of the turbulent boundary layer to be higher than the laminar boundary layer; but the turbulent boundary layer is not all bad, as you'll see later.

and slower on the windward side. A guy named Bernoulli proved that when air isn't sustaining any losses, which is pretty much true of the air everywhere but near the surface or in the wake, high velocities mean low pressure, and vice versa. So the pressure distribution has much the same shape, with low pressure on the lee side and higher pressure on the windward side. The area between these two curves represents an unbalanced force acting at right angles to the flow—the lift force. We want the two curves to be as far apart as possible to give us the most lift – but they have to come together at the end.

Now it's a strange but true fact that the air that is immediately in contact with the surface sticks to it and does not move! This air drags on the volume of air going by just outside of it, which drags a little less on the volume outside of that, and so forth. The result is a thin boundary layer, in which the airflow relative to the surface goes from zero velocity to whatever the local velocity is just outside the boundary layer. If you add the thickness of the boundary layer to the surface, you effectively get a new shape that the air has to flow around, and this determines the velocities of the flow throughout the rest of the flowfield. These velocities, through their corresponding pressures, have a profound influence on the boundary layer. So there's this intimate dance between the two.

It's another strange but true fact that all of the forces on a body are

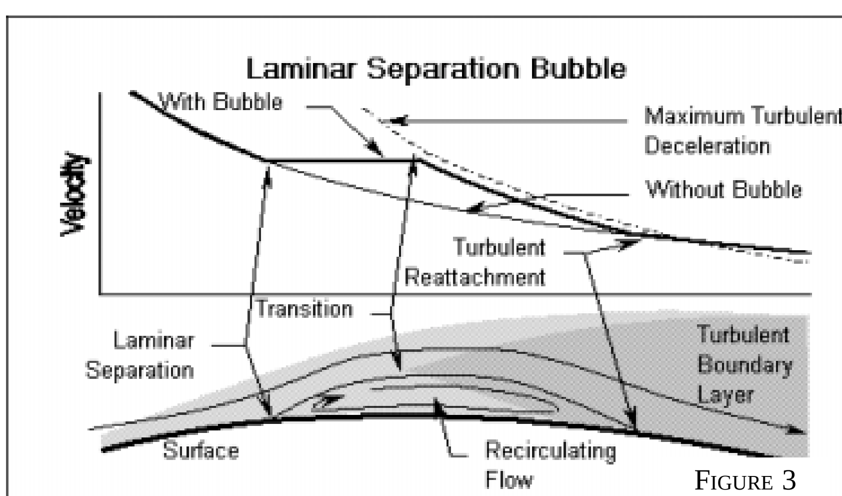

FIGURE 3

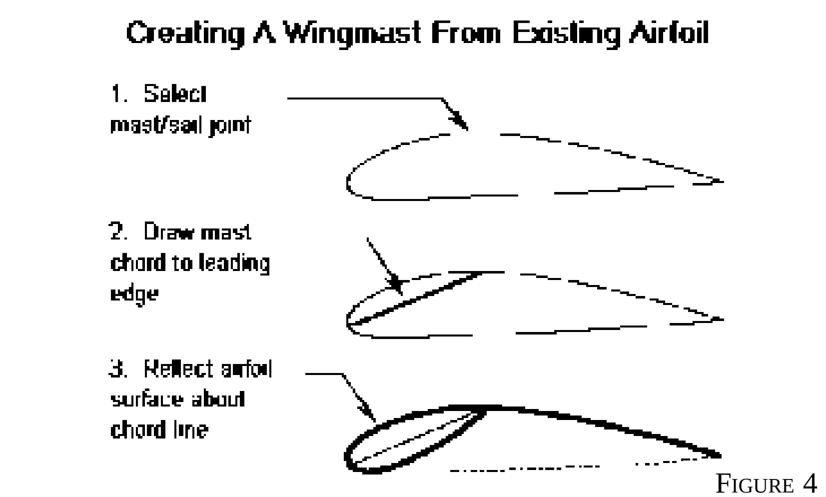

FIGURE 4

There are something like four ways the flow can transition naturally to turbulent flow. Two (cross flow and attachment line instabilities) only apply to swept wings at high speeds. Another, in which small disturbances moving downstream in the flow get amplified until they turn unstable and kink up into eddies, can occur in landyachts in high winds. Delaying this kind of transition (Tollmein-Schlichting instabilities) is what the famous NACA laminar flow airfoils (the 6-series designations) were designed to do, but, given the size of our rigs and the speeds at which we operate (especially in light winds), the laminar boundary layer is stable enough that we will almost certainly see the transition occurring after laminar separation.

If the pressure is decreasing (which means the air velocity outside the boundary layer is increasing), then it sucks the disturbed air along, and things keep flowing smoothly. If the flow is running into increased resistance, as when the pressure is increasing, then air next to the surface can finally run out of steam and get pushed backward. When this happens, the flow separates from the surface. Now a laminar boundary layer is much more fragile in this respect than a turbulent boundary layer. So we want to maintain a fair amount of laminar flow so as to keep skin friction low, but we want the flow to be turbulent as the air slows down heading back to the trailing edge. By using the turbulent boundary layer's ability to slow down more, we can use higher velocities up front and get more lift. A laminar boundary layer is a little like driving on ice. You don't dare go too fast because you can't slow down quickly. A turbulent boundary layer is like driving on wet pavement - you've got better braking, so you can go faster without breaking loose. We want to get off the ice and onto the wet pavement before we have to start braking hard or we'll lose it!

Figure 3 shows what we want to happen when the laminar boundary layer separates. Right after it separates, the pressure becomes constant, which is characteristic of all separated flow, and the flow becomes unstable. Soon eddies form and the flow becomes turbulent. When this happens, the pressure increases at pretty much the maximum rate that a turbulent boundary layer can sustain. If this pressure increase intercepts the pressure dictated by the shape of the surface itself, then the flow reattaches and forms a laminar separation bubble. If the two pressure curves don't intersect, the flow stays separated and the airfoil is stalled. Within the bubble, the air is recirculating; flowing backward next to the surface from the attachment point to the separation point. In marginal conditions, the bubble might cover a large portion of the surface, but this causes a lot of drag and is very fragile. A small increase in lift and poof – stall! We want a short, robust separation bubble that is positioned where we want it.

So, for a landyacht airfoil, you want to have high velocities on the lee side for high lift, but you don't want a really sharp pressure spike at the leading edge. This would mean a steep adverse pressure gradient there, and stall due to laminar separation without reattachment (the curves won't intersect).

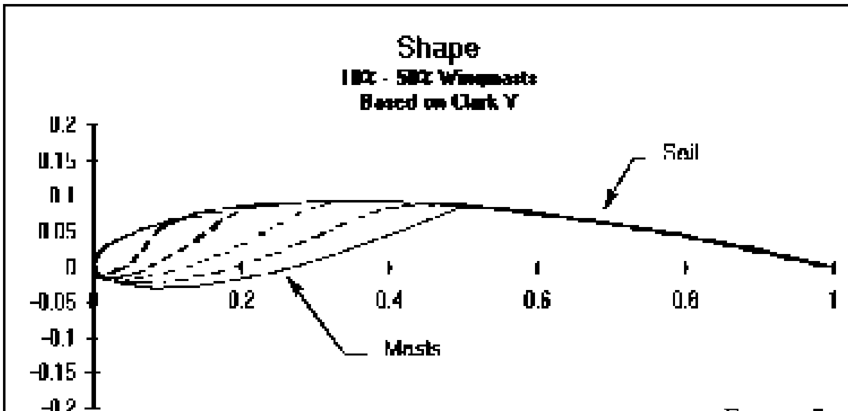

FIGURE 5

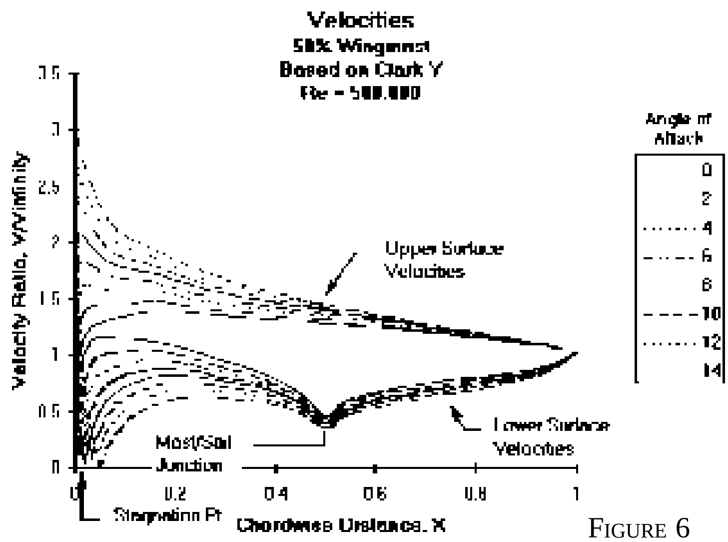

FIGURE 6

Instead, when stall occurs, you want it to start because you've stressed the turbulent boundary layer too much at the trailing edge, and you want the turbulent separation point to move forward gradually as you increase the angle of attack. This makes for a gentle stall and a forgiving sail rig.

Now lets take a look at *Figure 2* again, but this time focusing on the windward surface velocities. Notice that there is a peak velocity near the leading edge, and a steep drop to the joint between the mast and sail. This adverse pressure gradient will lead to laminar separation, hopefully followed by turbulent reattachment, and finally turbulent separation before the flow gets to the joint. But look what happens after the joint: the velocity is increasing all the way to the trailing edge, which means the air is being sucked along. It isn't fighting an uphill battle the way it is on the lee side. So once across the joint, the flow reattaches again. This forms a turbulent separation bubble near the mast-sail intersection. This isn't good, but it isn't disastrous, either. It is a price we have to pay for the symmetry of the wingmast.

If the pressure increase on the mast's windward surface is too great, which happens at low angles of attack, the flow separates and does not reattach. This pretty much sets the minimum angle of attack for that shape. Small wingmasts have a much shorter distance between the peak near the leading edge and the joint at the sail. So the pressure increase is much steeper for small wingmasts. This means that a small wingmast has a narrower range of useable angle of attack between separation on the windward surface at low angles, and stall at high angles. Of course, the mast can be rotated to help alleviate this. But the fact remains that a small wingmast will have a narrower "groove" than a large wingmast. This will make it more difficult to trim well, and it will be more affected by changes in the local flow angles along the mast, such as from gusts or wind shear. But it may also be lighter in weight and have less drag when it's in the groove.

Design

OK, so how do you come up with a shape for a wingmast? The best way is to design a mast and sail shape together, starting with the kind of pressure distribution you need. You want it to have characteristics which cause the laminar separation point to move smoothly from well aft on the airfoil at low angles of attack, to near the leading edge at high angles of attack. This will help to avoid leading edge stall due to laminar separation, and make for a progressive stall due to turbulent separation. Unfortunately, this requires a computer program to calculate the resulting shape.

An approach I've come up with is based on modifying an existing airfoil. The conventional way of looking at airfoil aerodynamics is to represent the airfoil as a mean camber line plus a symmetrical pressure distribution. This was a good way of calculating the velocities in the days before computers, because you could calculate each one separately and superimpose the results. However, another way of looking at it is to consider each surface separately.

