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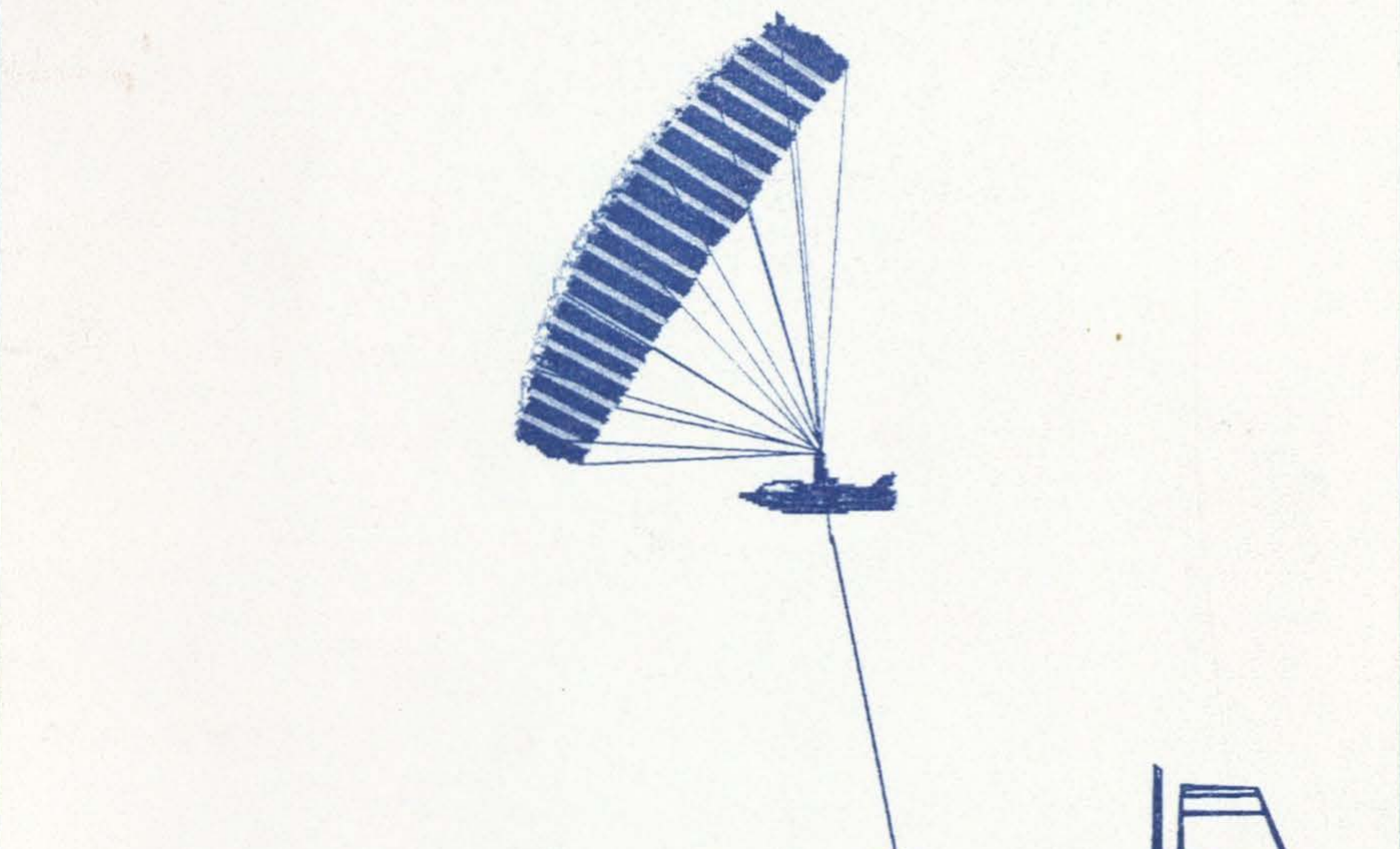
Transport Sailcraft



Edited by Simon Fishwick

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Journal of the Amateur Yacht Research Society Special Edition - Ultimate Sailing - Transport Sailcraft

Edited by Simon Fishwick

Amateur Yacht Research Society
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Submissions Guide

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

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

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Cover design by SheilaFishwick from original artwork by Michael Schacht

Introduction

This copy of the AYRS Journal is both the last and first of its kind.

The last, because it is the final part of the series on "Ultimate Sailing" - the use of hull-less wind-driven craft for pleasure and business - this edition concentrating on the business aspects of its subject.

We present three papers on this topic. The first, by Roeseler, Schmidt, Beattie, Roeseler, Culp Long McGeer and Wallace, was first presented at the 1996 World Aviation Congress of the US Society of Automotive Engineers, by whose permission it is reprinted here. It looks at the practicality of building large unmanned tethered air vehicles which can harness the power of the wind well above sea level to assist commercial sea transport to reduce its fuel consumption thus improving its economics as well as improving in some degree the quality of life in our ecosystem.

The second paper by Cory Roeseler returns to the recreational side of "ultimate sailing" by reporting on experiments Cory has done with an "Air Chair" - a hull-less, hydrofoil-supported seat, originally designed for water-skiing, but now proving its versatility as a new kite-powered sailing experience.

The third paper by Culp, returns to the theme of the first, by exploring the economics of Kite Tugs - autonomous sailing craft selling their towing services to otherwise normal powered commercial craft - a possible way by which sail power could assist the present transport fleet with requiring them to make major investments and adaptations in sail equipment.

But this edition of the AYRS Journal is also the first of its type, because in it we make a deliberate move away from the single-subject editions of the recent past, back to the more diverse publications with which AYRS started, albeit dominated by several papers on a single theme. This will be the shape of the AYRS Journal editions of the near future, although we will, available material permitting, produce single-subject editions when appropriate.

Simon Fishwick
AYRS

The Case for Transport Sail Craft

Billy Roeseler, Theo Schmidt, Andrew Beattie, Cory Roeseler, Dave Culp, Russell Long, Tad McGeer, & Richard Wallace

A version of this paper was presented at the World Aviation Congress, Los Angeles, California, on October 24, 1996. This paper is reprinted, with permission, from SAE Paper No 965611 © 1996 Society of Automotive Engineers, Inc.

ABSTRACT

The next oil crisis will create a new round of interest in alternative energy, renewable sources. The economics of military and commercial sailing will again be hotly debated by naval architects and marine engineers. The difference this time will be the abundance of data from the large world fleet of unmanned air vehicles (UAV), which just might be the key to wind assisted freighters. Our pioneering efforts with recreational kite sailing and buggies have provided part of the database needed to apply UAV technology to the task of wind assist for global transport. This paper will tie the UAV and kitesailing technology to military and commercial needs.

For example, the Boeing Condor (Fig 1), with her jumbo jet span and 40,000 lb lift capability, could generate 10,000 lbs of thrust from the trade winds, tethered to a ship at sea. Condor is one of a class of unmanned air vehicles, some with engines and some without, that could be used to extract wind energy to provide up to half of the total motive force for the ships of the world in the 21st Century, thereby conserving billions of barrels of oil, reducing pollution, and improving the quality of life in our ecosystem.

Thanks to extensive media coverage in Toyota truck, Levi jeans shorts commercials[36] and many other magazines and TV shows, the concept of taming the wind with large traction kites is no longer entirely unknown.

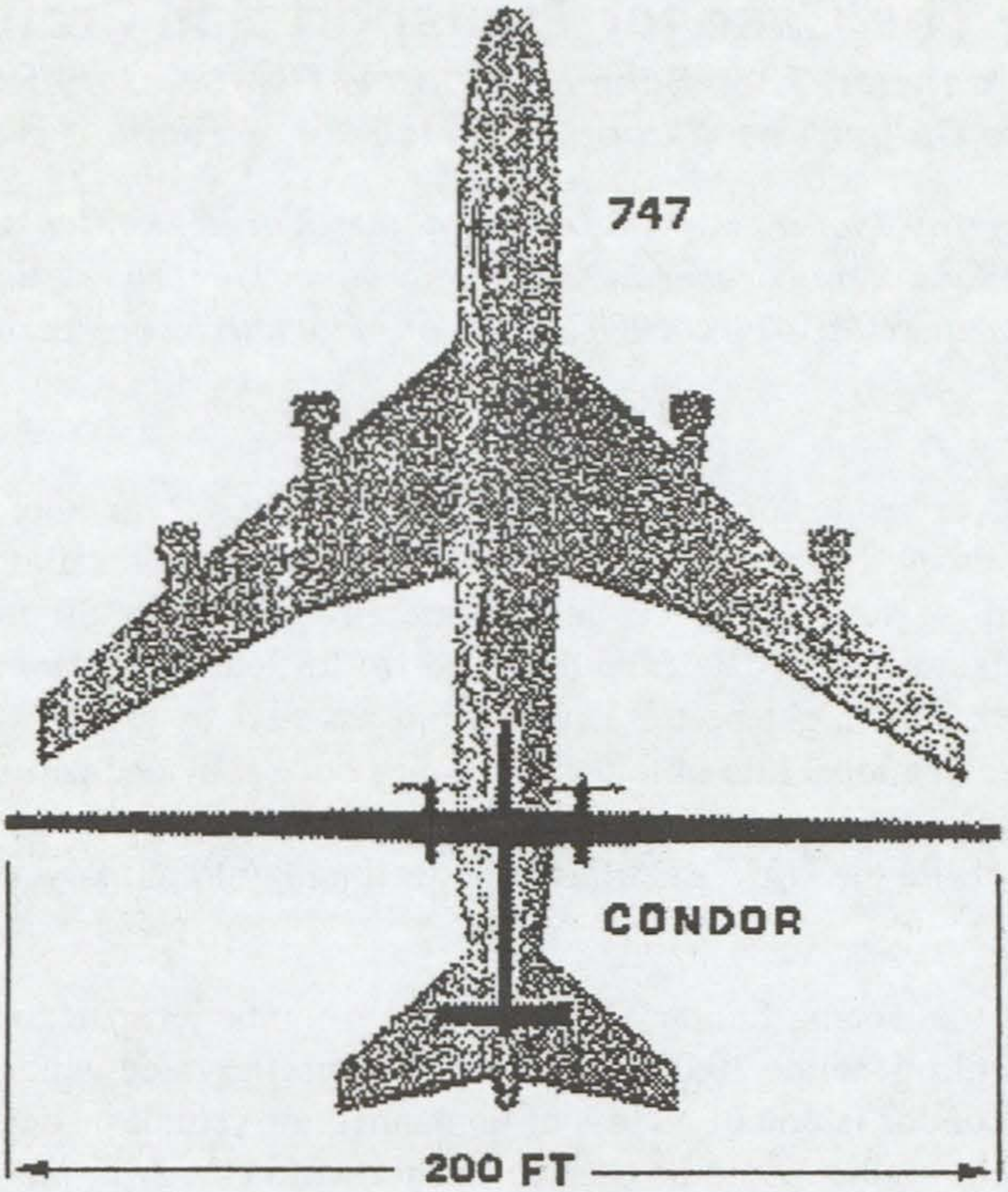

Fig 1 Boeing Condor and 747. [43]

INTRODUCTION

This paper is about the potential for economical transport sail craft, building on the technology developed in Europe, Japan, Israel, China, New Zealand, and the US in the last 20 years. Kites have already towed small craft across oceans and continents, and the addition of electronic flight controls from the modern UAV industry may allow us to scale up this technology to a point where it becomes commercially viable for large ships.

Prior to the invention of the steam engine, transport sail craft were the main means of intercontinental transportation. Then for over 100 years, we have relied on fossil fuel for running engines that turned propellers that pushed ships and planes over the sea and air. Now with the predictable increase in the real cost of fossil fuel over time, and the shift of focus back to renewable energy, we may once again see transport sail craft on some of the oceans of the world. This shift began in response to hotly debated environmental issues, but now the motivation to use wind assistance is to increase a ship's overall efficiency. The Windstar cruise ships and the Shin Aitoku Maru Coastal freighters[17] may be the first $100,000,000 examples of a resurgence of wind power for commercial shipping.

The relative cost of technology and labor will make the modern transport sail craft quite different from those of past centuries. Major advances in aerodynamics, structures, and flight control will make it possible to extract wind energy for a small fraction of the man-hours per horsepower hour that it took on the 19th century windjammers. One example is the unballasted sailboard invented in the late 1960's which extracts 10 hp from a 20 kt wind. This invention[6] by James Drake, an aeronautical engineer from southern California, has in 20 years become the fastest and most popular type of sailing craft in the history of the world. The advanced sensors and adaptive control system here were supplied by the magnificent human organism, and we now know how to supply these functions electronically at low cost.

Fig 2 Kiteski at ESPN Extreme Games, Newport, RI, 1995 [34]

The second example of enabling technology is the Kiteski, Fig 2,[45] which extracts 20 hp from a 20 kt wind and has the potential for sailing even faster than the sailboard. Fig 3 shows a speed polar for our production Kiteski. In terms of potential application to commercial sailing, the Kiteski takes the lifting wing of the sailboard one step farther by detaching the wing from the hull.