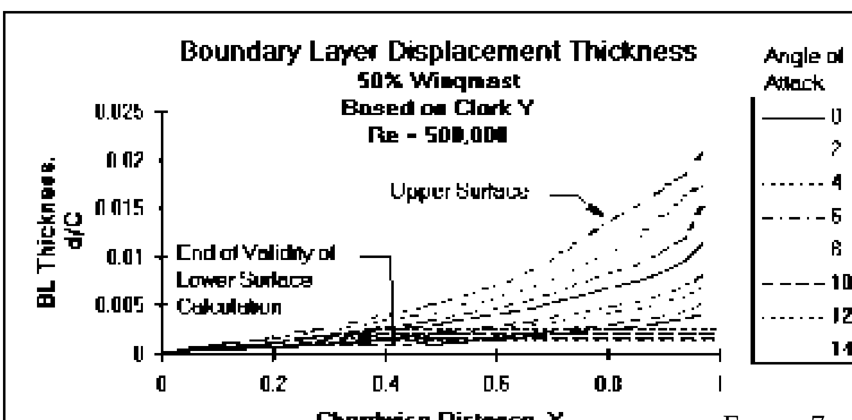

FIGURE 7

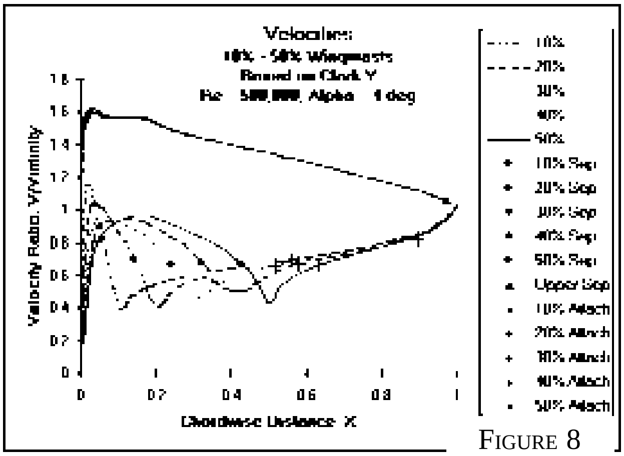

FIGURE 8

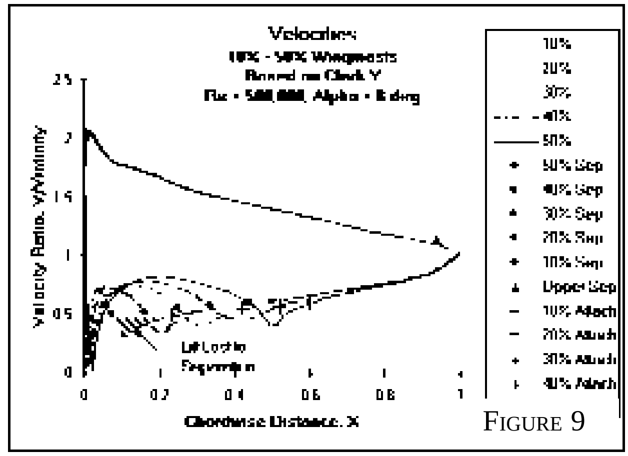

FIGURE 9

The velocity at a given point is heavily influenced by the airfoil's curvature at that point. The more convex the surface, the more negative the pressures will be in order to bend the flow. Likewise, a concave surface will tend to have high pressures or an adverse pressure gradient in order to bend the flow the other way. So if we base the wingmast-sail shape on the lee side contours of an existing airfoil, the characteristics should mimic that airfoil's characteristics to some extent. This approach works surprisingly well.

Figure 4 shows the steps in the process. First, select an airfoil that has the characteristics you want, especially near the leading edge. It should be fairly thick, because this will determine the draft in the sail shape. It should also have the characteristic that the lee side laminar separation point (transition) moves smoothly toward the leading edge as angle of attack is increased. Next, set the percentage of the chord you want to use for the mast, and mark that on the upper surface. I haven't looked at anything much past 50% chord yet, so I don't know how really humongous masts perform. But the trends up to half the chord have held pretty true.

Now draw a line from the mast-sail joint to just below the leading edge. You'll want to place the end of the line so that it is perpendicular to the airfoil contour. If it's too far up, you'll get a sharp crease at the leading edge, and if it's too far down, you'll get an indentation. Finally, measure off the distances perpendicular from the line to the airfoil contour, and lay out points equally distant to the other side of the line. This forms a reflection of the part of the airfoil and completes the wingmast airfoil. That's all there is to it.

Predicted Results

Let's work through a typical example. I picked the classic Clark Y airfoil, because it has been a proven performer over a wide range of conditions. I used the procedure above to create a family of wingmast/sail combinations, with mast sizes ranging from 10% of the total chord to 50% of the chord. The resulting airfoils are shown in *Figure 5*. With a larger chord, the wingmasts get physically thicker, and the mast rotation flattens out.

Velocity distributions for 10 different angles of attack are shown in *Figure 6* for the case of the largest mast (50% chord). Note that the lee side velocities peak near the leading edge, and nearly the whole lee side has an adverse pressure gradient. This is typical of airfoils designed for low speeds, in order to give the flow the maximum distance to coast down from the maximum speed and to avoid any steep gradients that might cause the laminar separation bubble to "burst" (fail to reattach).

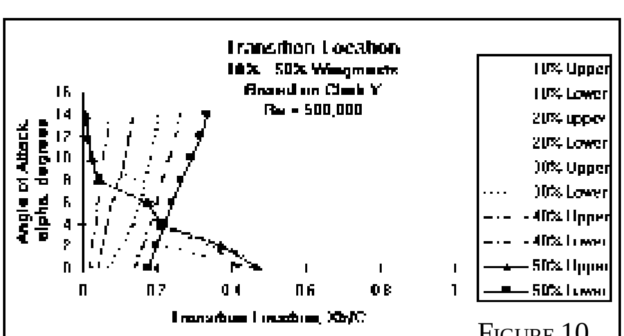

FIGURE 10

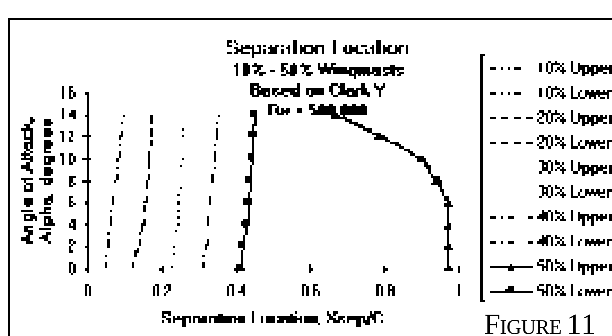

FIGURE 11

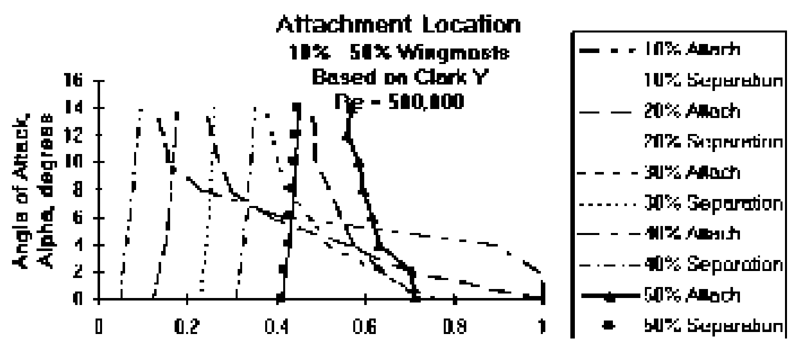

FIGURE 12

Figure 7 shows the corresponding boundary layer displacement thickness to give a feel for just how thin it is. These thicknesses assume that all the flow is attached. The boundary layer computation cannot handle separated flow, so it fails on the windward side approaching the mast/sail junction.

Figures 8 and 9 show the effect of changing mast size while keeping the angle of attack constant. The velocities over the lee side are nearly unchanged. But the big change is in the windward side. The windward suction peak is significantly smaller in magnitude for the larger wingmasts, and the steepness of the adverse pressure gradient is dramatically less.

I've marked the predicted separation points on these curves as well. At four degrees angle of attack, the upper surface is fully attached. At eight degrees, separation is just starting to set in on the upper surface, and as the angle of attack is increased, it will move forward on the sail and the stall will deepen.

The windward side is very interesting. The flow separates on the back of the mast because the flow is slowing down sharply as it approaches the mast/sail junction. As with the laminar separation bubble, the pressure is probably a constant in the separated region. So I've assumed that the flow reattaches when the velocity comes back up to the same level it was when it separated. This has the effect of chopping off the dip in the velocities there, and results in some loss of lift, as shown in *Figure 9*.

This loss is negligible at higher angles of attack, but at low angles of attack the rig suffers something akin to leading edge stall. *Figure 8* shows what's happening. The velocities form a sharp peak as the air has to turn through a greater angle going around the leading edge at low angles of attack, particularly for the smaller wingmasts. The steep deceleration after this sharp peak causes the flow to separate early, and for the 10% wingmast, the flow doesn't reattach until almost the leech; and at lower angles of attack, it won't reattach at all. A soft sail would be luffing under these conditions, but a wingmast might not.

The next figures show the trends in these key boundary layer events as the angle of attack changes. They also show how these trends vary with the different mast designs.

The transition location, *Figure 10,* shows where the laminar separation is taking place. Transition and reattachment are assumed to happen closely after that. As the angle of attack increases, the adverse gradient on the lee side becomes progressively steeper, *Figure 6*. So the velocity reaches the slope needed for laminar separation at an earlier point on the airfoil. The opposite is happening on the windward surface. However, the movement here is not very great - the slopes are dominated by the proximity of the mast/sail junction and the leading edge, rather than by the angle of attack.

The same thing is happening with the turbulent separation points, just farther back, *Figure 11*. On the lee side, the flow is essentially fully attached through six degrees angle of attack, and doesn't really move too far forward until after 10 degrees. The windward side separation on the wingmast stays parked just upstream of the mast/sail junction. Things get a lot more interesting on the windward side when the reattachment points are shown as well

Figure 12 has the same windward separation points as *Figure 11*. The distance between the

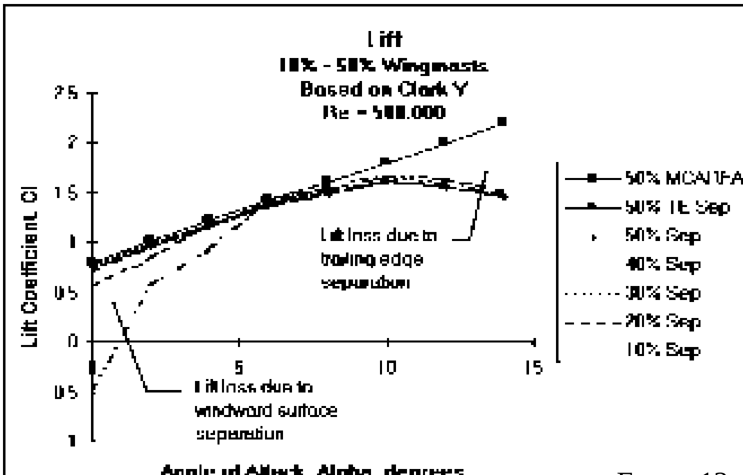

FIGURE 13

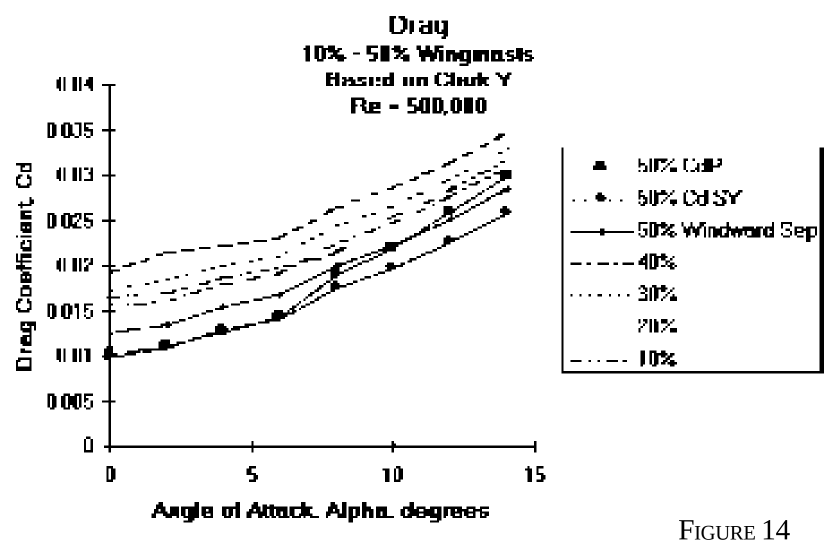

FIGURE 14

separation lines and the reattachment lines shows the extent of the turbulent separation. The sudden growth in the separated region at low angles of attack for the small wingmasts is clearly evident. The large wingmasts are affected, too, but not nearly as much. Besides having a smaller separation region, the large masts also have lower velocities to start with, so the separation penalty for them is not so great.

This is shown in *Figure 13*. The top line, labeled "MCARFA" is the lift curve as computed, assuming that the flow is fully attached everywhere. At large angles of attack, I've simply reduced the lift in proportion to the amount of separation predicted for the lee side. At low angles of attack, I've modified the results by assuming that the pressure is held constant across the windward separation region.

The narrow groove of the small wingmasts is apparent here. The 10% chord wingmast performs well between six and eight degrees angle of attack. Above 6 degrees it starts to stall, and below four degrees it starts to suffer separation on the windward side. The large masts (175 and up) have the same stall characteristics, but don't suffer from a loss of lift at low angles of attack. 20% chord looks to be just a little on the small side, as it suffers from a modest loss at low angles of attack.

The drag penalty of the windward separation region is shown in *Figure 14*. I haven't added any drag increment for leeward separation. The curve marked "50% CdP" was obtained by integrating the pressures around the largest wingmast section. Getting the drag this way is a notoriously unreliable way to do it. The curve marked "50% Cd SY" uses the Squire-Young formula which is based on the characteristics of the boundary layer at the trailing edge. This is much like measuring the losses in the wake in the wind tunnel to get the drag, and is a much more reliable method. I typically plot both curves as sort of a quality check on the results. When the two are close together, I tend to believe the results more than when they differ.

The curves marked "50% Windward Sep" and on, are the Squire-Young drag results with an increment derived from integrating the pressures with and without the windward separation region. I was surprised to see that this gave a drag increment that was consistent across the whole angle of attack range, and differs mainly with the size of the wingmast.

The 10% chord wingmast starts to approach the results for the largest masts, so it appears that both very large and very small masts can be equally efficient. Provided that the smaller mast is kept in its groove. This may require constant adjustment of the mast rotation to get it to perform.

Figure 15 shows the result of putting the lift and drag effects together. The "50% (Raw)" curve assumes

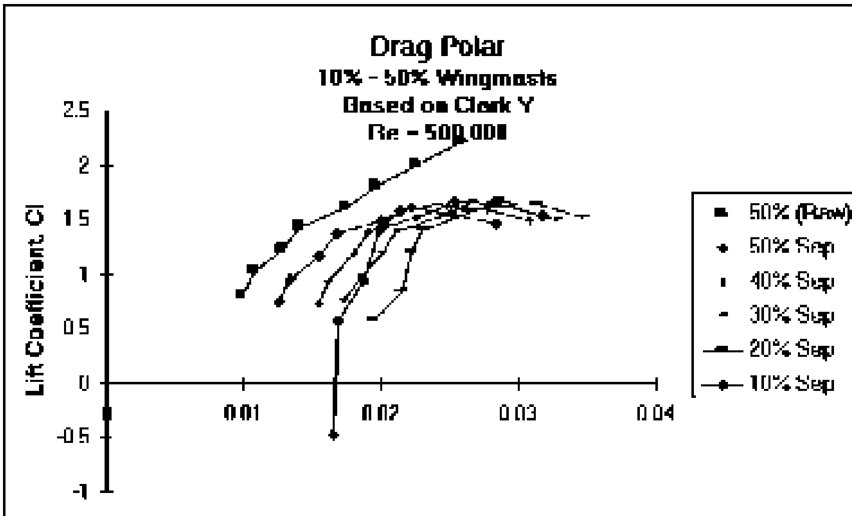

FIGURE 15

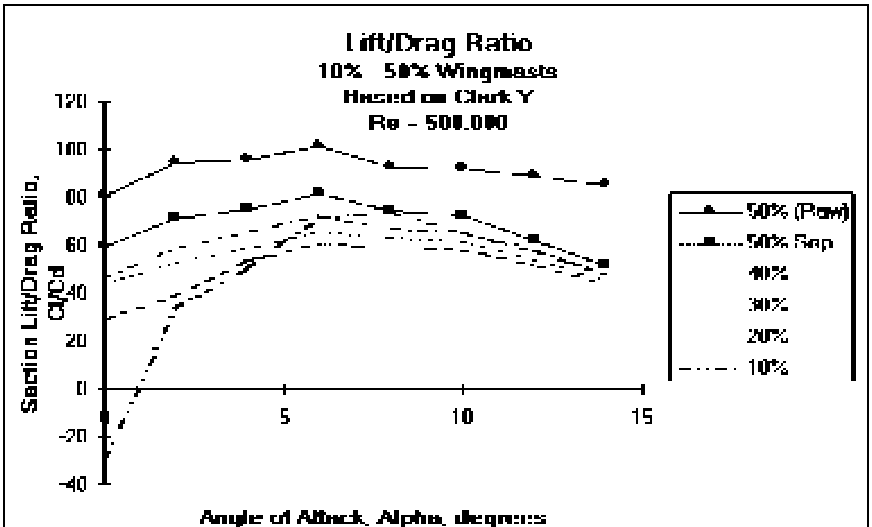

FIGURE 16

the flow is fully attached, while the "50% Sep" curve has both the lee side and windward side separation effects added. Again, the main difference between the different mast designs is their drag.

Finally, the sectional lift/drag ratio for the various masts is shown in *Figure 16*. Once again, the performance of the largest and smallest masts is similar at their peak. But the large mast maintains its performance over a very wide range of angles of attack compared to the small mast.

Wingmasts In Practice

So much for theory; what about real life? The essential flow features I've described - the laminar separation and reattachment, the turbulent separation bubble on the windward side, trailing edge separation at the leech - are real. You can see the larger features by the behavior of telltales. Predicting drag and maximum lift is a tricky business even for the best computer codes, and I don't pretend that the methods I've used will get it right. Experimental data are essential to get numbers you can believe in.

All of the examples I've given have been for one mast position - the one that results in a smooth contour on the lee side. Especially for a large wing mast, trimming the mast is as important as trimming the sail. Indeed, Bob Perry used to sail his big landyacht, *Excaliber Dream*, by sheeting the sail in hard, cleating it, and then trimming only through mast rotation for the rest of the race!

I was once in a position to carefully observe Charlie O'Leary sailing his landyacht, *Speed Squared*. Charlie is a sailmaker by profession, and *Speed Squared* is one of the fastest landyachts in the US. It has a wingmast that comprises approximately 30% of the sail area. Charlie was sailing at high speed almost directly at me, and I was sighting right down his boom. I was astounded to see that he had under-rotated the mast to the extent that the sail curved out to leeward of the mast's trailing edge, producing a pronounced kink in the lee side contour. I suspect that by reducing the mast rotation, he had cut down or even eliminated the windward separation bubble. There was undoubtedly a small separation bubble on the lee side, straddling the mast-sail joint. Evidently, this was the compromise which produced the best performance.

Likewise, wingmasts often have to be over-rotated to get the best acceleration at low speeds and for greater power when reaching. The best way to trim a wingmast will come from experience, but telltales strategically placed may help to make the trim more understandable and repeatable.

A small windvane placed just ahead of the leading edge can help to indicate whether the stagnation point is on the windward side or the lee side. A row of short telltales placed horizontally along the mast and across the sail luff can indicate the extent of the separation bubble. Telltales just ahead of the leech can track the onset of trailing edge stall. These clues can help make sense out of the rig's behavior as the sails are sheeted and the mast rotated.

So that's the story on wingmast-sail aerodynamics. It's not simple, but I hope that having seen the real numbers, you've got a better appreciation of what makes these things tick. It's all theoretical, so if anybody out there has some experimental data, I'd love to compare them with predictions.

See you on the race course.

— Tom Speer

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Modeling the Dynamics of Rowing

by William C. Atkinson

"Modeling the Dynamics of Rowing" describes the computer program ROWING 7.00, a comprehensive model of the dynamics of Eights, Fours (coxed or not), Doubles, and Singles propelled by sweeps or sculls. Given input on boat and rowers as dimensions, weights, inertial modes, coefficients, factors, and chain-pull forces the model estimates, among other things, steady-state boat speed and acceleration, oarlock and rower works (direct and inertial), rower power, and rower and oar blade efficiencies.

The design of Rowing did not emerge seamlessly from the rigorous application of highly theoretical first principles but, rather, took its form from relatively simple engineering concepts coupled with the use of practical mathematical approximations to reduce computational complexity. Rowing divides a single stroke cycle into seventeen "regimes" in each of which forces of friction, propulsion, or momentum act. In addition Rowing divides each stroke into 1,000 computational time intervals. An incremental solution then proceeds, via iteration, for any specified free-return time period or stroke rating. Using initial assumptions for shell speed and for the ratio of the drive (blades-in-water) to the free-return (blades-in-air) time periods, Rowing adjusts the drive/free period ratio until the calculated shell distance traveled during the drive portion of the stroke, as defined by the equation of motion, satisfies the corresponding shell advance, as required by the specified sweep lever geometry. The sweep geometry is a function of chain-pull, oar shaft stiffness, blade "aerodynamics", and the blade longitudinal slip and its zero-slip path. For the momentum calculations Rowing considers four mass concentration points: the shell, the center of mass of the oar, the rower's hip, and the rower's shoulder—to one of which the input assigns each of the various input masses).

Rowing models chain-pull force and the regimes of the momentum exchange forces by means of definable linear and parabolic force or velocity distributions. The ability to specify body momentum profiles may interest coaches who could experiment with pull force regimes and the management of crew momentum. The program interpolates blade hydrodynamics for various planforms and cant angles each from its own dedicated table of lift and drag coefficient vs. fluid attack angle. In this way one could test "row" experimental blade forms, whose characteristics have been carefully predetermined by experiment, by computer in the search for improvements in efficiency. The current state of blade design is a crude and groping process of building multiple trial units on speculation, making them available to understandably cautious crews, and then waiting months or years to discern whether an edge seems to emerge from the statistical noise of race results.

It should be thoroughly understood that this model is a work in progress in the sense that the field data from real, on-the-water boats necessary to confirm its validity are simply not yet available. Any future success for Rowing will depend upon that web of reliable input data and, sadly, there are some gaps and tears in the fabric. The stitching up of any one of these rents would provide a worthy project for any graduate student in applied physics:

No one to my knowledge has measured the air resistance of seated shells. The interpretation of data from instrumented boats depends crucially upon the effects of wind.

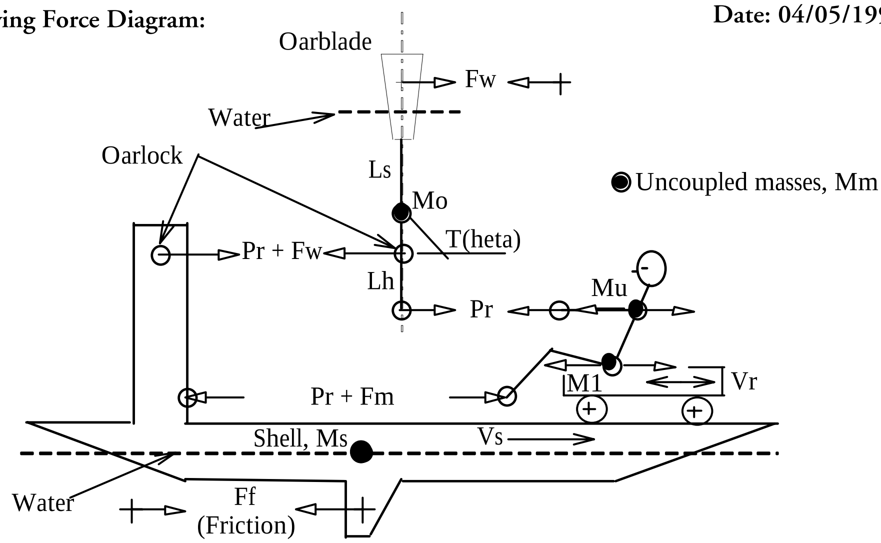
No one has estimated the so-called "added" mass of water bound to the hull as boundary layer thus materially altering the expected momentum characteristic of the boat.