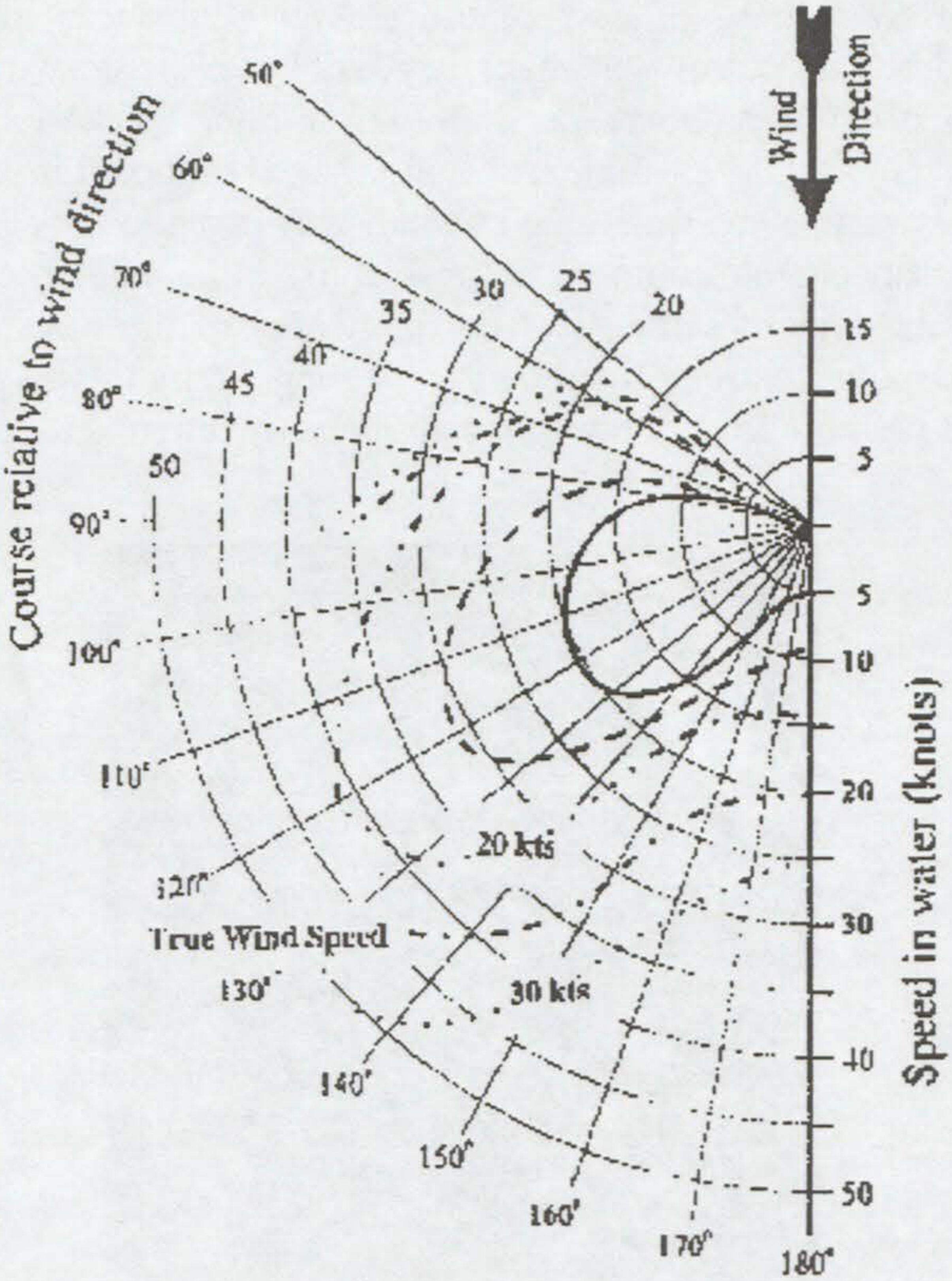

Fig 3 Kiteski Speed Polar[32]

The next step beyond the Kiteski may be the incorporation of automatic flight controls such as those described by McGeer and Holland on the Aerosonde type of unmanned air vehicle,[39] such that the man is taken out of the loop altogether, and we are able to eliminate one of the two drag producing tow lines. Wallace has already started testing this type of kite sail[48], and the results are encouraging.

It is not yet clear whether soft sails derived from modern parafoil technology or rigid wings more like those found on modern sail planes and Global Hawk (Fig 4) will provide the most economical wind energy extraction. However, the enabling technology continues to build internationally. The 1996 UAV survey article by Steven Zagala[33] gives data on 100 UAV's from 40 companies in 12 countries.

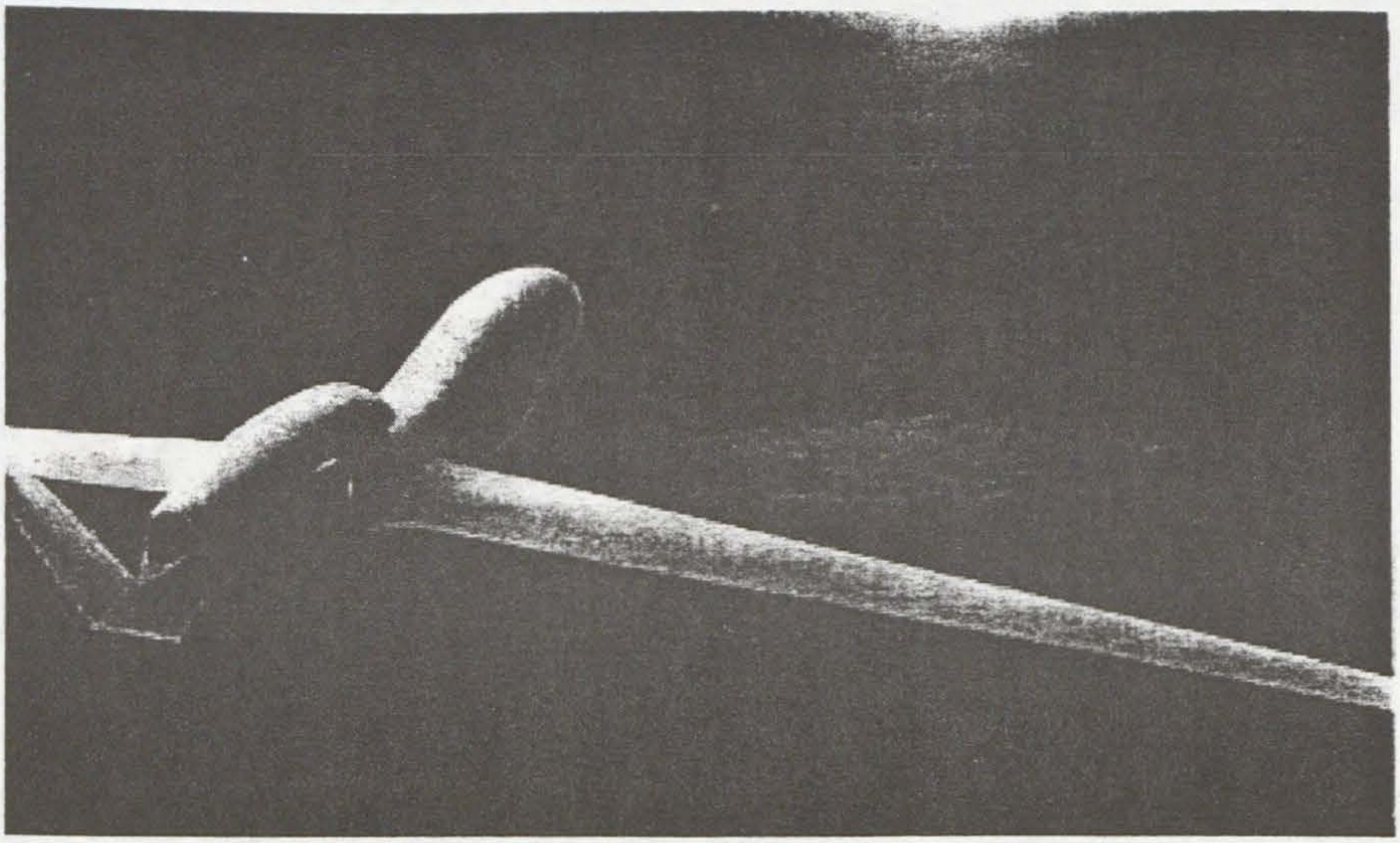

Fig 4 Global Hawk

A hybrid wing of rigid spar and soft sail based on multihull and land yacht technology may also be competitive. More research and development will be required. We are concentrating on the application of kite sails because they have the best potential for application to a wide variety of commercial ships. They also present some of the greatest control challenges. It is therefore likely more conventional sail arrangements[38] will be used prior to kites in commerce in the next century. In spite of much publicity, kite sailing is still not generally accepted. Much of the reason for this is explained by Francis Reynolds in "Crackpot or Genius"[41].

RECENT HISTORY OF KITE SAIL SYSTEMS FOR COMMERCIAL SAIL

A number of pioneering thinkers and experimenters have written about the application of kite systems for the propulsion of boats, principally in the pages of the Amateur Yacht Research Society publications[29 30 32] and the Ancient Interface Conference Proceedings[18 21 42]. Hagedoorn and Roeseler[29 8] suggested kites may improve sailing performance. A first reference of kite-sailing in a conference dedicated to commercial sail is given by Nance[11]. Schaefer and Allsop[12] presented the first scientific paper on kite-sails for wind-assisted ship propulsion at a well-attended symposium on wind propulsion of commercial ships in London in 1980. Other more well-known propulsion systems were also discussed in considerable detail:

> "traditional square riggers, modern fore-and-aft rigs using automatic sail furling, soft and hard wing sails, wind turbines, Magnus-effect rotors (Flettner, Thom, aspirated cylinder)."

Already apparent then, with decreasing oil prices eroding the beneficial shock of the so-called oil crisis in 1973, was the importance of low cost sails. The AIAA/SNAME conferences in San Francisco in 1982[17 18] and in Long Beach, California, in 1984[21] indicated ship owners and shipping companies are not likely to embrace sails, especially kites, unless based on proven technology with a large potential for cost reduction, minimal investment and no extra crew. Another similar symposium, Windtech '85, was hosted in Southampton, England[24 27]. Here there were several papers on kite propulsion and Duckworth presented perhaps the only serious work[1426] by a major ship owner (British Petroleum) to investigate kite propulsion. The BP team tested and measured several large kite systems and installed some of the simpler ones on a small research vessel. These were of the parachute type with a L/D ratio of 1, rigged in chains and launchable one by one, the first from a compressed air cannon. These kites could be steered 40 degrees to either side by a remote-controlled weight shift system which has also been used successfully by Stewart[25] and Schmidt[10 13 15 19]. Although the tests were successful, Duckworth concluded that scaling up to ship size would be so daunting as to be commercially non-viable. In particular, it was feared that any loss of control during a wind lull would mean irretrievably abandoning the entire deployed equipment for safety and operational reasons. High efficiency or even as were thought to be even worse in this respect and so "far-out" to be entirely unacceptable to ship owners.

Roeseler in 1984 invested $50,000 in a 46 ft, 10 ton research vessel "Tonto Maria" and fitted her with fuel flow instruments, knot meter, and sails. She demonstrated 30% fuel saving in 10 kt favorable wind. Also during this time Air Commodore Nance bought BP's research Vessel "*Assessor*" and with the help of Schmidt installed a launching and retrieval system for stacks of Flexifoil Power kites[7]. This unique type of kite has a single flexible spar but is essentially a ram air inflated wing capable of speeds up to 100 kts in winds of only 20 - 30 kts and of generating correspondingly great forces. Its greatest disadvantage in this application is the required large amplitude and rate of control movement in the two lines, meaning either sophisticated and expensive line handling equipment, or in the case of simple winches, very fast acting ones. It was indeed found possible to deploy and retrieve 4 meter span Flexifoil kite stacks on *Assessor*, but impossible to fly them dynamically because of this problem. Another unresolved problem is the control system. While a human can control the Flexifoil kites for up to several hours, this is extremely fatiguing work once the initial sporting sensation has worn off. Efforts were made to investigate the properties of appropriate electronic control systems, but at this point the project was terminated as much more effort and funding would have been required to proceed further. The technical problems described were thought to be solvable. The Achilles heel of this and most heavier-than-air kite systems was thought to be the extreme difficulty of retrieving kites in sudden lulls. (Of course, the ship's speed and/or course may be altered in these infrequent lulls to keep the kite up, but this will not be popular, especially if there is traffic.) Only auto-rotating, powered and free-fly able, or lighter-than-air kites were thought to be more or less immune from this severe problem.

Also around this time, Englishman James Labouchere built a kite-boat using an entirely rigid kite. Although model tests had been successful, he did not succeed in getting the system to work at full scale. We suspect the weight of the kite was above one pound per square foot (1 psf), and that it would not fly below 15 or 20 kts of wind. Hence the probability that the wind never exceeded minima during the short time period he was able to devote to demonstration, so the possibility of a successful kite sail run was taken away by Mother Nature.

We have had many similar experiences since 1980. One of them was at Ancient Interface in 1985[23] when we actually launched our 200 lb kite with teenage pilot and our 400 lb Dynafoil (personal water craft) with two teenagers onboard. We failed to achieve stable flight in front of a dozen or so interested observers. Our goal that day was to tow the kite up behind the 40 hp powerboat in less than 10 kts of smooth air, then maneuver the kite off to the lee of the foiler and motor sail as we made our way from Seattle to Blake Island some 5 miles to the west in Puget Sound. A year later we did achieve stable flight with the same 400 square foot kite which measured 56 ft from tip to tip. We never did get the kite to tow the little 400 lb hydrofoil boat, but we learned a lot about how much it might cost to make it happen. We had invested \$5000 in the commercial off the shelf (COTS) Dynafoil and \$20,000 in the Hobie 18 rigs that we lashed together with pop rivets, titanium tubing from Boeing Surplus, and a few hundred feet of light gauge stainless wire. Shop facilities were donated by the Flight Research Institute and a friend who lived on Lake Washington. We came at least half way to our goal with less than \$100,000 in 1996 dollars and less than 1000 hrs of volunteer labor.

A few years later in 1991 we invested another \$50,000 trying to get the same kite to tow a larger foiler made from a Capri 22 monohull. We were even less successful that time, never even achieving stable flight of the foiler under power, but we did learn that bigger boats cost a lot more, and older youth are more difficult to coax into these projects without near term financial reward. In 1995 we finally did realize Hagedoorn's dream by towing an Air Chair (a popular hydrofoil toy designed in 1985 by Mike Murphy and Bob Wooly for riding behind a ski boat) with a production Kiteski system.

During these same years, Ketterman was enjoying much more success with his Trifoiler *Longshot* (Fig 5) assaulting the unlimited sailing speed record above 40 kts. The sails on this boat were derived from Jim Drake's Windsurfer after 1,000,000 smart sailors had invested 10^8 hours and $\$10^9$ improving on the basic concept. At the same time a dozen or more large companies invested $\$10^8$ in gas powered garden tools to supply the demands of a $\$10^9$ world market for chain saws and grass trimmers. A company in China invested $\$10^6$ in development of a better hand truck for moving furniture, and now the price of a set of pneumatic tires, wheels, and ball bearings with 600 lb capacity has dropped by an order of magnitude from what was available 40 years ago when we were building go carts and motor scooters.