Few have seriously undertaken the comprehensive measurement of speeds, forces, accelerations, weights, and dimensions on the water. I emphasize comprehensive because, for example, a simple speed, force, and acceleration determination for the purpose of confirming a model would be useless without, at the same time, knowing all the pertinent dimensions and weights of the boat, the rowers, the oars, the rigging arrangements, the prevailing wind, and the current.

And most importantly, from the point of view of oarblade design, no one has successfully investigated the lift and drag coefficients of rotating and partially immersed blades. Until better information comes along Rowing can do no better than to make use of published data for totally immersed flat plates of various aspect ratios at various angles of attack.

Unfortunately, and unlike the cases of air resistance and added mass, the measurement of oarblade lift and drag is an order of magnitude more difficult both in cost and time, requiring fairly sophisticated towing tank or other physical arrangements. Nevertheless, as it stands, Rowing can make useful comparisons involving blade surface area. Rowing can usefully compare the effects of changes in shell, rower, and coxswain weights; putting the coxswain on slides; modifying the shape of the pull-force profile, shortening the free return period, changing oarshaft angles at catch and release, etc.. In addition the model can evaluate any variable change affecting shell speed at constant rower power output by varying either stroke rating or peak chain-pull.

Rowing Force Diagram: **Date: 04/05/1999**



Vs = instantaneous velocity of the shell relative to the water, ft/sec
Vm = instantaneous velocity of the uncoupled mass(es) relative to the water, ft/sec
Vr = instantaneous velocity of the uncoupled mass(es) relative to the shell, ft/sec (defined)
dVr/dt = dVs/dt +dVm/dt
Ms = deadweight mass of shell, coxswain, and bound fluid layer, lbm (defined)
Mm = uncoupled momentum mass(es) (Ml, lower, footboard; Mu, upper, oarlock), lbm (defined)
Mt = total mass of system, lbm = Ms +Mm
Pr = instantaneous longitudinal (chain) pull of the rowers on the oars, lbf (defined)
Fw = longitudinal force of the water on the oars, lbf = -Fs = Pr sin2(T) Lh /Ls
Fs = instantaneous net force on shell = -Fw (independent of blade characteristics)
Kf = fluid friction coefficient, lbf (sec/ft)2 (defined, water and air)
Ff = fluid friction force on shell, lbf = -Kf Vs2
Fm = uncoupled momentum force(s) on shell = Mm (dVs/dt +dVm/dt) = Mm (dVr/dt)
Fs = Ms (dVs/dt) = +Ff +(Pr -Pr +Fw) +Fm
Fs = Ms (dVs/dt) = +Ff +Fw +Fm
Fs = Ms (dVs/dt) = -Kf Vs2 +Pr (Lh/Ls) +Mm (dVr/dt)
Differential equation of motion: $T2 - T1 = Ms\int_{Vs1}^{Vs2} dVs \big/ \left(-KfVs^2 + Pr(Lh/Ls) + Mm\left(dVr/dt\right)\right)$
Note: Forces illustrated for 90 degree oar angle instant only (sin(T)=0; cos(T)=1).

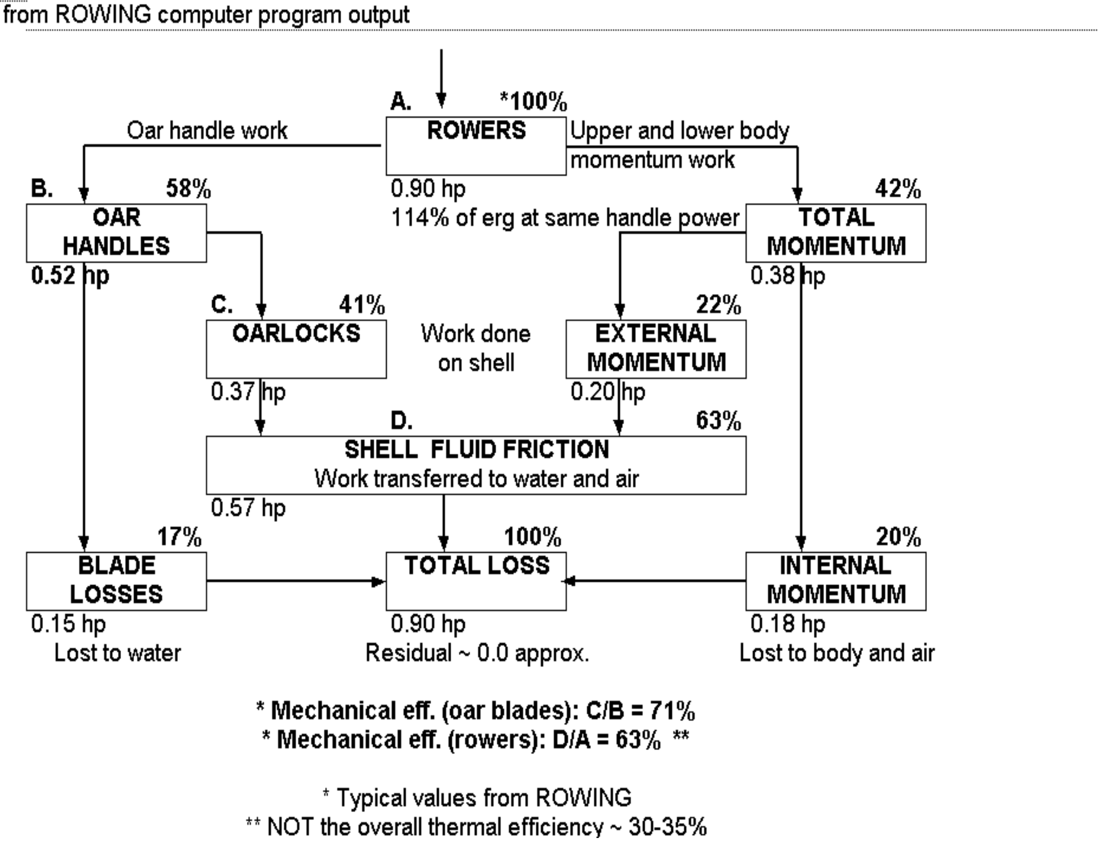
Heretofore no one has devised a practical or satisfactory method of evaluating (or even of measuring) the true longitudinal slip of an oar blade under load. I believe that Rowing, via its unique mathematical definition of the zero-slip path, provides a useful solution.

Examples of independent data taken from instrumented shells under field conditions on the water are extremely rare. Having found one such data set it has gratified me to find that Rowing will model its speed, acceleration, and footboard force curves almost exactly.

The Input Data Accepted by Rowing

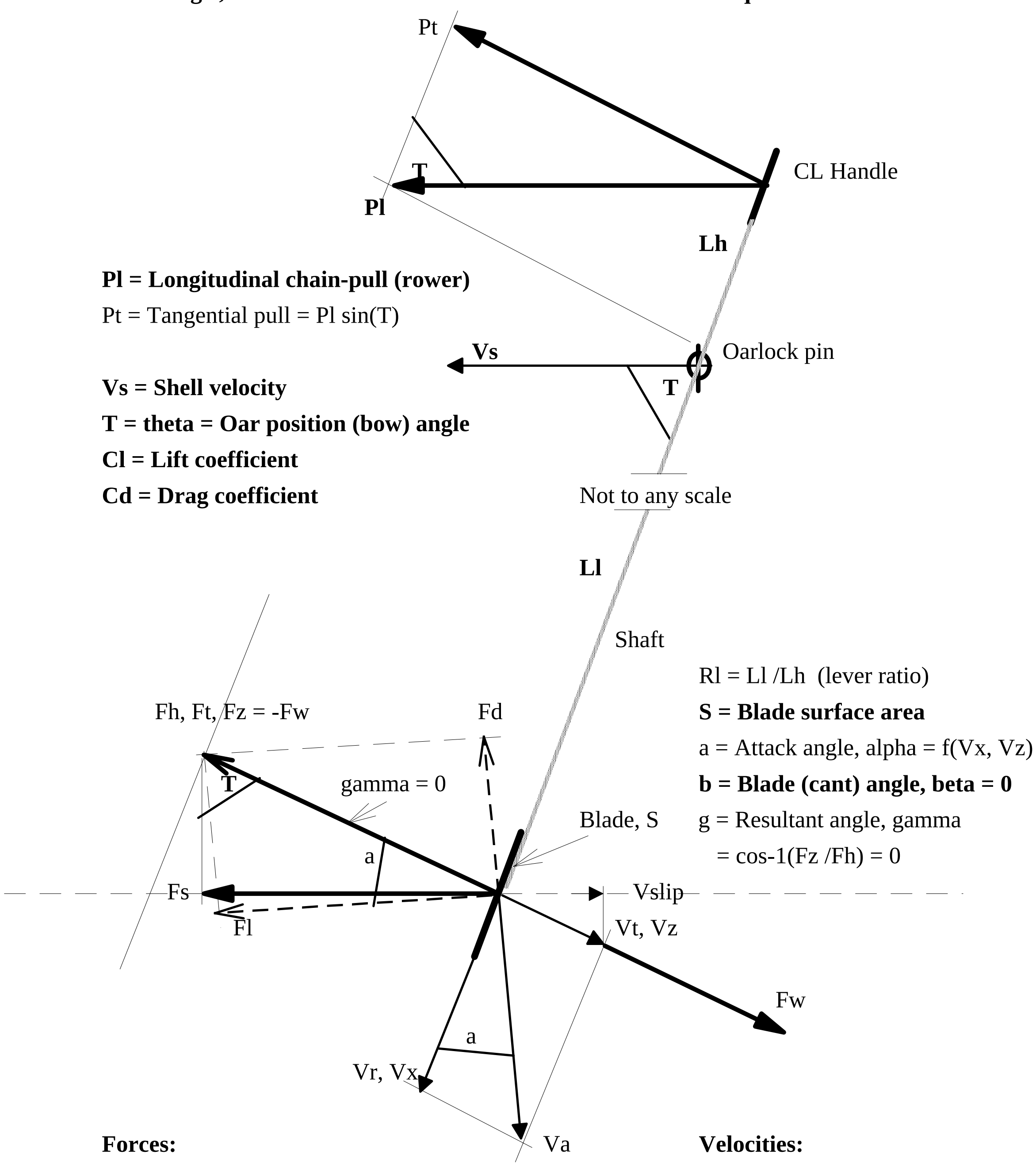
* Number of rowers
* Shell length, beam, and draft
* Shell block and surface coefficients
* Fluid resistance factors (water and air)
* Slide, arm-bend, and oar handle excursions (based on rower size)
* Rigger spread and rower reach
* Sweep code (sweeps or sculls)
* Sweep length, handle length, blade area, blade cant angle
* Sweep shaft specific stiffness in bending
* Blade hydrodynamic coefficients of lift and drag as functions of instantaneous fluid attack angle
* Blade (axial) fluid skin friction coefficient
* Weights of rowers, coxswain, boat, and sweeps
* Added mass: estimated thickness of the bound fluid layer
* Peak oar handle chain-pull and pull force regime accelerations
* Free (blades-in-air) time period
* Momentum and momentum force regime acceleration timings for body mass points (upper: torso, arms, head; and lower: hips, thighs)
* Free acceleration of sweeps and upper body mass from the start to the catch and the corresponding deceleration from the release to the finish
* Exponent of shell velocity (Vx) where x may take any positive value in the expression for the hydrodynamic resistance of the shell-commonly 2.0 but smaller values sometimes indicated
* Initial estimate of shell speed and drive/free period ratio