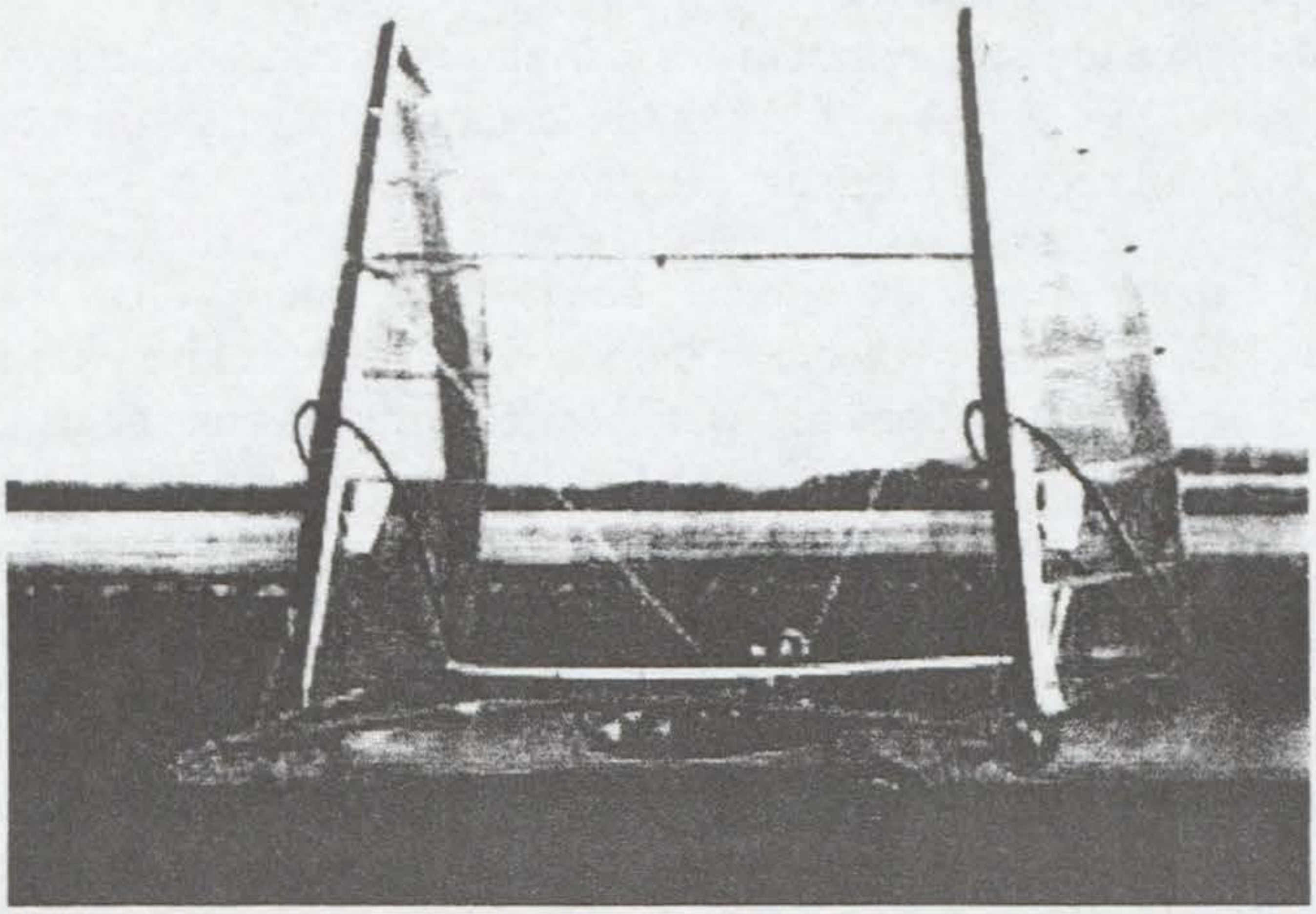

Fig 5 Russell Long Sailing his Greg Ketterman-designed Trifoiler *Longshot*[40]

We could now build a kite based on this new technology. It would have a span less than 40 ft and a wing area less than 200 square feet, but it would weigh only 20 lbs, and it would fly very nicely at 10 kts. We could add a $50 30cc Weedeater motor, a $300 Israeli autopilot, and $20 pneumatic tires from China, and we could have ourselves a very capable little UAV kite for less than $3000. Such is the pace of COTS product development over just the last 10 years. That is a unit cost of just $100/lb or $15/square foot of wing area. ($15 psf) This cost for a highly specialized UAV based on mass produced COTS components beats the best military systems by at least an order of magnitude. Fueled by demand from recreational sailors, gardeners, and people on the move, these COTS building blocks may now be used to create still more useful products and systems to address the transportation and environmental needs of our day.

If Labouchere had the motor, landing gear, and autopilot on his rigid wing kite at the speed trials in Portland Harbour ten years ago, he may have been able to put on quite a show for the assembled British royalty, the Grogonos, and other members of the AYRS. With a motor and wheels to get started, a rigid wing of more than 1 psf unit mass could indeed be flown, and could extract more than ten times the power of its engine from a 10 kt wind. We suspect Labouchere may indeed have been capable of sailing at speeds up to perhaps 30 kts in a relatively modest wind of less than 15 kts. The power required may have been of the order of 30 hp, or ten times what would be available from the $50 motor.

Inflated wings represent another unique category of semi-rigid kites. Using a buoyant gas, the problems associated with light winds disappear, to be partly replaced with operational difficulties in high winds. Englishman Keith Stewart developed a number of such kites and with Culp[28] and Schmidt[20 44] experimented with on-board launching systems on small boats. These systems were entirely successful in light or moderate winds and some were steerable on a single line using radio control. Besides boats, such kites were also used with hull-less hydrofoils, some submergible, also radio-controlled, making an extremely basic and low-cost sailing system useful, for example, for oceanographic data gathering.

The last ten years have seen little or no progress in kite system research for ships or even boats, but considerable activity in sporting applications, notably kite skiing on water and snow and kite-buggy racing on land. Several Arctic and Antarctic expeditions have kite sailed thousands of miles pulling heavy sleds, all using the German Beringer parawing system, soon to be covered by a book about kite traction systems. Another similar short-line system developed by German Strasilla allows the instantaneous switching from sailing to flying mode, allowing a skilled pilot to sail up and across mountains and take off at will. New Zealander Peter Lynn has shown his traction kites and buggies at hundreds of kite festivals all over the world.

Reviewing all the above, it is seen that the most successful kite-sailing systems are those which are entirely manageable using the strength of one person. Larger systems would only be feasible using automated handling and flying equipment and so far very little work has been done here. There is a good case that such systems could prove economical in spite of the cost of such specialized equipment. The available small-scale kite-sailing equipment is considerably cheaper than conventional sailing equipment of the same power, even though the former is manufactured in far smaller quantities than the latter. As an example, the custom-made Flexifoil stack and associated equipment of one-time C-class speed-sailing world record holder "Jacob's Ladder"[16] was cheaper than the standard Tornado rig it replaced or the wing sails[37] used by other C-class racers.

WHY KITES ?

One of the big advantages of kites over conventional rigs, rotating cylinders, and wind turbines is the relative freedom from heeling moment. This will allow us to attach kites to most commercial ships without significant modifications. Another advantage is dynamic sheeting, or the ability to fly patterns in the sky to maintain relative winds at the kite that are several times stronger than the wind on the deck. For example, a Kiteskier running downwind in 10 kts of true wind will outperform a sailboard of the same sail area. Both sailors will choose a broad reaching course to maintain 10 kts of relative wind on the deck, but the Kiteskier will fly patterns in the sky to maintain a relative wind at the kite of more than 20 kts. This mechanism is similar to that of a windmill or autogyro. The wind energy extracted is not so much a function of the blade area, but the entire disc area swept by the blades.

A related phenomenon is the Flettner or Thom rotor. Here the lift coefficient based on area of the rotor can be increased from 1 to 10 by dragging the air column using its viscosity. Frenchman Jacque Cousteau has done much to popularize this type of sail rig. These devices are of interest to the shipping community due to the ease of de-powering them when entering port or in high winds. The theoretical advantage of kites relative to cylinders and wind turbines is covered by Wellicome[27].

Fig 6 shows the power extracted by various sail types at various course angles. This was originally published by Loyd Bergessen in support of the design of "*Mini Lace*" in 1981, then adapted for kites by Schmidt in 1985, and finally by Roeseler in 1996 for more efficient kites. The advantage of efficient kites over conventional sails in assisting slow moving cargo ships will approach 10:1. *Mini Lace* was a 220 ft Greek freighter outfitted in 1981 with a 3000 square foot Dacron sail by Windship Development Corporation of Norwell, Massachusetts. This sail was hydraulically furled from the bridge. The mast rose 116 ft from the deck. No extra crew members were needed to operate the $500,000 sail on this 3,000 ton cargo ship because its 53 ft boom was sheeted automatically to optimize fuel saved. This and the tugantine "*Norfolk Rebel*" were discussed at some length at the National Conference/Workshop on Applications of Sail-Assisted Power Technology at Virginia Institute of Marine Science, College of William and Mary in May of 1982.

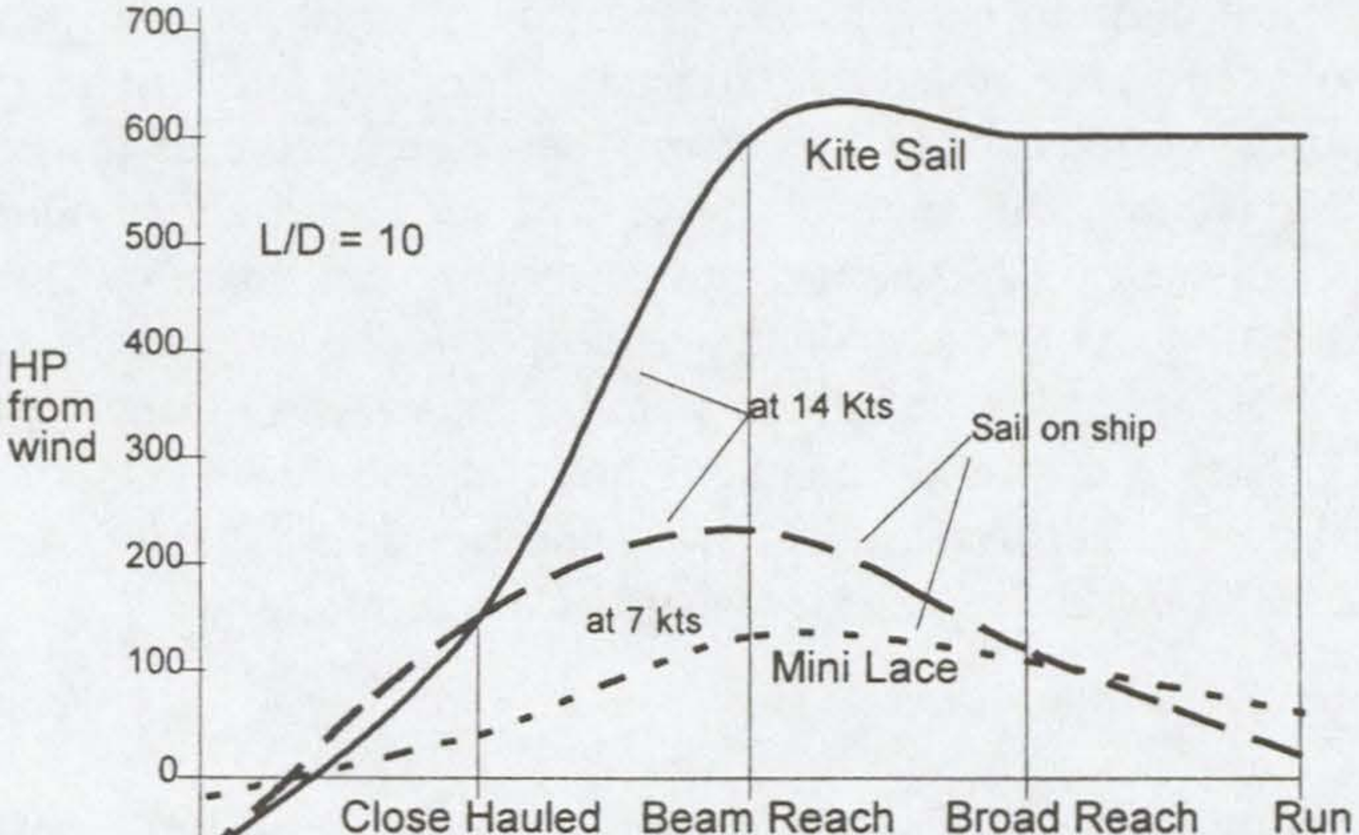

Fig 6 Power From the Wind

Fig 6 shows why kites may replace prior commercial rigs once the problems of launch, retrieval, and control are worked out.

MATERIALS

Our ability to build and sail systems that fly high above the ships depends in part on advanced materials that have specific strength and stiffness an order of magnitude higher than what was used in the last round of commercial sail craft a hundred years ago. Spectra, a remarkable polyethylene fiber invented in the early 1980's in Europe and currently in mass production at Allied Chemical, is stronger than steel and floats on water, making it an ideal material for tow line and other elements of large sail systems. Filament fortified film, invented in 1991 and used in our successful defense of The America's Cup in 1992, combines Spectra with carbon fibers and other space age materials to create sail material an order of magnitude better than 19th century canvas in terms of strength, stiffness, and life.

SOFT SAILS

In the rapidly growing sport of traction kiting, soft sails derived from modern parafoil technology are becoming more popular than stick kites like the Kiteski. The main reason is a lower unit weight. Popular soft kites like the Peel, Sputnik, and Chevron extract 20 hp from a 20 kt wind and weigh less than two lbs. Their unit weights are of the order of .01 lb/square foot (psf), which enables them to stay aloft in relative winds down to 2 kts, where the dynamic pressure is also of the order of .01 psf. Fig 7 shows a large parafoil kite used for traction on land and water. Although small kites are easily launched, a mechanism such as the one invented in 1994 by Bill Schrems[46] would be required for larger soft kites.

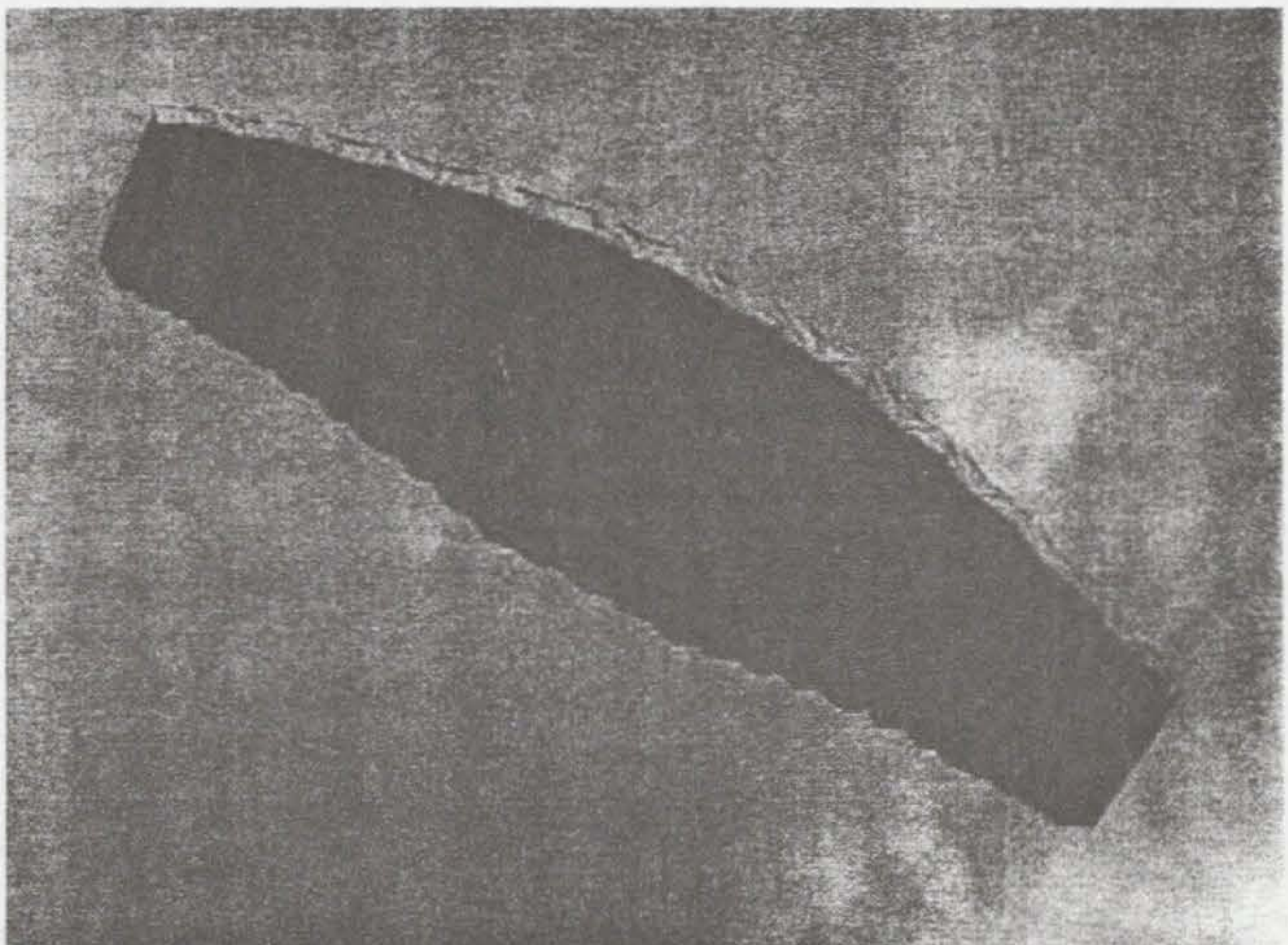

Fig 7 Chevron Power kite. Photo and kite by Andrew Beattie

At the end of the spectrum of soft kites is the 30,000 square foot lighter than air wing (Fig 8). This 360 × 90 × 20 foot wing would float in the sky thanks to 300,000 cubic feet of helium that would support her 30,000 lb mass. She would have 50 ribs tied to the upper and lower surfaces to maintain a good foil shape in relative winds up to 100 kts. The 100 bridle lines would attach to some of the ribs and transmit up to a million lbs of force to the ship at the other end of the tether. The bridle lines are 3/8 inch dia Spectra and have an ultimate breaking strength of 11 kips at 100 ksi.* They weigh .03 lb/ft or 300 lbs total if they average 100 ft in length. The main tether is 2 inch dia and weighs 500 lbs at 1000 ft length.. The control lines might be led to winches on the deck of the ship or connect to servos in a radio control pod between the ship and the wing.

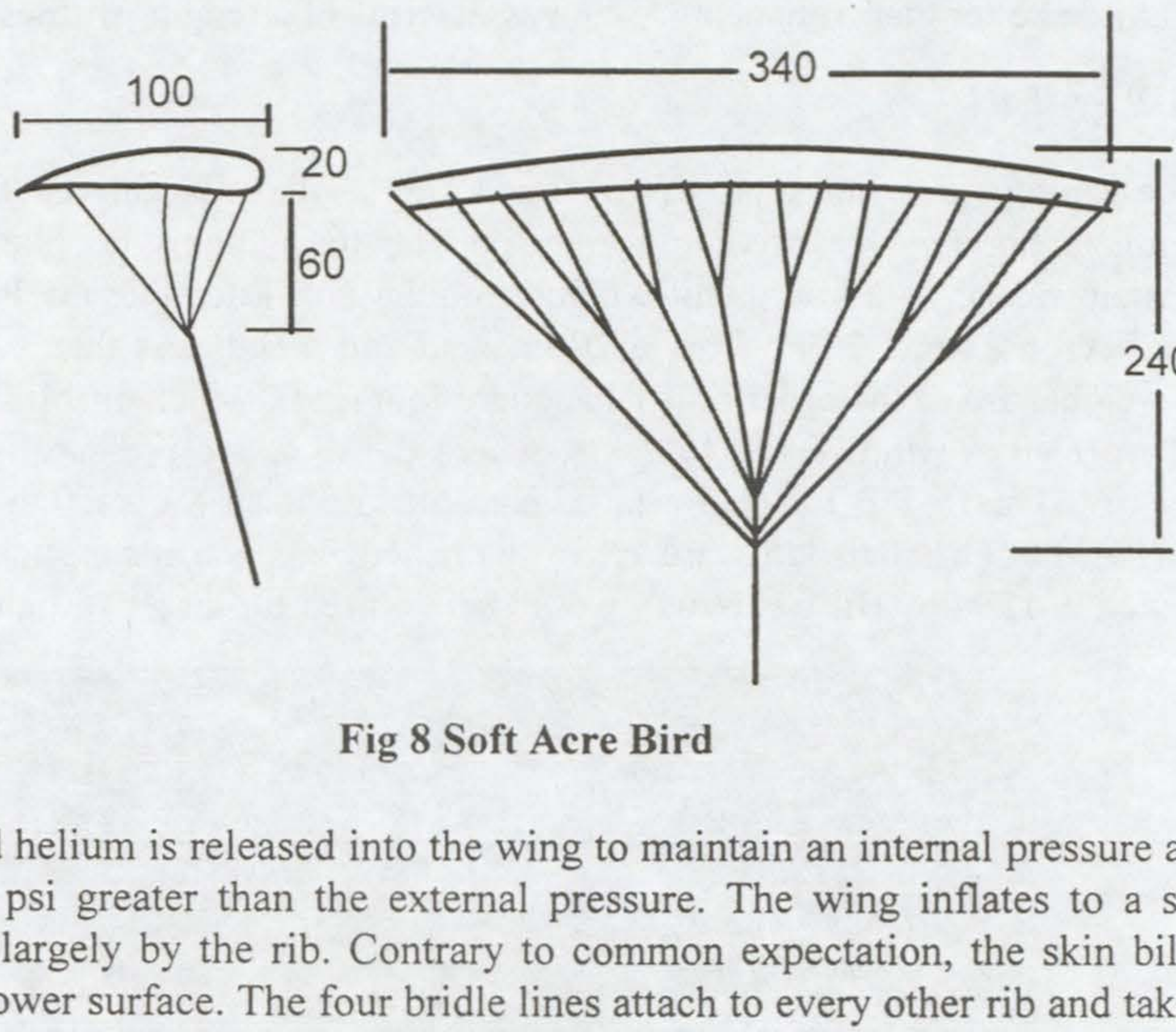

Fig 8 Soft Acre Bird

Compressed helium is released into the wing to maintain an internal pressure a few tenths of a psi greater than the external pressure. The wing inflates to a shape determined largely by the rib. Contrary to common expectation, the skin billows out on the lower surface. The four bridle lines attach to every other rib and take the internal rib loads to the tether.

The 30,000 lb weight estimate is based on a fabric weight of 10 oz/square yard. This is an order of magnitude heavier than hot air balloon material, but less than many airships. The ribs are of similar material, reinforced at the bridle attach points and tied to the upper and lower surfaces for tension loads of 100 lbs/inch associated with the inflation pressure. The projected cost of this wing is $100/lb for her Spectra reinforced Mylar surfaces. That works out to $3m for a wing capable of exerting 400,000 lbs of towing force on a ship operating at 14 kts in the typical 20

* 1 kip = 1 kilopound = 1000 lb force. 1 ksi = 1 kip per square inch.

kt trade winds. The power extracted from the wind is 400,000 lbs × 24 ft/sec = 107 ft lb/sec or over 20,000 thrust horsepower. The cost of helium to fill this wing is $30,000, and it may need to be replenished each year during the ten year life of the system.

Semi rigid wings such as the Kiteski have unit weights of the order of 0.1 psf, which causes them to fall out of the sky when the relative wind drops below 5 kts. Rigid wings like the Global Hawk have unit weights of the order of 1 psf, so they must maintain a flight speed above 15 kts to stay in the sky. The goal, of course, is not just to stay aloft, but to do useful work. Staying aloft is merely a prerequisite.

The largest modern parafoil is the 7000 square foot wing being developed by the US army for flying payloads up to 35,000 lbs which exit from the back door of a C-130 cargo plane. These payloads are guided to a precision landing up to 15 miles away by a control system hooked to the risers. As a kite tethered to a ship, this wing could provide 20,000 lbs of thrust on points of sail within 45 deg of a beam reach in 20 kts of true wind. Assuming the ship was making 14 kts along her course, the wind energy would be 14 × 1.69 × 20,000/550 = 860 hp, or about the same as that of the Condor described in our abstract. The difference is that the soft sail weighs two orders of magnitude less than the rigid wing, can stay aloft in much less wind, and can be stowed and deployed from a tidy little bag on deck. The down side of the soft sail is that it is not very weatherly, having significantly less lift to drag ratio (L/D) than the Condor, and would not be able to tow the ship to weather in more than about 20 kts of true wind. The Condor would be able to exert her 10,000 towing force in relative winds up to about 100 kts, although the turbulence associated with these once a year storms may cause a rigid wing to break up.

RIGID WINGS

A great deal of operational data is being obtained on rigid wings thanks to the Aerosonde[39], Predator[47], and other UAV's. Although rigid wings have the best lift to drag ratio of all types of kites, they are more expensive per unit area and are more difficult to build and fly at the low speed end of the useful wind spectrum. They are best in storm conditions, where soft sails may need to be furled. By flying larger patterns in the sky, the rigid wings can be competitive with soft sails having much more area. Rigid wings such as the one used in San Diego in 1988 to defend the America's Cup are only marginally more efficient than soft sails attached to a wing mast. While a small speed advantage in a sailing race is worth the trouble, a commercial shipper may opt for the lower cost, lighter weight, and other advantages of soft sails.

HYBRIDS

By combining aerospace technology with that used on the successful America's Cup defender in 1992[50], we could build a wing of 360 ft span, 30,000 square feet in area, which would weigh less than 30,000 lbs, cost less than \$3M, and would develop up to 400,000 lbs of lift at 60 kts. (Fig 9) We might start by laying a two inch thick plate of carbon/epoxy tape using our automated tape laying machine, then cure it in our autoclave. It could be sliced into 16 bars each 2×2 inches by 90 feet in length. These could be bonded into a set of 4 honeycomb wing sections each 90 ft in length with a 10 ft chord.

Spar weight $360 \times 12 \times 8 \times 2 \times .056 = 4$ kips

Sail wgt = 3,000 square yds $\times$ 1 lb/ square yd = 3 kips

.050 skins weigh $.2 \times 10 \times 360 \times 144 \times .06 = 6$ kips.

2 inch core adds 5 kips,

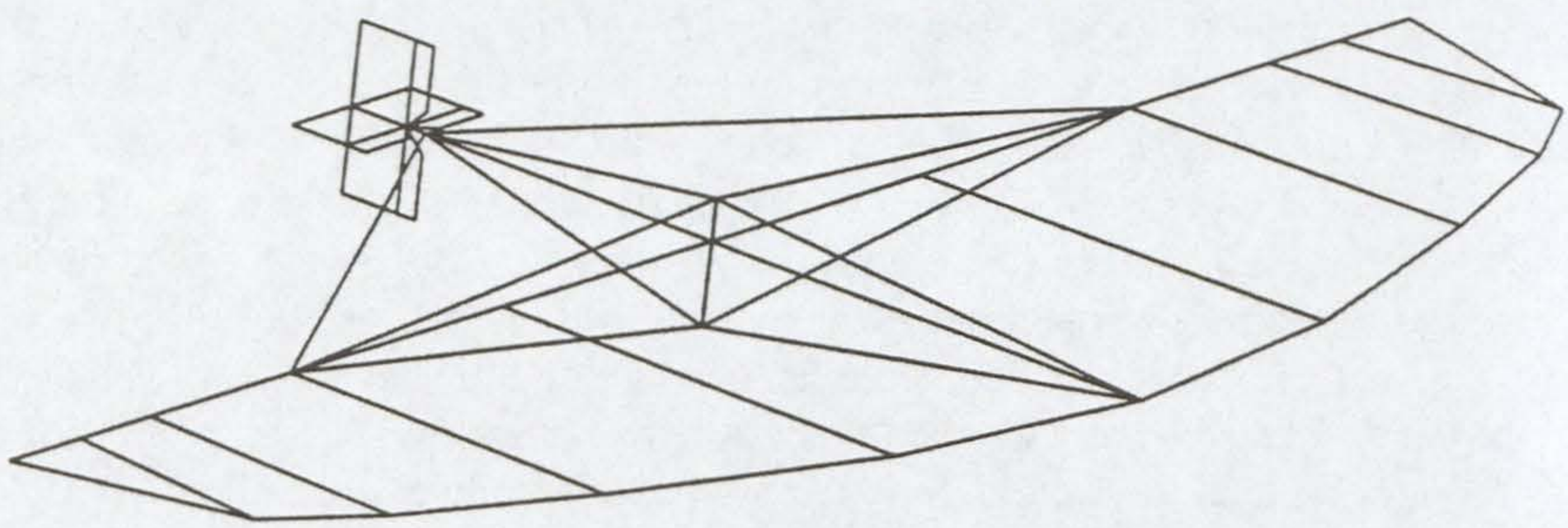

Fig 9 Wing based on America's Cup Technology

This type of construction is similar to that of the Boeing Condor and the wing masts of many ocean going multihulls. It is related to America's Cup by the tubular carbon battens, external bracing and advanced sail laminates.

LAUNCH AND RETRIEVAL

Kites may be more difficult to deploy and retrieve than conventional sails, but not as difficult as carrier based aircraft. One alternative is to keep the kite aloft between towing jobs by using a small engine. The cost of keeping a UAV aloft in still air or while in port may be less than the cost of launch and retrieval onboard the ship. Kite sail systems based on Condor technology might stay aloft for periods up to a year, landing only for maintenance. The tether would be disconnected from the ship as the ship steamed into port, then dropped to the deck of another ship leaving port for another towing job at sea. Another technique[32] may be to make the kite lighter than air by inflating all or part of it with helium or hydrogen.

FLIGHT CONTROL

As mentioned by Duckworth and others, the task of controlling a high performance kite can be daunting. However, skilled oriental kite flyers have developed techniques for controlling unstable single line kites that would boggle the minds of most kite sail critics. Simply stated, the technique is to take in line when the kite is headed in the right direction, and to pay out line when it is not. This is a technique that must be seen to be believed. Most of us are so convinced of the virtue of multiple line stunt kites that we cannot conceive of a single line kite that might be even faster and more maneuverable.

A related technique is used by two line stunt kite experts during periods of light air in competition. By pumping energy into the system by moving both hands together, the kite can be kept aloft in below minimum wind conditions. Both of these techniques could be used by commercial kite sailors during periods of light air, but radio control techniques based on modern model and UAV technology probably hold more promise.

While prior research[26] has shown that "application of parachute kites to large ships of the BP fleet is uneconomic", the possibility is left open. "Ram air wings should be considered as their increased complexity and cost might be offset by increased thrust and greater utilization than parachute sails". These conclusions are equally valid today as they were in 1985, although we would add the possibility that low cost, automatic flight controls derived from modern UAV technology might further increase the thrust and utilization, thereby improving the economics of the system. We showed in Fig 6 how flying patterns in the sky will improve wind power extraction on most points of sail by up to an order of magnitude. The price we pay for this increased performance is "increased complexity", including the need for sensors, processors, and servo controls.