Energy (Work) Balance: Rowed Shell
Typical figures from ROWING computer program output



Oar and Blade Vector Diagrams: Gamma = 0.0

Blade angle, beta = 0 **Bold items indicate known quantities**



Pl = Longitudinal chain-pull (rower)

Pt = Tangential pull = Pl sin(T)

Vs = Shell velocity

T = theta = Oar position (bow) angle

Cl = Lift coefficient

Cd = Drag coefficient

Rl = Ll /Lh (lever ratio)

S = Blade surface area

a = Attack angle, alpha = f(Vx, Vz)

b = Blade (cant) angle, beta = 0

g = Resultant angle, gamma
 = cos-1(Fz /Fh) = 0

Forces:

Fw = Shaft-tangential (blade on water) = Pt /Rl

Ft = Shaft-tangential (water on blade) = -Fw

Fs = Net propulsive on shell = Ft sin(T)

Fz = Ft /cos(b) = Fh cos(g)

Fl = Lift = f(Va, rho, Cl, S)

Fd = Drag = f(Va, rho, Cd, S)

Fh = Hydrodynamic resultant = sqrt(Fl^2 +Fd^2)

Velocities:

Vr = Shaft-radial = Vs cos(T)

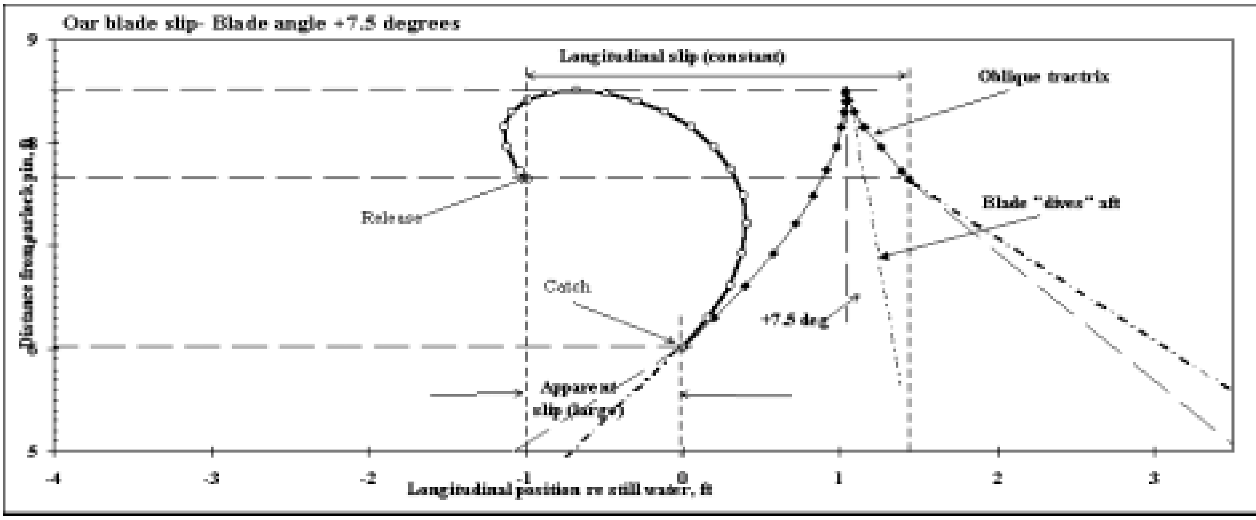
Vz = Blade normal = f(Fh)

Vt = Shaft-tangential = f(Ft)

Vx = Blade chordal = Vr

Va = Attack = sqrt(Vx^2 +Vz^2)

Vslip = Vt sin(T)



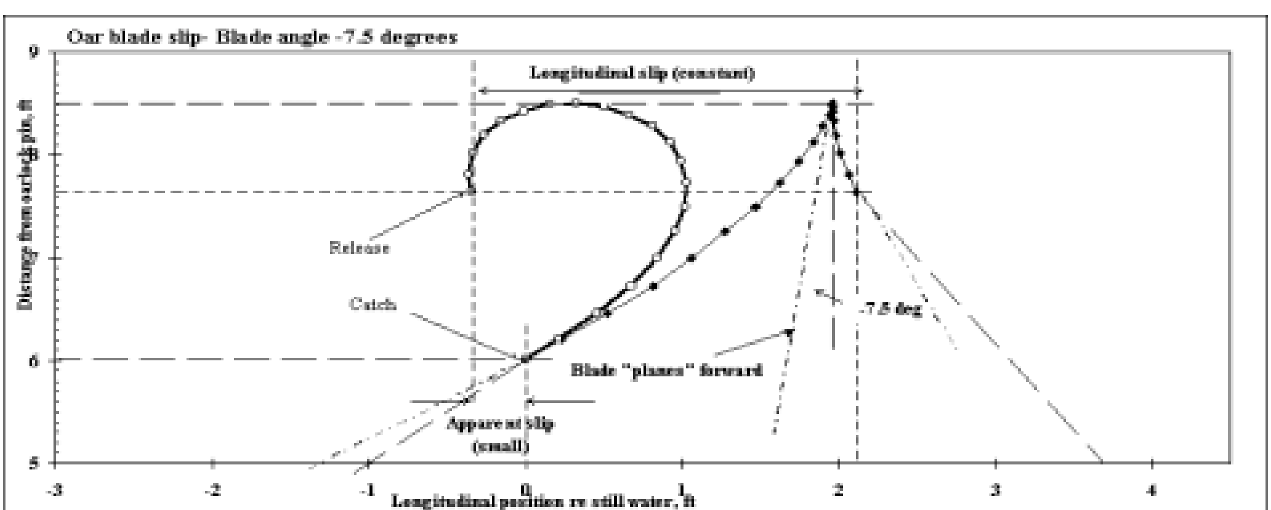
The Output of the Rowing Model

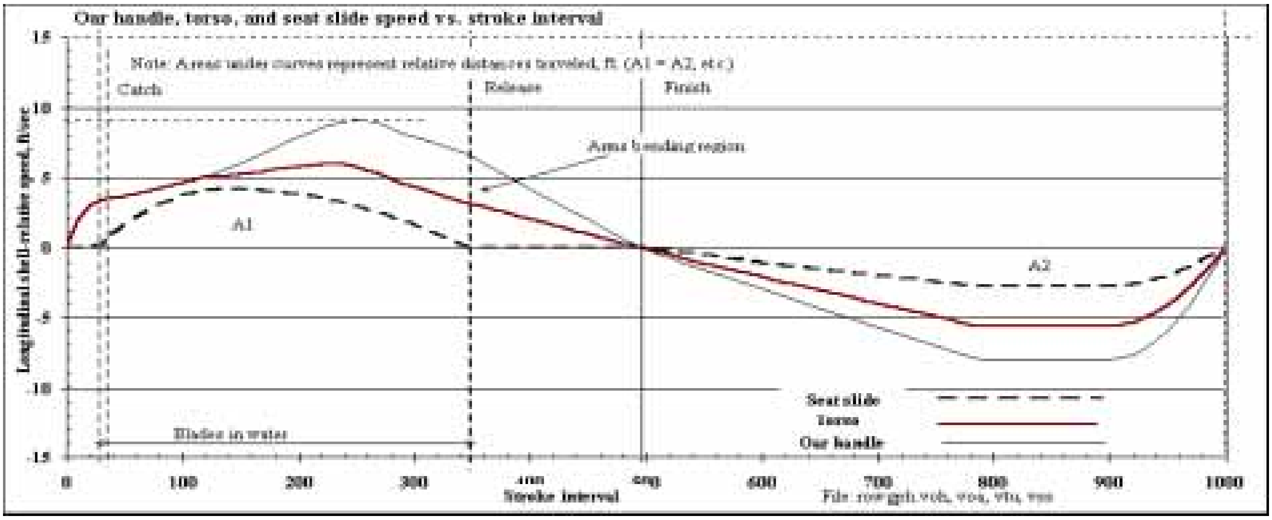
Here I will dwell more on some results. In order to show the capability of the model some details of the program output are listed at the end of this text. It may interest readers to note some results discovered in the course of developing and testing the rowing model.

Rowing can be run in a mode in which variables may be changed while the resulting shell speed is calculated for constant rower power output. This permits best-speed alternatives to be evaluated on a constant power basis.

Rowing considers not only the direct (external) momentum work done on the shell at the footboard, but also the indirect (internal) momentum work done on the rower's body itself. Internal momentum work is not usefully applied to the boat; it appears as an internal loss (heat) in the rower's tissues. Furthermore, the internal momentum work done in one direction (in the drive for example) is not recovered on the return—the body having virtually no springs for storing energy and in, any event, using a different set of muscles in each direction. Because internal loss is part of the rower's power output one will find Rowing's computed power values to be higher than one is accustomed to seeing.

Usually it is only the work at the oarlock that is considered in rowing and rowing ergometer power measurements. For activities where inertial forces are relatively small (cycling, hiking) momentum work may be overlooked, but in rowing it comprises as much as forty percent of the rower's total effort . Furthermore, the rowing community does not yet recognize that as much as twenty percent of the total useful propulsive effort driving a sliding-seated boat is delivered via a net external momentum work imbalance at the footboard and not solely via work



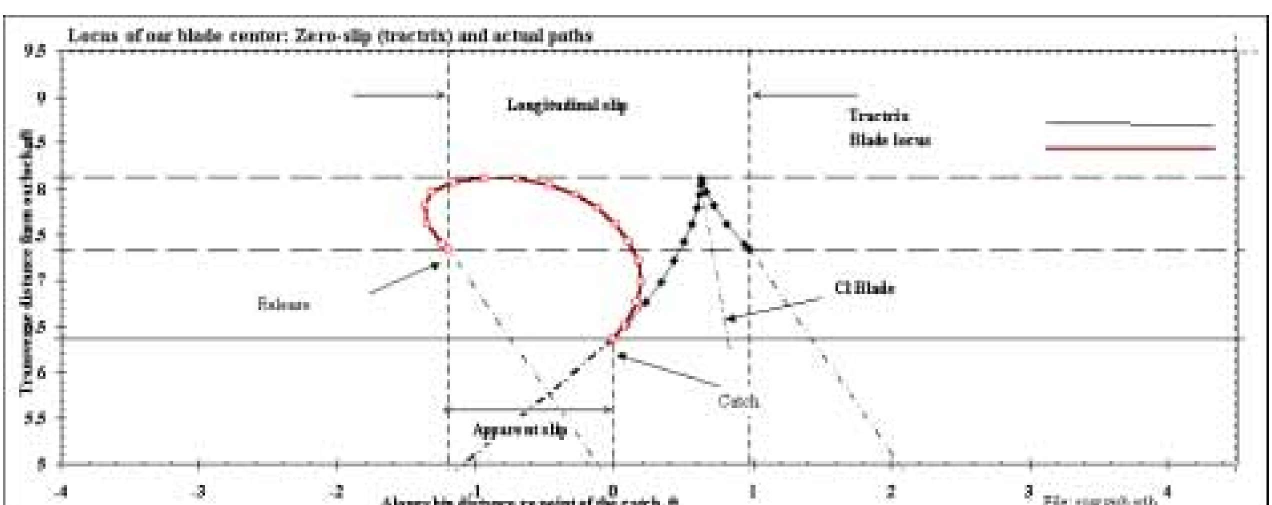


done at the oars and oarlocks). This could put a new face on future research which currently evaluates performance by considering forces only at the oars.

For a given rower size and strength there seems to be an optimum oar and rigger geometry owing to the inter-relationships between oar lever ratio, chain-pull and propulsive force, and the hydrodynamic slip of a particular blade in the water. As one might expect there exists a best lever ratio between high force (good) with resulting high slip (bad) and low force (bad) and its low slip (good). Unfortunately, measuring the strength (impulse/stroke) of rowers on the water is a neglected art and knowing the hydrodynamic characteristics of oar blades is a nonexistent one. And so, sadly and until future researchers fill these gaps, a coach could not yet effectively use a model such as Rowing to counsel his rowers on their rigging arrangements.