Automatic flight control has become a way of life for large segments of the aviation community, and the cost is not always high. The Rutan Voyager could not have been piloted around the world on a single tank of gas without an autopilot to relieve the workload on the pilots. These general aviation autopilots use signals from flight instruments to maintain altitude and heading. Then in 1989 a remarkable new product became available, a full performance autopilot for model airplanes. This $300 electronic device uses static and dynamic pressure and a magnetic compass to maintain altitude and heading through elevator, rudder, aileron, and throttle servos. A similar device could be used to control a high performance kite during long ocean passages.

We found in 1992[48] that kites with L/D above 20 could be controlled by adding rate gyros and servo controls. Then in 1993[39] we showed how the autopilot and stability augmentation could be combined to provide completely autonomous flight operation, including navigation, for days and even weeks at a cost less than $3500. Both of these flight demonstrations were carried out at model scale with a wing span less than 10 feet and max. wing lift below 100 lbs. There is no reason the flight control task would be more difficult for much larger wings, and the cost may be even less if the ship's captain retains the job of navigation.

The proposed flight control system would include a rate gyro, pitot, echo altimeter, computer, data link, rudder, and elevator servos. The computer would also need data from the ship's wind speed and direction instruments in order to optimize the wind energy extracted. Tow line angle and force might also be useful, but the key will be development of the software that will keep the kite safely above the wave tops while flying patterns in the sky to maintain optimum performance. The complete system might include a weather station and some degree of control of the ship's rudder and engine to optimize the economics of the entire system.

Modern aircraft use over a million lines of code to handle flight control and flight deck status display for the flight crew. Much of this is devoted to failure status of the various systems. The cost of development of similar code will dominate early commercial kite sail systems, but it would become reasonable once the basic parameters are developed through fleet experience.

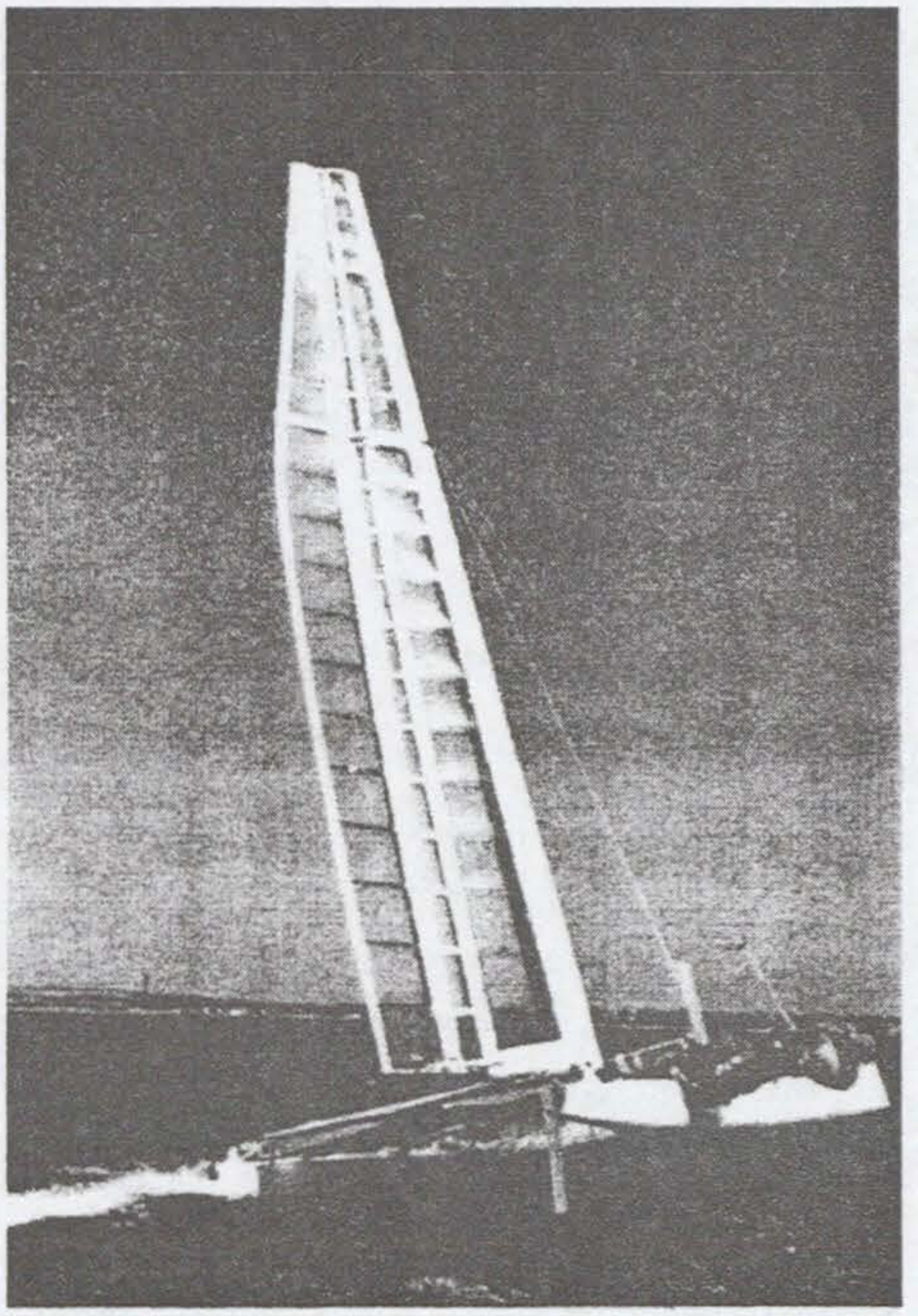

Fig 11 Cogito Catamaran[37]

COST AND VALUE

In order to be commercially viable, the sail must be built and operated for less cost than the cost of the oil saved by its use. For the 1000 hp sail described in the abstract, the cost must be less than \$100/hr. Current rigid wing UAV's cost more than that, especially those that are large enough to extract 1000 hp from a 20 kt wind. Perhaps the technology used in the marine industry would be more appropriate. Consider, for example, the Cogito catamaran of Fig 11 which recently won back the Little America's Cup in Australia.

This 30 × 8 ft wing was built of carbon and Mylar at a cost of less than 4000 man-hours. A kite sail based on this technology would have a span of 60 ft, an area of 600 square feet, and would weigh less than 400 lbs. It would be capable of operating at a lift coefficient of 1 in relative winds up to 50 kts at an L/D greater than 10. That would yield a force of 6000 lbs, perhaps 3000 lbs of thrust, which would extract 300 hp from a true wind of 20 kts. The fuel saved would be 150 lbs/hr = 20 gal = \$20/hr. The cost of the first unit was more than \$400,000. That included the cost of the design and tools. If more than 100 units were built, the cost per unit should be less than 400 lbs × \$100/lb = \$40,000. Assuming a useful life of 5,000 hrs, that works out to \$8/hr, so it looks like we may have a profitable system if we can keep the cost of the systems below the cost of the structure. The systems in this case would include the electronic flight controls needed to keep the wing up there doing useful work and the cost of the winch and retrieval mechanism on the deck of the ship. The large fleet of parafoil tow boats operating in tourist areas of the world convince us the winch and pylon should cost less than \$10,000. In this example, the tail of the bird would fold parallel to the wing so the entire sail could be stowed on the deck of the ship when not in use. There would be a 1 hp winch with 1000 ft of line to tether the bird, and a small ram air turbine would supply 100 watts of electrical power for the flight. Thomas Jeltsch in 1995 helped Kiteski perfect a manual winch and brake for this purpose with a retail cost below \$1000.

The following table summarizes some of the wings discussed in the text. The Aerosonde, Kiteski, and Predator are operational, providing actual cost and performance data to the industry. Cogito, Trifoiler, Parafoil, and Condor have flown extensively in related modes and represent technology that could be readily adapted to kite sailing. Global Hawk will fly this year, at a unit cost of \$10m including engine and electronic payload. Our \$100k cost estimate would cover only a simplified wing and kite sail controls. The two versions of the Acre Bird, one based on America's Cup technology and the other an inflated wing, are awaiting major capital investment to get into the hardware stage.

TABLE 1 RELATIVE COST OF VARIOUS KITE SAIL SYSTEMS: *

	Span (Ft)	Area (Ft^2)	Weight (psf)	Average Power (HP)	Life (Hours)	Cost ($)	Relative Cost ($/hp-hr)
Aerosonde	10	10	0.5	2	10,000	10k	0.5
Kiteski	20	70	0.1	20	100	0.8k	0.4
Trifoiler	40	200	0.2	30	1,000	3k	0.1
Predator	48	150	1.3	40	10,000	80k	0.2
Cogito	60	600	0.7	200	5,000	80k	0.08
Parafoil	150	7,000	0.01	1,000	100	70k	0.07
Global Hawk	116	250	2.0	300	10,000	100k	0.03
Condor	200	1,200	1.0	1000	10,000	200k	0.02
Acre Bird	360	30,000	1.0	10,000	30,000	3,000k	0.01

MILITARY NEEDS

Today, the case for transport sail craft depends mostly on commercial, not military needs, as the nuclear powered aircraft carrier is hard to beat in terms of speed and range. However, there are several scenarios less unlikely than Kevin Costner's "Water World" where military sail craft may play a role. For example, the recent war between the UK and Argentina over the Falkland Islands taxed the payload/range capability of the British Royal Navy. As oil reserves are further depleted in the 21st Century, the logistics of such a conflict may create a need for wind assisted propulsion to extend the range of the smaller ships and to reduce the dependence of the fleet on underway replenishment from the oiler. Even in the US and Russia, the days of unlimited military spending are clearly at an end, and our ability to project global power on a budget may depend on innovative technologies such as wind assisted shipping.

Many critics of wind power found it difficult to believe Costner's 60 ft trimaran could outrun the jetskis, but we have personal experience in the Columbia River Gorge where several types of smaller sailcraft will outrun all of the motorboats. When the significant wave height exceeds about two feet, the jetskis are slowed below 20 kts due to ventilation of the pump inlet between waves. (The same thing happened to the 100 ton Jetfoil when it was briefly in passenger service in Hawaii.) The sail boards and Kiteskis can still operate above 30 kts in these conditions, as the need for lateral resistance is moderate on the broad reaches, and they can stay powered up when only kissing the tops of the waves, jumping over (getting air in) the wave troughs.

Even the larger propeller driven power boats have trouble keeping up with the Windsurfers when it's blowing hard in The Gorge. Although the prop may stay in the water and continue to provide thrust, the boat and driver cannot take the beating from pounding on the waves, and they must slow below 20 kts. Interaction between sail force and ship motion can be important on much larger vessels in terms of crew comfort.

Hence the case for military sail craft may depend on the economics of war, and to a lesser extent on the possible speed advantage of wind assisted ships. The possibility of greatly improving the operating radius of small patrol boats may also be attractive, especially for island nations like Polynesia where the land masses are separated by many miles of ocean. Non-nuclear powers that run short of oil reserves in the next century may also find wind assistance of some military value.

CONCLUSIONS

1. The smallest sail that could compete today with diesel power for commercial shipping would be a kite with a wing span over 30 ft.

2. One critical technology for transport sail craft is electronic flight control.

3. Much larger kites may bring the cost per horsepower hour down from around $0.10 to $0.01.

4. Launch and retrieval present the greatest technical challenge.

5. As oil prices rise in the 21st Century, the case for transport sail craft becomes much stronger.

6. Thanks to major development in the last decade in recreational traction kites and UAV's, wind assisted commercial shipping will soon be viable.

BIOGRAPHICAL INFORMATION

Billy Roeseler: BS, MS Aeronautics and Astronautics, MIT, Associate Fellow, AIAA, 17 years research in traction kite power, 30 years practicing engineer, commercial and military aircraft, founder and former CEO, Kiteski Inc., Currently Boeing engineer assigned to Joint Strike Fighter. kiteski@interserv.com

Dave Culp: Studied at Stanford, UC Davis, NAEBM/Westlawn. Designs and builds kite powered high speed sailcraft. Kite drawn entries at John Player World Speedsailing Trials, Weymouth, England, 1978,79,80; Johnnie Walker World Speedsailing Trials, Weymouth, England, 1986,87; Ned Snead Invitational Speedsailing trials, Lake Buchannan, Texas, 1990. Editor of Kitesailing International newsletter.

Theo Schmidt: BSc, University of Wales, Physical Oceangraphy, Electronic Engineering, kite traction research 1980-1985, solar/human powered vehicle development 1985-1990, also solar hydrogen, currently working on stirling engines, solar and human powered boats, vehicle safety study, board member: Amateur Yacht Research Society, Ingenieurbuero Schmidt, CH-3612 Steffisburg, Switzerland.

Cory Roeseler: BS Mechanical Engineering, UCSB, Professional Kite flier, World Champion Kiteskier, 42 mph Speed Sailor, Co-Inventor of Kiteski, currently employed by Hood Technology Corp., Hood River, OR, developing systems for active control of sound and vibration.

Richard Wallace: BS in Naval Architecture from Michigan, MBA from Wharton School, and a career spanning over 20 years with Booz Allen, Stevens Yachts, Texaco, International Energy Agency (Paris), Majestic Shipping Services, and Papachristidis Ship Management Services, Ltd. (London). He is also the only one in the world who has flown a rigid wing kite (L/D>10) with an autopilot under radio control.

Andrew Beattie: Designer and builder of soft traction kites. An enthusiastic newcomer, with the cheek to stand on the shoulders of long standing experts in the hope of beating them. Often to be seen disrupting rec.kites on Usenet news.

Tag McGeer: Phd MIT, Former Chief Scientist Aurora Flight Systems, Currently founder and CEO The Insitu Group, designers and builders of a class of low cost, long endurance, unmanned air vehicles for scientific research on the oceans and atmosphere of our planet.

Russell Long: product of Harvard, MBA Columbia, PhD CIIS, America's Cup Skipper, held 7 world records in speedsailing--still holds Class A record over 40 kts on Trifoiler Longshot, second fastest boat sailor in the world, currently Director, Bluewater Network, Earth Island Institute, an environmental advocacy organization.

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A field study of Kite Powered Hydrofoil Theory

Cory Roeseler, Hood River, OR, USA

INTRODUCTION:

Thanks to the recent advent of a popular hydrofoil waterski toy called the "Air Chair™", (Kitson, B. Roeseler; AYRS 118) and the modern Kiteski™, exciting sailing theories proposed by the Dutch Professor, J. G. Hagedoorn, in the 1940's may now be proven (or disproven as the case may be.) A skilled rider may now take "off the shelf" hardware, ordered by phone and shipped to one's doorstep via UPS, and sail at 2.5 times wind speed while enjoying a hydrofoil smooth ride, kite sailing in a relaxed, sitting position (Fig. 1).

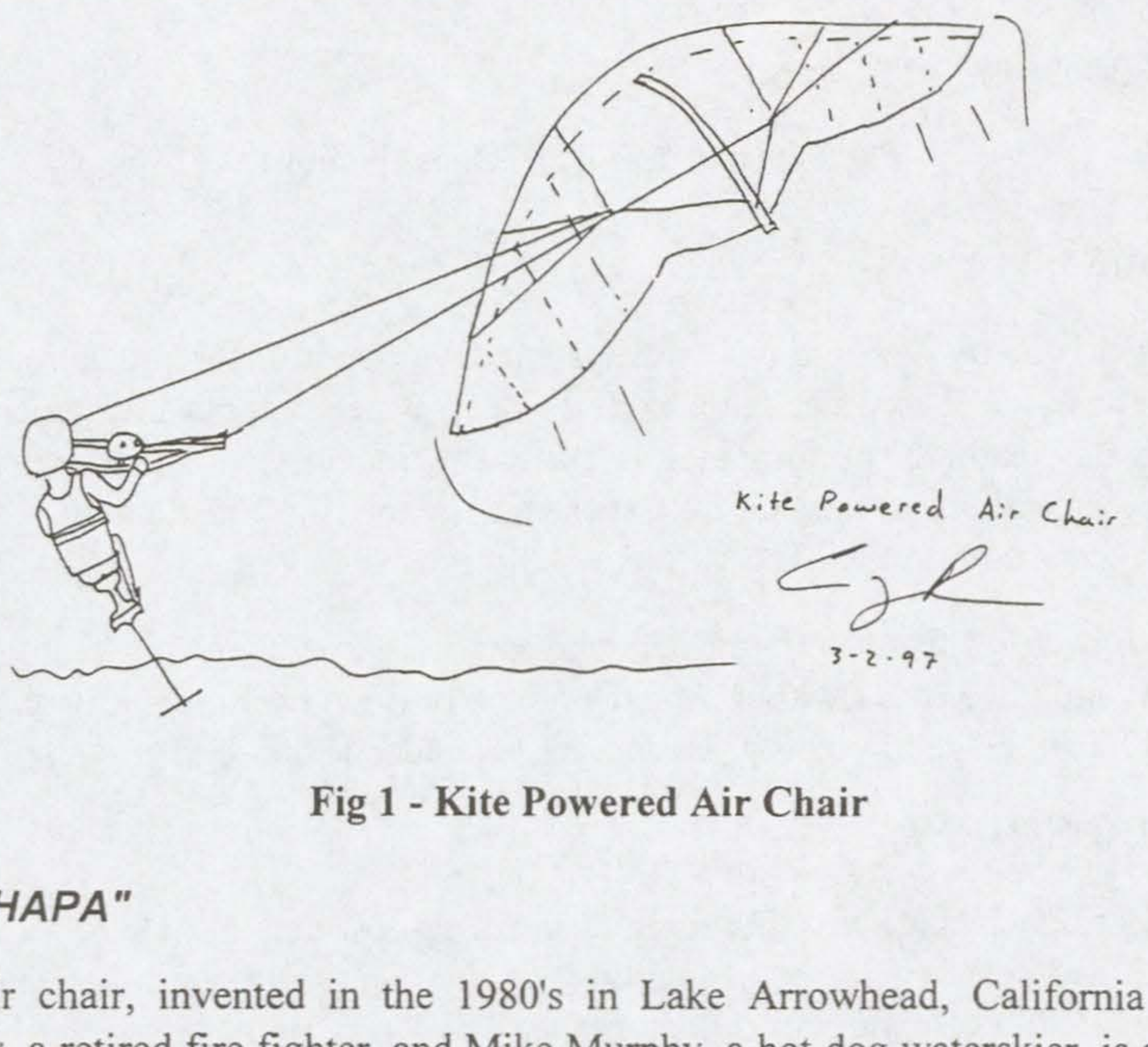


Fig 1 - Kite Powered Air Chair

THE "HAPA"

The Air chair, invented in the 1980's in Lake Arrowhead, California by Bob Wooley, a retired fire fighter, and Mike Murphy, a hot dog waterskier, is a 5 ft × 1 ft water ski with a short stool and sturdy lap belt bolted to the tail. Sturdy bindings fix the feet to the nose. Directly beneath the stool, a single 3 foot vertical strut is fastened. A flat plate aluminium foil of aspect ratio 1.5 and 18" span provides lift at the bottom of the strut. A 1" × 1" solid aluminium fuselage extends aft 10 inches to a horizontal tail stabiliser of aspect ratio 2 and 12" span. The tail stabiliser has slightly less angle of attack for pitch stability and snappy jumps.

We measured a required towing force of 20 lbs at 10 kts boat speed using a spring scale in series with the tow rope. With a total weight of 200 lbs, we get

L/D = 200/20 = 10 (Fig. 2).

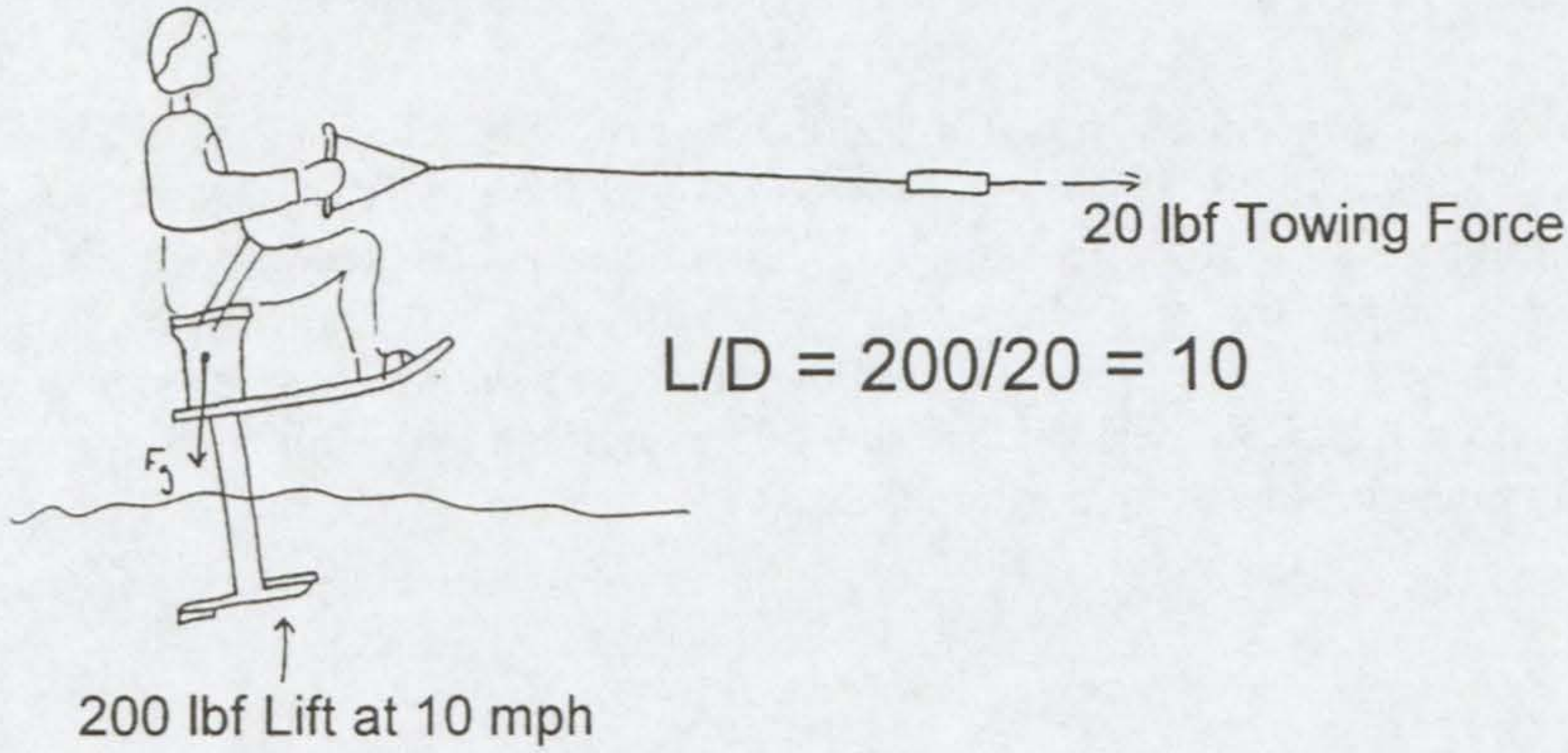


Fig 2 - Air Chair L/D Measurement

THE "SAIL"

The Kiteski is a kite powered waterski system developed for the recreational water sports enthusiast. It is water launchable in deep water without assistance of any kind, and its weatherly performance is sufficient, in most cases, to return to the starting point without an upwind hike at the end of the ride. The standard "skiing" version is featured in AYRS 118 Ultimate Sailing III.

These two toys, coupled with a rider who has mastered the Air Chair behind a motorboat and the Kiteski with its standard skis, provide useful data for the system proposed by Dr. Hagedoorn 50 years ago, all for under $3000 US.

THE COMPETITION:

Three years ago I made my first attempt at "Kite-powered Air Chair" with little success. I had been trying, unsuccessfully, to keep up with Greg Ketterman in his Tri-foiler in 10 knot wind and 6 inch chop while I was riding a standard Kiteski. He was literally sailing circles around me.

FIRST TRY:

This motivated me to replace my draggy skis with the more efficient Air Chair. I was able to get planing and speed across Los Angeles Harbor for 200m sprints, but could not manage a water start without help from the chase boat crew, nor could I make use of the windsurfing seat harness that I wore. My grip only lasted a few minutes and the ride ended with sore forearms.

THE LEARNING CURVE:

I tried the kite powered Air Chair again in '94 and '95 and once or twice in '96, but I was mainly learning to loop and double loop the "fun board" with the Kiteski. More advanced forms of sailing could wait, I felt, until the TV people quit drooling over the aerial tricks possible with the standard Kiteski.

MASTERY:

Late last summer I found myself riding the kite powered Air Chair increasingly more often, until I felt comfortable going out alone. By the end of the summer, the waterstart had been mastered, sailing to windward was possible but still inconsistent. I still had to rely on the 2 knot favourable current which makes the Columbia River Gorge famous as a "user friendly" sailing spot. The best conditions seemed to be when the windsurfers were idling/swimming in at the end of the day, and parts of the river almost seemed to glass over.

I would see a dark patch of water and burst onto a plane. By keeping the kite fairly low, hooking into the chest harness, and "edging" the Air Chair at roughly 30 degrees I could manage short, close hauled reaches at 70-80 degrees to the true wind. Inevitably my speed would either increase to the point where the loads stood me up and steered me to leeward, or I would lose power and stall the hydrofoil, sinking to my neck. At rest, the net buoyancy of the whole system may only be 10 lbs including the life vest.

THE SHOW:

The high points occurred when a gust came at the right time, and I zipped past a windsurfer heading for the beach. The others were packing their gear while cheering on the crazy guy on that "chair thing." Once or twice I was able to give a show with a high flying backwards loop on the chair thrown into a jibe near shore, and sail away without falling off a plane. (Can Tri-foiler do that?) A loop with the kite was then required to untwist the lines on the ensuing reach.

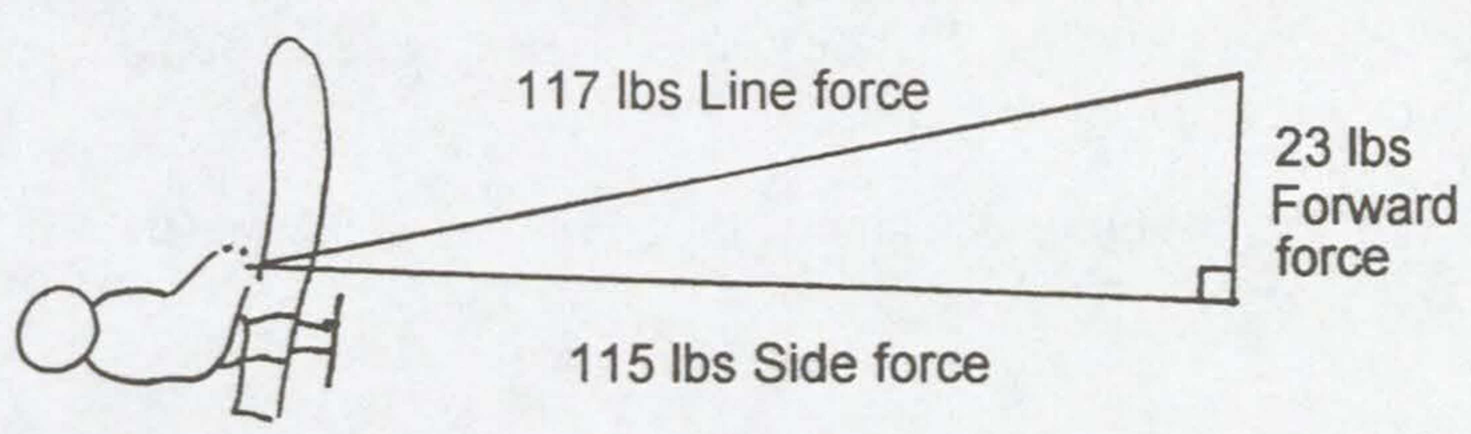


Fig 3 - Air Chair Force Balance - Top View

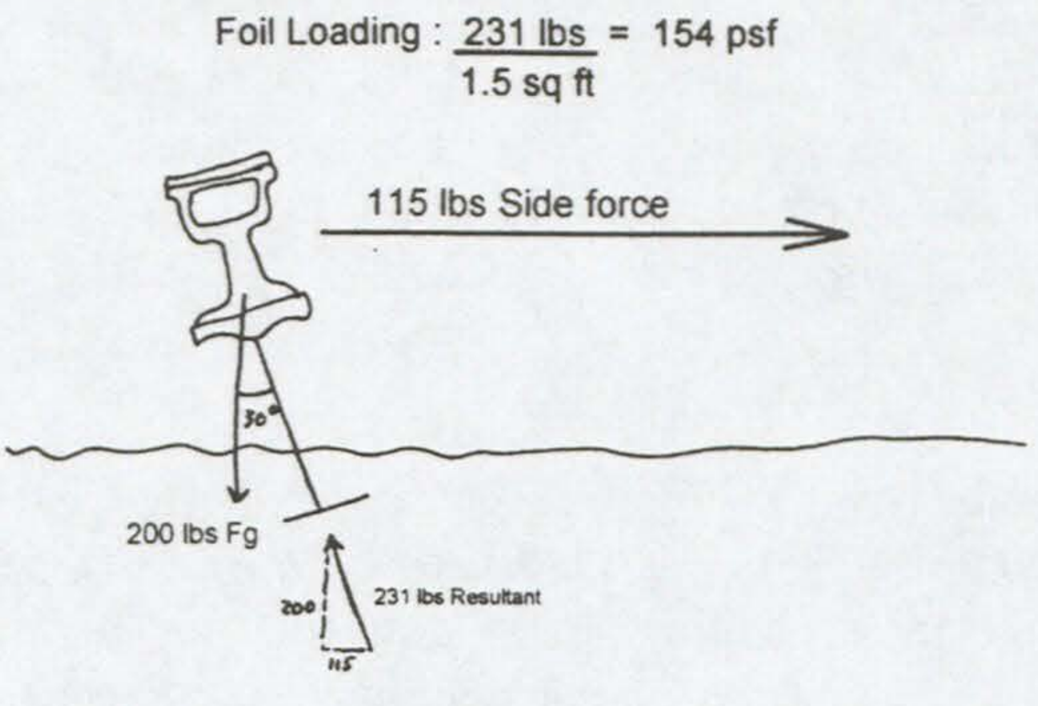


Fig 4 - Air Chair Force Balance - Aft View

ATTAINED SPEEDS:

Unfortunately, I have no speedometer on the Air Chair (yet), and have not used it on a speed course. However, I can guess the speeds based on a similar 'feel' while being towed behind a ski boat equipped with a speedometer. In 10 knots of wind, the kite powered Air Chair will cruise at 10-15 knots at 90 degrees to the true wind. Note that the ski is often kissing the wave tops under these conditions. Intermittent hull drag may not be avoided.