Even to an intent observer from above (watching from a bridge) the oar blade seems miraculously to exhibit almost zero slip through the water in the course of a stroke. Under circumstances of long oar and light stroke, as often in sculls, the slip seems even to be negative! The illusion owes its existence to the fact that the observer cannot visualize where the blade would have been had there been, in fact, no slip. During the Rowing development this lack of observable slip troubled me greatly because it ran counter to mathematical expectation and to the results of backyard trials using flat plates in buckets of water under the force of gravity. It wasn't until I hit on a model of the zero-slip path of the blade (mathematically approximated by the tractrix) that I could resolve truth and observation. Rowing now accomplishes the calculation of slip very nicely .

One may get the best overall impression of the capability of Rowing by studying the figures and the accompanying numerical output table.



Nelson-Kellerman Co.; data from coxed four instrumented shell (09/22/98)
Input tailored to reproduce the N-K, Co. shell speed curve of 9/25/91
Oarshaft stiffness (infinite)
+Unison stroke cycle- (At iteration 13; interval 0) 3/14/99 21:23:56

Peak parabolic chain-pull-	195.00 lb/oar;	Total deadweight.-	441.71 lb
Catch oar shaft angle-	51.53 deg;	Zero-slip sweep-	9.64 ft tractrix
Release oar shaft angle-	114.82 deg;	Calclated angle-	115.69 deg
Blade cant angle-	6.00 deg;	Oar lever ratio-	2.40; SwpEff=0.77
Stroke period length-	1.69 sec/cycle;	Rating-	35.42 strokes/min
Drive/run period ratio-	0.473;	Longtd. blade slip-	2.21 ft; Hydrfoil
Oar blade surface area-	1.10 ft^2;	Apparent slip-	1.21 ft approx.
Calculated sweep: DrvC-	7.464 ft;	Geometric: DrvA-	7.430 (iterated)
SHELL SPEED: Initial-	15.26 ft/sec;	Final-	15.26 (iterated)
Minimum (109)-	10.39;	Maximum (784)-	22.92; Amp.=12.5
Average-	18.51 ft/sec;	Free period-	1.150 sec
Resist. facts. KWa,KA,KTa-	0.150 0.028 0.202;	Implse-	74.26 lb-sec/oar
WORK: Shell friction work-	-2173.66 ft-lb/stroke;	Expt.V-	2.000
Momentum lower, shell-	336.08;	Momntm. lower, crew-	274.53; L= 642 lbm
Momentum upper, shell-	421.80;	Momntm. upper, crew-	462.56; D= 310 lbm
Momentum total, shell-	757.87;	Momntm. total, crew-	737.09; T= 953 lbm
Direct shell oarlock-	1415.92;	Oar blade slip loss-	-584.59; N= 4 oars
Shell net (residual)-	0.13;	Oar blade skin loss-	-2.95
Total oarhandle work-	2003.46;	Oarhandle power-	0.5376 hp/oar
Total rower work-	3498.43;	Rower power-	0.9387 hp/oar
EFF: Oarblade mechanical-	0.707;	Rower mechanical-	0.621

Table 1: Example of data output by Rowing

Output (Emergent) Values Calculated by Rowing

* Shell speed (average, max/min)
* Mass-center speed
* Stroke rating, 1/min
* Shell accelerations
* Distance traveled per stroke
* Work done (on sweeps, shell; in momentum (internal, external))
* Frictional forces on the shell
* Losses (shell friction, blade slip, blade skin friction)
* Oar shaft angular; blade radial and tangential velocities
* Oar blade angles of attack, lift and drag forces
* Forces resulting from oar handle and shaft mass accelerations
* Chain-pull impulse
* Power expended by crew (internal, external, total)
* Crew mechanical efficiency
* Oar blade mechanical efficiency
* Oar blade longitudinal slip
* 'As loaded' shell waterline length, waterline beam, draft, 60F displacement volume (fresh water), wetted surface area
* ITTC-63 and residuary resistance coefficients (water, from hull parameters), and calculated hull Reynolds' number
* Oar handle and shaft lengths
* Oar shaft catch and release point bow angles
* Stroke period, blades-in-water and blades-in-air periods
* Weight summary (boat, coxswain, crew, sweeps; live, dead)

Tables and Plots Produced

(Ordinates vs. stroke interval 1,000 instantaneous values per stroke cycle)

1. Cumulative time increments
2. Shell speed
3. Shell acceleration

4. Cumulative shell distance traveled
5. Chain-pull force
6. Propulsive force (on water)
7. Shell fluid friction resistance
8. Upper body momentum force
9. Lower body momentum force
10. Footboard force
11. Oarlock force
12. Upper body (torso) relative velocity
13. Cumulative net work done on shell must sum to zero
14. Seat slide relative velocity
15. Oar shaft angular velocity
16. Oar shaft bow angle
17. Blade angle of attack
18. Blade attack velocity
19. Hydrodynamic lift and drag forces
20. Shaft tangential velocity (at blade center)
21. Shaft radial velocity (relative to water at blade center)
22. Speed of center-of-mass
23. Oar handle relative velocity (longitudinal)
24. Oar blade zero-slip and actual path loci

William C. (Bill) Atkinson

Written in FORTRAN, Rowing runs under DOS 6.2. Copies are available the author at nominal cost to cover reproduction and postage.

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Bibliography

Affeld, K., K. Schichl, and A. Ziemann. “Assessment of Rowing Efficiency”. International Journal of Sports Medicine. Vol. 14, Suppl. 1, pp S39-S41, 1993

Alexander, F. H. “The Theory of Rowing”. University of Durham Philosophical Society, Proceedings. Prof. G. W. Todd, ed. Vol. VI— 1915-1923. Andrew Reid & Co, Newcastle-upon-Tyne, England, 1925.

Alexander, F. H. “Some Further Points in Connection with the Theory of Rowing”. University of Durham Philosophical Society, Proceedings. Prof. G. W. Todd, ed. Vol. VI—1915-1923, 1925. Andrew Reid & Co, Newcastle-upon-Tyne, England, 1925.

Alexander, F. H. “The Propulsive Efficiency of Rowing”. Institution of Naval Architects, Proceedings. Sixty-eighth session, Vol. LXIX. Institution of Naval Architects, England, 1927

Cameron, A. “Some Mechanical Aspects of Rowing”. Rowing- A Scientific Approach, J.P.G. Williams, ed. A.S. Barnes, New York, 1967.

Cardanha, Timothy. “Development of an Algorithm Simulating Rowing”. Dept. Theoretical and Applied Mechanics, Cornell University, Ithaca, NY, 1993.

Carmichael, A. D. “Rowing Model for Single Sculls”. Carmichael, MIT, 1980?

McMahon, Thomas A. “Rowing: A Similarity Analysis”. Science. Vol. 173, (1971) pp. 349-351.

Wellicome, J. F. “Some Hydrodynamic Aspects of Rowing”. Rowing-A Scientific Approach, J.P.G. Williams, ed. A.S. Barnes, New York, 1967.

Rotary Sailing Research

By Peter Worsley

Many yacht research projects are concerned with speed or breaking records, and, although some useful things may be learned on the way, the main end result is an entry in history books, and as a record is only of interest until it is broken, the glory is but short-lived. My rotary-sailing research is not concerned with record-breaking, (only maybe incidentally) but more with addressing the age-old drawbacks and inefficiencies of sailing craft which have resulted in their decline as a serious form of water-transport.

The fact has to be faced, that watercraft powered by wind are no more than toys at present, and whilst they provide interesting challenges and entertainment, their practicality as a serious form of transport is almost nonexistent.

Jensa
photo P Worsley

There are two areas in which a sailing boat is not practical – its inability to sail in a region of approximately 45 degrees either side of the direct head-to-wind direction, and the impossibility of it making progress when there is no wind to drive it.

The Rotary Sailing project is aimed at dealing with both of these problems in the following way.

Firstly, a properly-designed Rotary Sailing craft does not have any difficulty in sailing directly against the wind in the 90 degree "no go" zone which is prohibited to ordinary sailing craft.

Secondly, a Rotary Sailing craft can also be viewed as an extremely large floating wind-driven electricity generator, the electrical power from which can be stored, and then used to power the vessel when there is no wind. If used in this way, power can be extracted from the environment even when the craft is not in use, for instance, when moored, so there is plenty of time for sufficient battery-charging.

Is it impossible? A word is required here about the "impossibility" of sailing directly against the wind. I hope those who fully understand the situation will bear with me if I explain once more that it is possible, and, in fact, presents no special problems. I was quite sure that everyone understood this, but have been surprised that there seems to be an inbuilt natural disbelief from some traditional sailors. I will try to be brief, and will give the best example I know to prove the case.

Consider a small sailing boat trying to get upwind and making short 45 degree tacks to windward. Attached to the stern of the boat is a line about 1 mile long, the other end of which is attached to a small dinghy in which a person rides. As the sailing boat is so far away from the dinghy, the short tack oscillations are completely damped out and all the person in the dinghy experiences is a steady progression towards the eye of the wind.

Another way of explaining the situation, is a extract from an American correspondent's posting to an Internet newsgroup, where controversy on the subject recently took place. I cannot explain it any better:

Note: Throughout this article, the term "propellor" refers to the underwater driving device and "rotor" refers to the device in the air collecting energy from

"You [a third party] *are actually the first person so far who has taken on board the chief difference between a sailboat and a turbine/water-propeller boat, that, where a sailboat loses power as it heads up to windward, the power output from a turbine remains constant, (or even increases slightly as the apparent wind increases), the only adverse effect on the turbine/water-propeller boat being an increase in wind-drag (agreed this will be quite substantial, but when you consider the propulsion system is still working at full power…)" "….there are no "theoretical" reasons why a turbine/water-propeller boat cannot go directly to windward, however, many practical reasons there may be, then we can leave Peter Worsley and his fellow members of AYRS to tinker around overcoming the practical problems"* - Roger Wollin.

Why try to optimise upwind performance only? I have concentrated almost exclusively on the direct upwind performance of my experimental boats. This strategy may result in a less than optimal performance in other directions, i.e. crosswind, and directly downwind. But I feel that it does no harm to specialise in this, because the more normal methods of wind propulsion can always be added to a vessel in addition to the rotor whenever necessary. (I would probably consider "normal" to mean wingsails and not traditional sails).

Twice Lucky

photo: R Downhill

How it got started: the "analogy" method. When I started doing research into the subject, I had very little knowledge of the previous history of rotary sailing, and so I proceeded by a process of analogy to see if I could make a working model. I looked at an average sailing dinghy, and checked the area of the sails and the area of the centreboard, and worked out a ratio between these two elements. I then transferred these findings to the rotary sailing craft model in the following way: My device in the air, the rotor, was deemed to be the equivalent of the dinghy's sails, and the device in the water, the propeller, was taken as the equivalent of the keel or centreboard. I ensured that the rotor area to propeller area were in the same ratio as the sails/centreboard area. I then made sure, by means of suitable gearing, that the rotor blades moved through the air at the same velocity as the propeller blades moved through the water. In this way, I considered I would achieve the exact rotary equivalent of the sailing dinghy, with each air-rotor blade performing a continuous close-hauled tack, and each water-propeller blade performing the same function as a boats keel, but in a constant way, by rotating.

The model worked perfectly, and almost leapt out of the small test tank against the wind.

My approach is completely different from that of many before. I don't believe that best performance will be achieved by simply selecting the most efficient land-based electricity turbine and putting it on a boat. It's not as simple as that: there are some forces which affect a moving base wind-turbine that do not apply to a fixed base land installation. It seems to me that many previous designs have ignored these forces and subsequently not achieved an optimum performance upwind.

I achieved some success with models almost as soon as I started and my further research has been based on a step-by-step progression based entirely on practical testing. The mathematical analyses and predictions on rotary sailing I have seen in the past are very obscure and sometimes incomprehensible. Armchair theorists delight in playing with figures, but nothing is ever achieved!