As you bear off to 120-130 degrees off the wind, it becomes much easier to keep the ski off the water, with maximum speeds around 25-30 kts. A constant, 30 degree lean to windward is required to balance side forces generated by the kite. The resultant is a 231 lbs lifting force on the main hydrofoil. For L/D = 10, the hydrodynamic drag is 23 lbs, and the required line force on the tether is 117 lbs (Fig. 3 and 4).

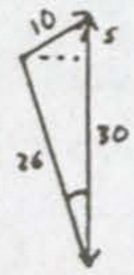
THE AERO-HYDRODYNAMIC FORCES:

Figure 5 balances the forces for a kite powered Air Chair flying at 30 knots, 120 deg. off the 10 knot true wind. The relative wind is 26 knots at 19 deg from the port bow, and the 117 lbs required line force "seems" realistic from my experience. This has not yet been measured.

Above 30 kts. the foil becomes "sticky," thus, I prefer a single waterski.

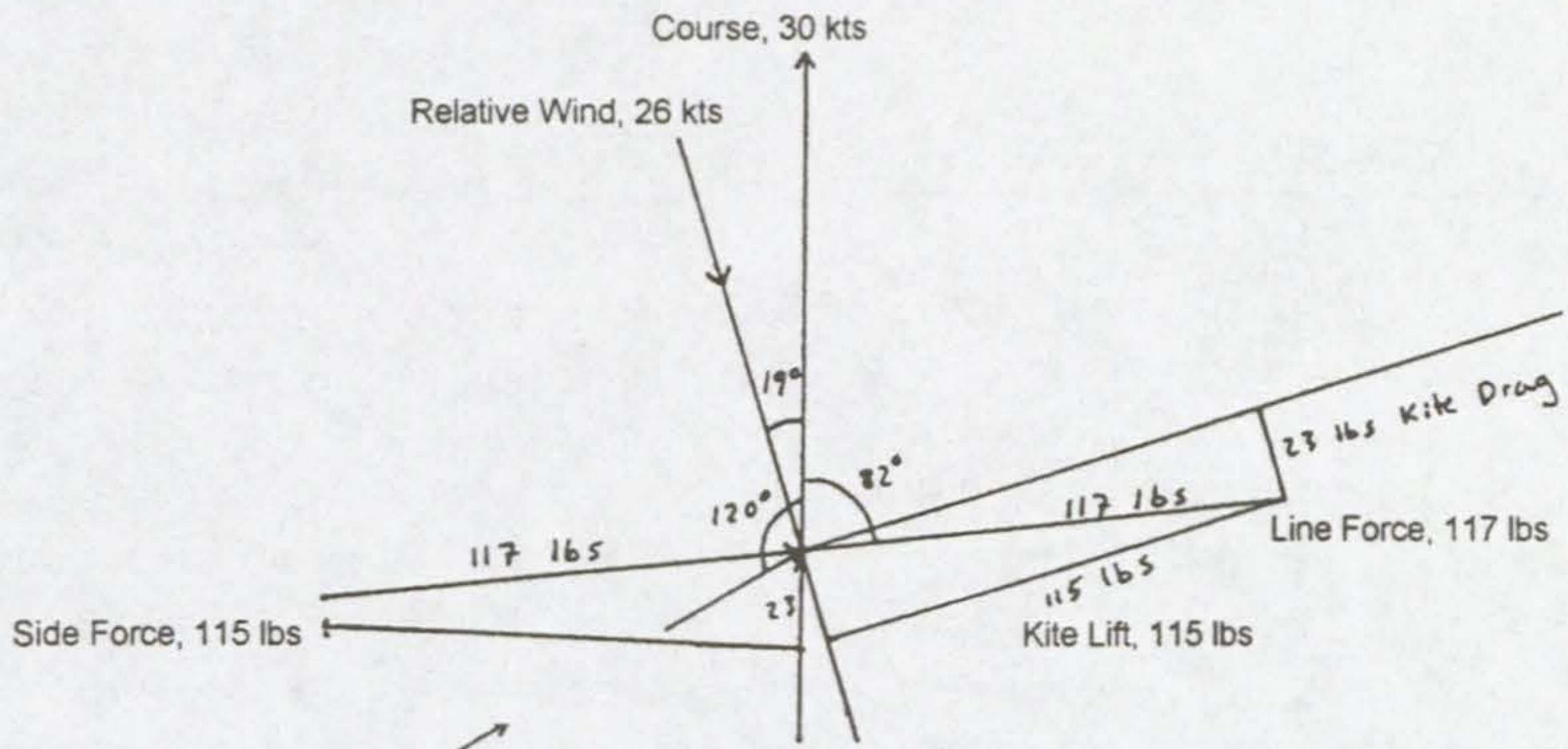
Assume —

- Zero Kite mass
- Zero line drag
- Steady State conditions
- Pilot aerodynamic drag included with total Air Chair drag (23 lbs)



$V_{rel} = \sqrt{25^2 + 10 \text{ Sin } 60°}$

$= 26°$ @ 19° off port bow



Wing Loading : $\dfrac{117 \text{ lbs}}{70 \text{ sq ft}} = 1.7$ psf

Fig 5 - Kite Force Balance

RELEVANCE TO ULTIMATE SAILING:

I realise Hagedoorn proposed that the hydrofoil be tilted to leeward with the strut under tension and negative net vertical lift of the foil (hapa or sea dog), and I understand and admire the extensive studies performed by Theo Schmidt, Didier Costes, and Paul Ashford on this subject (and presented in AYRS 114 and 118). I regret to report that I have tried this method too. When hooked into the chest harness with the kite flying at a high angle the Air Chair has a tendency to dive. This gives the foil a negative attack angle, and my spine becomes a tension member in series with the tether— a very uncomfortable sailing position. (I expect criticism for this). My physical therapist suggests that this may be a more primitive form of ultimate sailing.

AYRS pub. 118 illustrates this concept in a paper by Theo Schmidt. The caption reads: "Kite and Hapa of Dr. Collodon (1845) see AYRS 108" — certainly an early concept, if not primitive. (Fig. 6)

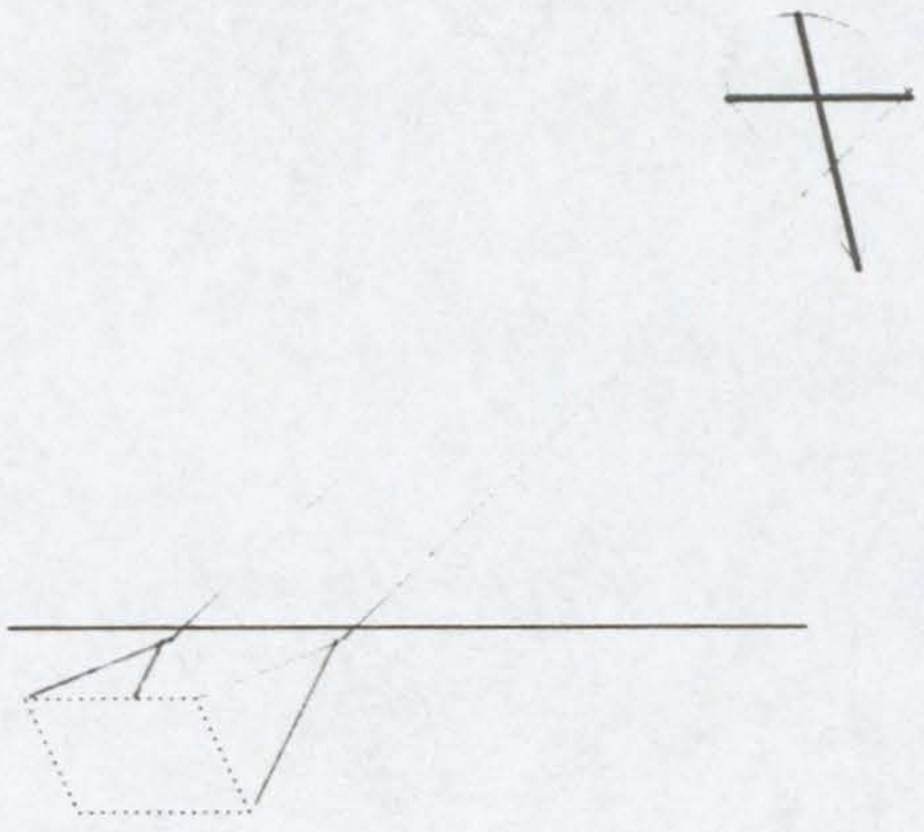


Fig 6 - Kite & Hapa of Dr Collodon - See AYRS 108

I also understand that Hagedoorn and others have proposed parafoil type kites for this application. I wholeheartedly disagree. Much of the time spent with the existing contraption is indeed swimming with it, and I would much prefer to swim with a framed kite and 8 bridle lines than a parafoil and 100 bridle lines. Even a fully inflated, water-launchable parafoil like the French "Wipica™" doesn't interest me since it would never completely stop pulling, even after it hit the water.

An Air Chair crash often ends with the chair behind the rider, and the kite dragging him face first through the water. At this point, the kite hitting the water comes as a great relief and opportunity to take a breath.

THE PLAN:

This summer, I hope to refine my ability to sail to windward on the Air Chair. I promise to record some speeds with a Speedwatch™ and take pictures now that survival is not the main objective. Mike Murphy may be joining me, and we hope to find a way to teach others to enjoy the thrill of sailing/flying at three times wind speed for under $3000 US. As always, feedback is not only welcome, but expected.

NTSC or PAL Video available upon request.

SPECIFICATIONS:

L.O.A.	5 ft	Beam	1 ft
Sail area	70 ft^2	Wing span	22 ft
Hydrofoil span	1.5 ft	Hydrofoil area	1.5 ft^2
Kite weight	6 lbs	Air Chair weight	45 lbs
Line length	150 ft	Wind range	10-20 kts.

On KiteTugs

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ABSTRACT:

This study summarises the current status of sail assisted commercial steamships, the industry's strengths and weaknesses, and why it isn't widespread today. Ways in which free flying kites used in place of conventional sail may ameliorate some of these negatives, while incurring new problems, are examined. The specific advantages and limitations of crewed and self-sufficient KiteTugs, a new class of lighter-than-air sailing vessel/sail assist device are investigated. A detailed breakdown of potential KiteTug cash flows and cost-effectiveness is included.

CURRENT STATUS OF COMMERCIAL SAIL

Though numerous studies, proposals and tests have been conducted within the past 20 years[1], widespread commercial sail assist, whether conventional sails set on masts, wingsails, or powered Flettner rotors or aspirated cylinders, is not prevalent on commercial ocean going vessels today. While upwards of 25 vessels, from 50 to 50,000 tons have either been retrofitted or studied for sail retrofit[1,2], we do not see a viable sail assist industry today. The simple reason for this is the same as it was 100 years ago; fuel oil is inexpensive, powered vessels are not labour intensive and powered vessels' performance is both reliable and repeatable. For sail assist to make inroads, it must be cost effective, it must incur minimal degradation of performance, and it must not entail significant retrofit expense or increase in crew load.

Currently considered designs generally envision "assisting" a powered vessel's engines only; few envision pure sailing[1,2]. There are several reasons for this. Retrofitting an existing vessel is expensive. Hull shapes, control gear and deck space are not optimised for large pure sail rigs. Capital cost and space limitations demand that the sail rig be as small as practical. Rig sizes are thus optimised for high winds, while the vessel's engines are expected to supplement them in lighter winds.

Thus, currently envisioned schemes result in average fuel savings throughout a vessel's voyage on the order of 10-30%[1,3]. This is not enough saving to warrant re-routing vessels to the old windjammer trade wind routes, which further degrades savings available. The vessels travel more of their route on courses which do not benefit from sail assist, or even suffer degrading drag from the furled systems while under power alone. There's a "chicken and egg" issue here. If large, efficient, purpose-built sailing vessels existed, even if ship owners would not re-direct them on the old routes, then capital and operating costs of sailing vessels would compete favourably with powered vessels[2]. Indeed, this is the case in some parts of the world today. "Niche" markets, especially small ports located on trade wind routes, are currently profitably served by sailing vessels[3]. However, for the foreseeable future, except for these niche markets, retrofit is the likeliest route to sail assist.

Most currently envisioned schemes are not reliably profitable. Often, the difference between 10% fuel savings on a voyage and 30% can be the difference between profit and loss on the sail equipment investment. Ship owners and operators incur substantial financial risks in their day-to-day operations, and aren't interested in assuming new ones, so sail assist isn't currently popular. As fuel costs rise, sail assist becomes more and more viable. Historically, however, such costs are variable over time and again we see a reluctance to make the long term capital investments necessary for sail assist. This study assumes that the current world price of diesel oil is $1.00 US per gallon, or $320/long ton.

HOW CAN KITES CHANGE THIS?

Kite rigs (free-flying kites) have several inherent advantages over conventional sail, plus some distinct limitations.

A strong advantage of kite rigs is that since the rig isn't actually on the ship, minimum retrofit, and minimum deck and storage space are required[4,5,6]. This is particularly important while at dockside, when deck space is fully utilised. Wing masts, Flettner rotors, etc. are prone to damage or are a hindrance to cargo loading/unloading.

In addition, the kite rig is substantially manufactured away from the vessel. Downtime and retrofit costs are minimal. Further, a kite rig can be carried from one ship to another, as for varied testing, or as vessels change routes, or owners.

Kites fly at higher altitudes than conventional rigs. Wind velocities increase with altitude above the water. A large kite flying at an altitude of 1000 ft. will typically see winds of 15-30% higher velocity than a conventional rig whose centre of effort is 60-80 ft. above the water[7,10]. As energy derived from the wind varies with the square of its velocity, this translates to 30-50% more energy available to the kite, on a per sq. ft. basis.