My system uses a trailing rotor which is mounted downwind of a vertical axis pivot and the rotor is allowed to pivot freely where it likes, and in this way aligns itself automatically to the wind. This method eliminates the need for a wind-vane, the rotor assembly being behind the vertical pivot axis and behaving the same way as a weathercock.

Although a drive system using bevel gears with a vertical shaft has proved attractive to many in the past, I decided not to use this system for several reasons. Firstly, the torque of the vertical shaft would make the automatic weathercocking action difficult or even impossible, and then the only way to align the rotor to the wind would be manually, an extra complication, and tiresome for the helmsman. Secondly, its likely that bevel gears would absorb some power, and you need every bit of power you can find to penetrate the wind! Thirdly, the bevel gearing system would be expensive because it would probably have to be specially made, and it may be heavy, too. Fourthly, on such a system there is no easy way of changing the gear ratios, as there would be when using pulleys and belts, or sprockets and chains.

So, in the light of these drawbacks, I elected to use a pulley and belt system, and, for the models, I managed to devise a virtually frictionless and nonslip drive, using rubber-covered pulleys and string.

The top pulley on the rotor assembly is positioned directly over the vertical pivot point, the rotor-assembly is allowed to pivot 90 degrees each way. The belt, or chain, descends to a fore-and-aft driveshaft in the boat to which the bottom pulley is fixed. A belt or chain-drive can accommodate this degree of movement, if the tension in the drive is adjusted automatically. The driveshaft is then connected through another belt of chain to the propeller shaft. The rotor is not used for downwind sailing. This general arrangement I have patented.

The above system refers to the two, man-carrying small catamarans I have put together. For the models, a simpler system is used with one drive belt which goes directly from the pulley on the rotorhead to the pulley on the propeller shaft.

Twice Lucky

I will now describe the latest full-size version, called *Twice Lucky* (no particular reason for this name, only that it happened to be painted on the side of the hulls when I acquired them). A pair of Hawke Surfcat hulls are connected by their normal aluminium tube structure, less trampoline, and two wooden fore-and-aft supports are bolted between the front and rear transverse alloy tubes. The wooden supports are boarded up top and bottom and they form a box which supports the transmission shafts, bearings, rotor tower and prop-shaft, and of course the "driver". The rotor tower is set well to the rear of the boat and the vertical axis pivot of the rotorhead coincides with the CLR of the whole boat. The rotor assembly, which is a certain distance behind the vertical axis pivot, is balanced forward of the pivot by an arm with a counterweight, on any windward course this arm always points directly to where the wind is coming from.

Transmission starts with the pulley on the front of the windshaft, (which is directly over the vertical axis pivot). The belt drive is led downwards behind the drivers' seat to the intermediate shaft which projects forwards, within the box (which the driver sits on) to a forward position where it is led through a six-speed cycle gear system and then to the propeller shaft which in turn, projects aft, through a universal joint to the propeller shaft which is supported by an underwater bearing near the prop and has the ability to fold up sideways for beaching purposes.

The earlier boat, *Jensa* had a slightly different system involving an underwater skeg with a toothed belt inside with the propeller mounted on a small shaft at the bottom. The skeg could be folded sideways for beaching . The boat sailed well, but only had one gear-ratio, the present use of a six-speed variable gear has great advantages because it is simple to test different gear ratios, whereas previously, different pulleys, would have to have been fitted to achieve this.

Ideas from different fields have been used on the present boat, main ones being the use of aeromodelling experience for the rotor blades and cycle technology for parts of the drive-train.

The six rotor blades are standard model aircraft wings using built-up construction in balsa on a spruce main spar. Each wing has about fifty different parts including 32 ribs with sheet balsa covering. Each blade is covered with plastic "Solarspan" heat-shrink material and took about two weeks to make. I probably would use foam with obeche veneer covering next time!

The pitch of the blades can be varied from a fully "feathered" position to a maximum drive setting. The inspiration for the pitch-control system came from that used on a fly-ball governor on a steam engine, and was made by an engineer who specialises in model railways. Control input to the pitch-control mechanism is by cycle "Bowden" cable, using a standard cycle lever. In practice, the blade setting is either full on or completely off.

Latest move in development is the construction of a stationery-adjustable variable pitch underwater propeller, on which different pitch settings can be tried easily. There is still some room for further optimisation, although the performance of the boat is never going to be impressive with such a small blade area (about 12 sq foot) which is used at the moment.

An interesting discussion would be whether to count the swept area of the blades or just the area of the blades themselves. As the blades are slow-rotating, it might not be so appropriate to use the swept area.

At the present time, work on the man-carrying version is shelved and attention is being given to measuring the thrust of models directly against the wind, similar to the "bollard pull" test used on outboard motors. The plan is to use a simple data-logging system with a video camera recording the pull and windspeed simultaneously. In this way I hope it will be possible to produce some figures which will relate thrust to blade area/windspeed. This kind of test is particularly appealing because it takes everything into account and produces an answer of what is actually achievable in real life, as opposed to hypothetical figures. It might be possible to extrapolate a graph and predict the performance with much larger rotors (most likely this would be on the pessimistic side as one would expect better efficiency with larger scale). All the foregoing refers to performance directly into the eye of the wind.

Comments on the above are always welcome.

--Peter Worsley

Peter Worsley is a world-renowned enthusiast for rotor powered boats. He is regularly active on the Internet defending the idea that boats really can sail directly upwind without contravening the Laws of Thermodynamics. (It's all a matter of gearing) His website <http://www.pworsley.dircon.co.uk> is often cited as evidence that these things are possible.
He can be contacted by email at pworsley@dircon.co.uk; address: 125 Jasmin Road, Epsom, Surrey KT19 9EA; Tel:+44(20)8397 4427

For those who wish to see these things for themselves, Peter Worsley is very likely to take his craft to the Winds of Change Rally on the R Orwell, UK, on 18th August.

A Rope Experiment

Does Rope Have An "E"? What Is "E"?

by Frank Bailey

There are two reasons why I hope you read this article through to the end. We should all learn as much as possible or convenient about the lines on our boats, what they are capable of and not so capable of and perhaps learn some of their peculiarities. Secondly, in this age of composites, carbon fibers, kevlar, etc. we should become familiar with the term "E" (also known as "Young's Modulus"). No doubt some of you are quite familiar with this term but other members may not be. So, we might say, this article is also an experiment.

A few years ago I purchased a spring scale. It measured up to 400 pounds. I used it to measure the pounds thrust of some outboard motors from 9.9 horsepower down to about 2 horsepower and then put the scale away. While measuring the thrust, it appeared rope burns on the hand were de rigueur. I recently spied it hanging on its peg at the Toad Hill Boat Shop and decided to try and get some more use from my purchase. Because of another project, I found that I would like to know the "E" of a typical piece of rope. I use the term "rope" since I choose to call a line a rope and not until the rope is on a boat will I call it a "line".

I did the tensile testing using two schemes, A and B, as shown in the sketches. I wanted to generate great tension in my testing so originally resorted to Scheme A. With small loads and a small slope angle, great tensions can be generated. With the application of a little geometry, one can figure out the pounds of pull in the length of rope "L". This scheme was not as good as Scheme "B" for two reasons. First, the ropes I used stretched so much that it was hard to generate higher tensions than Scheme B. Secondly, I used a horizontal arrangement and the initial tension was unknown so no doubt the data obtained from Scheme "B" is a bit more reliable. Further I ran out of time and weights so total pounds load only approached 200 pounds. I did not test the ropes to the breaking point. Why waste a good piece of rope? There are so many different types of rope now available, the results described below are for the rope I had and other than the manila, the description of the ropes I used may not be precise so you should consider the results I obtained order of magnitude only.

Please refer to the next page where I tabulate the raw data for the 1/4 inch nylon. It should be self-explanatory. The actual diameter of the rope was about 0.205 inches and did not change appreciably during the testing. Obviously putting a micrometer on a piece of rope to measure its diameter to the nearest thousandth is a bit absurd but so be it. I do not include the data for the manila or the 3/8 inch rope. Incidentally, the manila, when stretched, appeared to stay stretched and did not unstretch.

I next plotted, for the 1/4 inch nylon, a graph of stretch length versus pounds load. As you can see I added load and reduced load twice. From an inspection of the graph you can see that the two up load lines are not coincident while the two down load lines are, a curiosity in itself. Since the two down loads were so closely associated, these are the numbers I used to calculate "E". Note then, that the calculation was done when the load was being reduced which test might not actually be considered a tensile test.

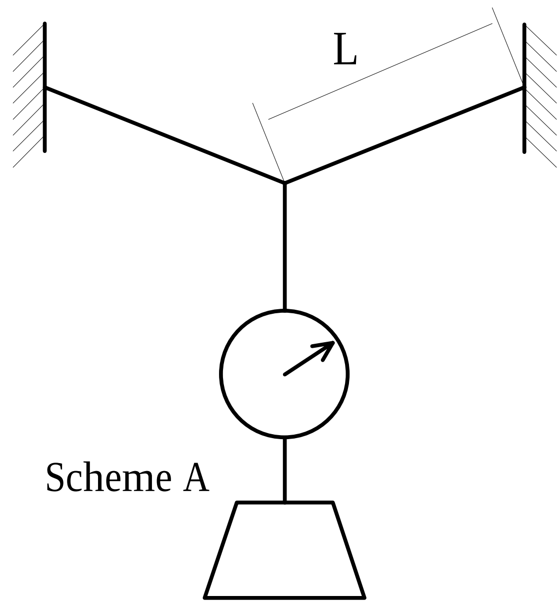
The results for the three ropes tested are shown on the graph showing strain on the horizontal axis and stress on the vertical axis. We must define these two terms. Strain, actually unit strain, is obtained by measuring the stretched rope and dividing that number by its original length. The number has no units as it is a length divided by a length. It will always be a number greater than one and we might say, the smaller the stretch the "stronger" the rope is, maybe. Stress is easier to understand. It is the pounds load divided by the cross sectional area of the rope so the units are pound per square inch, in this case.

Now, what is "E"? In 1676, Robert Hooke of the Royal Society said stretch varies directly as the force applied. This applies to very many materials. Taken a step further, today, and maybe even then, we say stress is proportional to strain and the constant of proportionality is "E", or the modulus of elasticity as it is also called.

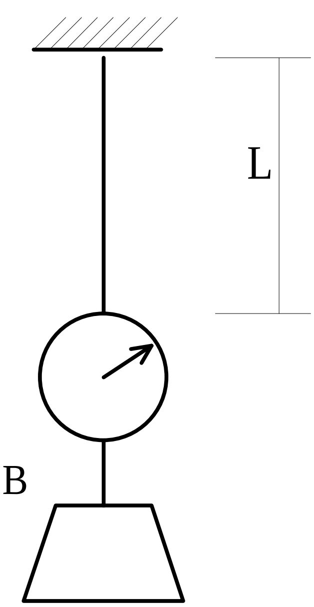
For example, from the curve and data for the 1/4 inch nylon, dividing the stress of about 455 pounds per square inch by the strain of 0.029, we get a value of E of about 16,000 or 0.16×10^6. E for the manila is about half this and for the double braided nylon it is about 0.47×10^6. Summarizing and comparing with some other materials:

Steel	30.00×10^6
Wood, compression	about 1.70×10^6
1/4" nylon	0.16×10^6
3/8" manila	about 0.08×10^6
3/8" braided nylon	about 0.47×10^6

Please look once again at the load/stretch length curve for the 1/4 inch nylon. The curve exhibits a hysteresis type curve similar to those curves generated when you examine a graph of magnetic field of intensity versus flux density, the definitions of which it is exceedingly unnecessary to go into nor would I understand them. Hysteresis is evident from the shape of the curve when the weights are increased and decreased. There is on the graph an area inside the up and down lines proving there is hysteresis. The point here being that when the rope is stretched and relaxed, there is a loss of energy which takes the form of heat loss so that, in effect, the rope, going through its cycle, probably heats up and then cools off minutely.



Scheme A



Scheme B

Here are a few miscellaneous remarks. The above experiment merely touches the surface of rope technology. No doubt there is much data somewhere on all kinds and types of rope along with values of modulus of elasticity, stretch or no stretch figures, working strength, breaking strengths, etc. There is today on the market a plethora of weaves, materials, and characteristics. No doubt much of this material is proprietary. Further, If you had a text book, you could have looked up the values of E for a variety of materials. If you don't have a text book, perhaps the above experiment will start you thinking critically about how "strength" is defined. Perhaps it will also make us more aware of the types of lines we use on our boats. So, Mesdames and Monsieurs, look to your boat lines closely. There is more there than you might think.

—Frank Bailey

Frank Bailey is an indefatigable experimenter and enthusiast for ideas. He is a great exponent of the ability of the amateur to discover the unusual. In his spare time, he looks after the AYRS dollars. Email: fbailey@pathway.net; address: 415 Shady Drive, Grove City, Pa, USA; tel/fax: +1 (724) 458 8306

Raw Data and Calculated Data

This sheet lists the raw data taken with the weigh scale plus some calculations. The pounds are the individual scale weight loads. The lengths are measured in feet and each is the amount of stretch over the original length of the rope of 5.25 ft. There are four runs as follows: increasing weight, then decreasing weight, then increasing weight, then decreasing weight. The stretch obviously increases and decreases as the load is applied and removed. This is the data plotted on "Original Plot" of stretch versus load.

For the last run:

Column A is the computed stress or the pounds per square inch using a rope diameter of 0.205 inches or quarter inch nominal for the last run. Example: 114 pounds divided by 0.033 sq. inches is 3454 pounds per square inch.

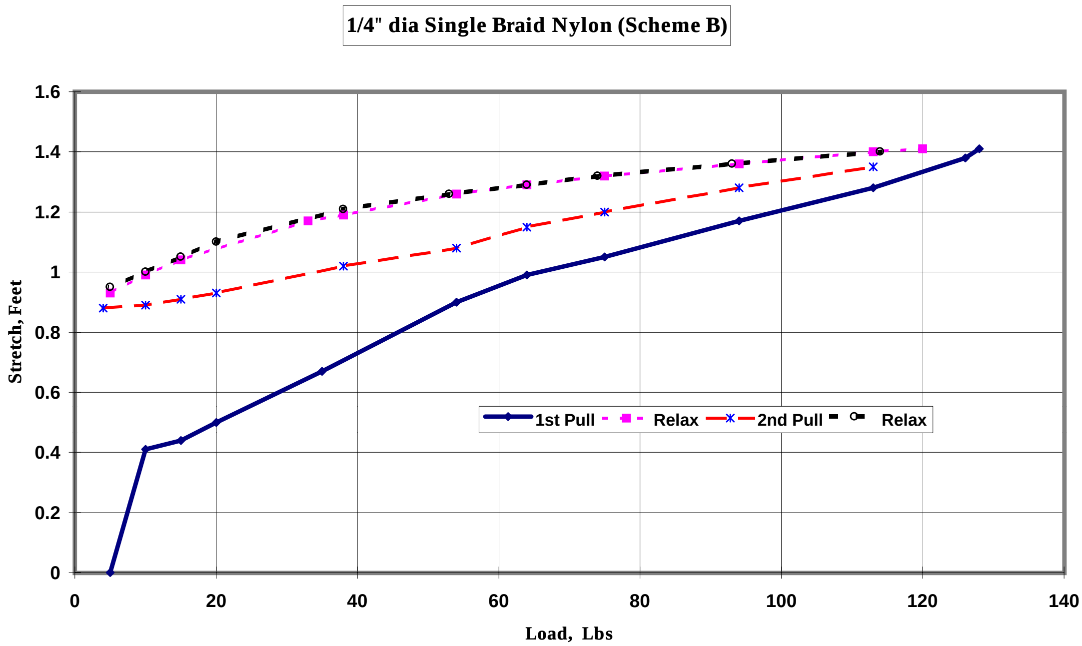
Column B is the lengths with 0.95 subtracted from each entry. For example: 1.40 minus 0.95 equal 0.45. This is done so that the subsequent plot will go through zero.

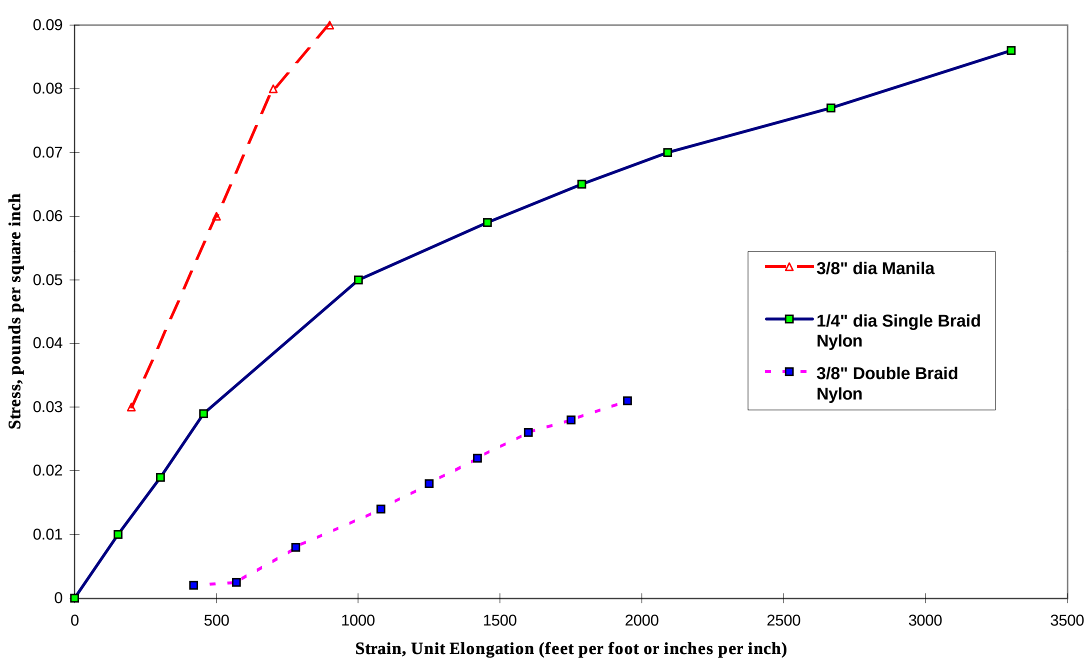
Column C is column "B" with 151 pounds subtracted from each pounds per square inch entry so that the subsequent plot will go through zero.

Column D is column "B" with each entry divided by the original unstretched length of 5.25 ft. giving the strain per unit length. For example, 0.45 ft. divided by 5.25 ft. equal 0.086 ft. per foot.

Using columns C, stress pounds per square inch, and column D unit strain, the plot of stress versus strain is achieved and thus a measure of E is determined.

Lbs		Length	A	B	C	D
5		0.00				
10		0.41				
15		0.44				
20		0.50				
35	1st	0.67				
54	Pull	0.90				
64		0.99				
75		1.05				
94		1.17				
113		1.28				
126		1.38				
128		1.41				
120		1.41				
113		1.40				
94		1.36				
75	Relax	1.32				
64		1.29				
54		1.26				
38		1.19				
33		1.17				
15		1.04				
10		0.99				
5		0.93				
4		0.88				
10		0.89				
15	2nd	0.91				
20		0.93				
38	Pull	1.02				
54		1.08				
64		1.15				
75		1.20				
94		1.28				
113		1.35				
114		1.40	3454	0.45	3303	0.086
93		1.36	2818	0.41	2667	0.077
74		1.32	2242	0.37	2091	0.070
64		1.29	1939	0.34	1788	0.065
53	Relax	1.26	1606	0.31	1455	0.059
38		1.21	1152	0.26	1001	0.050
20		1.10	606	0.15	455	0.029
15		1.05	454	0.10	303	0.019
10		1.00	304	0.05	153	0.010
5		0.95	151	0.00	0	0.000


1/4" dia Single Braid Nylon (Scheme B)
Stretch, Feet
Load, Lbs
1st Pull
Relax
2nd Pull
Relax
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0
20
40
60
80
100
120
140


Stress, pounds per square inch
Strain, Unit Elongation (feet per foot or inches per inch)
3/8" dia Manila
1/4" dia Single Braid Nylon
3/8" Double Braid Nylon
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0
500
1000
1500
2000
2500
3000
3500

Catalyst Calendar

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

August

18th-20th "Winds of Change" rally for innnovative boats.
Royal Harwich Yacht Club, Woolverstone, Suffolk UK. Contact: Bob Quinton, 7 Holland Road Felixstowe Suffolk, tel: +44 (1394) 670 302; Bobgen@boatek.demon.co.uk; http://www.boatek.demon.co.uk
[See advertisement on page 51]

September

15th "Show and Tell"
NW Multihulls Assoc meeting at 7pm at Corinthian Yacht Club at Lechi, 106 Lakeside Ave., Seattle, WA 98122 USA. Contact NWMA, 2442 NW Market PMB#513 Seattle or www.nwmultihull.org

30th-6 Oct Weymouth Speed Week
Weymouth Sailing Centre, Portland Sailing Academy, (old RNAS helicopter base) Portland Harbour, Dorset UK. Contact: Bob Downhill, 40 Collingwood Close, Eastbourne, UK; tel: +44 (1323) 644 879 email: robert@speedweek.demon.co.uk; http://www.speedsailing.com

October

4th "Speedsailing"
AYRS meeting 19.00 for 20.00hrs at the Royal Dorset Yacht Club, Weymouth, UK. Contact: AYRS Secretary, BCM AYRS London WC1N 3XX; tel: +44 (1727) 862 268; email: ayrs@fishwick.demon.co.uk

November

7th AYRS London meeting
Subject to be announced. 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) 862268; email: ayrs@fishwick.demon.co.uk

December

5th AYRS London meeting
Subject to be announced. 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 2001

4th-14th London International Boat Show
Earls Court Exhibition Centre, http://www.bigblue.org.uk
(AYRS will be there as usual)

26th-27th 15th Chesapeake Sailing Yacht Symposium
Annapolis, Maryland, USA. Sponsored by the Society of Naval Architects and Marine Engineers, US Sailing, the Chesapeake Bay Yacht Racing Association & the Naval Academy Sailing Squadron. Details at http://wseweb.ew.usna.edu/nahl/csys/ email: anderson@gwmail.usna.edu

Your Letters

Continued from Page 8

Catalyst No 1

Heartiest congratulations on Volume 1, No. 1. Super Issue, good pix, good coverage. Just back from helping translocate the endangered Turks and Caicos rock iguana from Ambergris Cay (impending development) to Long Cay (a nature preserve). Now off to New Mexico to visit family.

John Sieburth
seabugs@gsosun1.gso.uri.edu

Congratulations on your excellent *Catalyst*! Nicely laid out, filled with good stories and photos. What an improvement over other AYRS pubs, and a joy to read.

The articles for coming issues are mouthwatering.

David Stookey,
Editor, Open-Water Rowing

Catalyst is one of our best publications ever. It made me proud to be a member of our little society.

Billy Roeseler,
AYRS US West Coast Coordinator,
billy@seatac.net

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

On the Horizon . . .

Low Reynolds Number Aerodynamics — Tom Speer
The Maximum Speed of Yachts — Bob Dill
Electric Propulsion Design — Theo Schmidt
Alerion Electric Auxiliary Conversion — Charles Houghton
Maxed Out with Five Masts — Richard Boehmer
Power Alternate Sailing — Peter Sharp
Wind Direction and Sails —Mike Brettle
Inspired Designers — Jim Champ
More sources and resources: reviews, publications and Internet sites

Amateur Yacht Research Society
BCM AYRS, London WC1N 3XX, UK

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