When on downwind courses, conventional sail becomes inefficient, due primarily to reduced apparent wind (the vessel's speed is subtracted from the actual wind speed to yield apparent wind), and also to blanketing effects from the vessel's superstructure and/or additional sailing rigs aft blanketing those forward. Not only is a free flying kite immune to such blanketing effects, the kite may also be manoeuvred in the sky independent of the boat (typically in a horizontal "figure 8" pattern). This results in far higher apparent wind speeds at the kite than those experienced by the hull, and thus far more energy available than to a hull mounted rig . Calculations, and actual experience with kite rigged boats, indicate that these rigs may extract 4-10 times the energy of a conventional sail on these courses[4,8,9]. An analogy may be seen in a modern windmill's moving blades. The energy extracted from the wind is related to the blade's swept area over time, not to the blade's actual surface area.

Very large kites are feasible. Since deck space is not compromised, and the vessel experiences minimal heeling from the deck- or gunwale-mounted kite, far larger kites may be carried than conventional rigs. Coupled with the higher power available from winds aloft, plus the advantage of off-wind "sweeping" of the kite, far more energy is transferred to the hull. Pure sailing vessels, which do not anticipate substantial motor/sailing modes, are feasible. The kite powered ship will return a higher average fuel saving to the ship owner, without requiring a purpose-built vessel. Fuel savings and higher potential vessel speed could even crack the routing problem. A ship's master might be persuaded to sail on wind-favourable routes, rather than direct great-circle ones, at significantly greater fuel savings. The question of the vessel's net average speed, port to port, remains to be addressed. A combination of direct and wind-favourable routes is perhaps likeliest.

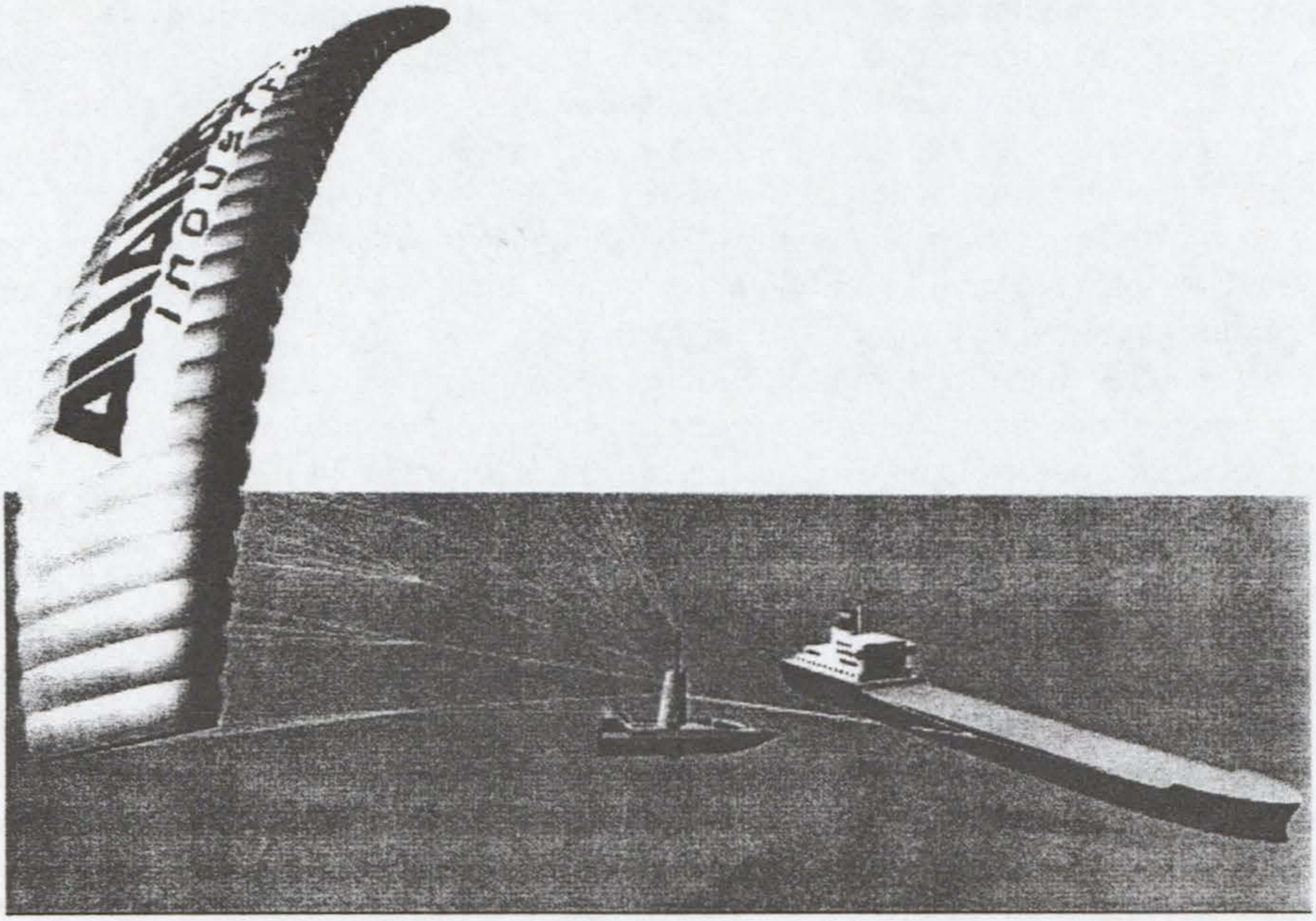
LIMITATIONS OF KITES

There are unique problems associated with using kites as sailing rigs. The greatest, perhaps, relates to keeping the kite aloft, particularly in low or no wind situations. One study concluded[10] that the potential hazard of the kite falling in the water, particularly in the ship's path, outweighs any financial benefits associated with kites. Very fast retrieval methods have not been worked out, and such a grounding would destroy the kite at least, and foul the vessel's propeller and rudder, at worst.

Fast, efficient launch and retrieval of heavier-that-air kites, and/or altering the vessel's heading during wind lulls may ameliorate this problem. Another solution would be to use a lighter-than-air, helium filled kite[4,6], so as to maintain positive buoyancy in any wind condition. Near neutral buoyancy is desirable, so as to allow retrieval when desired. This introduces the added complications and cost of helium and its storage, as well as potential problems with reducing sail in high winds.

The general difficulty of launch and retrieval of any kite, particularly by a vessel at sea, will remain a challenge. Although total retrofit costs are lower, costs of line handling winches, and reinforcement of the hull for midship towing are still substantial[10]. Also, the vessel might need to change course or to stop in order to launch or retrieve the kite. Though solvable[4,6,11,12] specialised skills, space robbing deck mounted gear, or luck might be necessary for solid, successful launches and retrievals. This process has been compared to launch and retrieval of aircraft from aircraft carriers[4]. Risks .and manpower requirements acceptable to à military organisation are not necessarily acceptable to the merchant marine. Such a kite might only be launched and retrieved once per voyage, however.

Last, the simple "difference" of the scheme may doom it. Like many businessmen, ship owners are conservative. "Selling" a sail assist system with no historical precedent will be an uphill challenge. Viability of the concept will likely have to be demonstrated to the industry before it will be accepted. This is another chicken and egg issue.



WHY KITETUGS?

First, a definition: "KiteTug" refers to a crewed and independently powered and manoeuvrable, lighter-than-air dirigible kite. It will closely resemble a "powered parachute," or paraglider, though far larger. It will be helium inflated, yet retain ram air over-pressurisation to retain rigidity. Its crewed portion will be a "nacelle" suspended within the canopy's bridle. This nacelle will contain all living quarters, instrumentation and auxiliary power. The KiteTug will be flown in three modes;

1) as a pure kite, attached to a vessel on the water's surface. In this mode, it is the sailing rig for the vessel, and "tows" it on its voyage[4,6,14].

2) as a powered airship or dirigible, free of attachment. In this mode, it can fly inland to hangar or docking facilities, or fly through windless areas, or over land en route to a paying tow. Its motive power will likely be petroleum fuelled internal combustion engines, but solar/electric, photo voltaic/hydrogen/Stirling engine or other combinations of alternate energy systems are certainly feasible.

3) it will deploy a small hull carrying a keel, paravane, or "water kite," (or deploy a hull-less paravane or "hapa"[4,6,13].

In this last mode, it operates as a sailing vehicle in and of itself, and is capable of long voyages, at high speed, without using power other than for auxiliaries and control.

The KiteTug's control system will make extensive use of computerised fly-by-wire technology[4,15,16,17]. Its autopilot will monitor not only altitude, direction and speed, but also very accurately its rate of turn, rate of climb, plus local air flow and pressure characteristics throughout the canopy's structure. In addition, all sailing, navigation, and course-keeping control will be from the Tug. The ship becomes a "dead" tow and may even lock her rudder. The KiteTug will monitor the vessel's speed, course, surface winds, and, if applicable, her power and fuel usage functions. Her computers will then optimise course, canopy attitude and shape to maximise power transmitted to the ship's hull. Physical control of the kite may be through actuated control surfaces (rigid flaps, rudders, etc.)[4,15,18], but more likely through sophisticated wing warping, accomplished by varying bridle line lengths between the nacelle and canopy. This is an efficient and elegant method of controlling a flying wing, not normally available to conventional aircraft.

The KiteTug would likely not be owned by an individual ship or ship owner, nor would it be assigned to a single vessel. Rather, it would be independently owned and operated, and would roam the world's oceans in search of paying tows, typically on routes or during the portions of voyages where wind patterns favour sail power. This solves a number of general sail assist and kite rig related problems.

ADVANTAGES OF KITETUGS©

First, such a scheme requires no retrofit to vessels of any kind. Indeed, the concept requires no long term commitment from ship owners at all. They would be met at sea (or, more likely, through a KiteTug dispatch service via radio), and offered a tow. Through the KiteTug owner's foreknowledge of the specific ship's fuel requirements for the existing conditions, a tow rate is offered which would be substantially lower than fuel costs for the vessel. Tow lines are passed over and the job begins. The ship takes lines from the KiteTug to her fore and aft mooring bits. The KiteTug varies the length of these lines (likely from a second, smaller nacelle near the ship where the bow and stern lines join to become the main flying towline), in order to vary the vessel's course in relation to the KiteTug's position. The ship's rudder will only be used in emergency manoeuvres, and perhaps for tacking ship. The tow continues until either the voyage ends, or wind conditions drop to the point where tow rates become uneconomic, or until the KiteTug finds another tow available, steaming in more favourable wind, and within economical sailing distance. The KiteTug then disengages, sails (at speed) to the new tow, and re-attaches to the new vessel. The KiteTug can thus "cherry pick" only the most lucrative jobs, and tow vessels only during the best wind conditions. Revenue streams will remain high, as the gear remains fully utilised and seldom becalmed. Vessels not under KiteTug tow not only have no need to carry expensive, unused, sailing gear, but they suffer no added air resistance when steaming to windward. The issue of the launch and retrieval of large kites at sea disappears.

A dispatch service will need to be created, recording and predicting weather and ship movements world-wide. Embryonic versions of such services exist today, and are used to route long distance balloon and experimental aircraft voyages. It will need to maintain an extensive database, preferably specifying every sea-going vessel's capabilities, current load factor, and likely fuel usage at all times. Ship owners would be expected to comply, and to provide historical performance and fuel usage records, in order to "qualify" for KiteTug assistance. Tow rates offered by the KiteTug will vary widely, based on how much it can save a particular vessel in a particular set of conditions. Rates will be for towed miles, in order to account for variable speeds of the vessel due to wind variations. In addition, differential rates will need to be calculated and charged for when a ship's captain decides that the towed speed is unacceptably slow, and re-starts his engines, effectively converting the "pure" sailed tow to a "sail assist" tow. For purposes of calculations in this study, average days under tow are used rather than towed miles.

There will be minimal or no light wind or "contrary" wind conditions, as with conventional sail. In these conditions, a conventionally rigged ship either derives a much reduced utility from her rig, or suffers a penalty as she carries her drag-producing rig upwind. In these conditions, the KiteTug simply disengages, and goes in search of more lucrative tows. Further, the KiteTug can generally avoid both gales and doldrums, through careful planning via her dispatch service. If caught, she can disengage and fly through either condition on her own power, in free-flying mode. (The physics of helium-filled flying structures precludes gaining great altitude in order to fly above storm systems.)

In addition, the KiteTug may free-fly overland en route to lucrative tows. Panama and Suez come immediately to mind, but trans-Florida, trans-Mexico via the Yucatan, and perhaps even trans-Iberian Peninsula flights are feasible. In and out of the Great Lakes, the Black and Caspian seas, and across the Straits of Tierra del Fuego may be profitable. Similar shortcuts present themselves throughout the island nations of the Western Pacific and Indian Oceans.

The KiteTug, which may become very large, will not normally inflate and deflate her canopy between voyages. Indeed, she will have few "betweens" at all. KiteTugs will be either towing vessels, or deadheading to new tows, nearly all the time. The Tug can come to land-based hangar facilities, or more likely mooring masts, for maintenance or overhaul. She'll be deflated only occasionally, for major maintenance or canopy replacement.

LIMITATIONS OF KITETUGS

The fact that a KiteTug is crewed means manpower is needed. A well planned and computerised conventional sail assist system might add no additional crew load to a ship at all[1,2], although the crew will have to be specially trained, and their workload will increase. Thus hourly labour rates and overall labour costs will also increase. A KiteTug requires a minimum of two crew, and more likely three to four. Although costs are effectively split over the many tows the Tug is involved with, there will be a net increase in "crewed miles" for towed vessels, and thus inherent cost increases. However, these are offset by increased revenue streams.

A KiteTug is essentially a tethered aircraft. Such devices are potentially very dangerous as they are susceptible to fairly fast-onset oscillations and crashes. The best controllable kites today still occasionally smash into the ground or sea. A crewed event would be disastrous. There are two attributes of KiteTugs which are expected to ameliorate this. First, the kite is very large. Sizes to 15-30,000 square feet will be commonplace[4]. Such large structures tend to be more stable than small ones. They do not react to relatively small gust cells in the wind, and events like stalls happen relatively slowly. Second, the KiteTug will be heavily instrumented and largely computer controlled (fly-by-wire)[4,15,16,17]. It is quite possible to fit the entire canopy with pressure sensors and to model pressures and flows throughout the structure via computer. Unstable events will be discovered and corrected before any human becomes aware of them. In addition, an emergency cut-away system may be rigged. When a situation arises, such as a high velocity dive below a specified altitude, an emergency system could cut away the tow, which would instantly convert the KiteTug into a low flying and stable glider[15]. After recovery and correction of the problem, the KiteTug will start her auxiliaries, manoeuvre back alongside the vessel, and continue the tow.

Another issue concerns KiteTug handling and safety in high winds. The KiteTug cannot be effectively reefed. Historically, however, other large sailing and inflated flying structures of this size have shown the ability to continue operations in these conditions. The largest sailing ships 100 years ago were on the order of 400' long and spread upwards of 50,000 sq. ft. of working sail. These ships rarely reefed, and gave their best performances in the Southern Ocean, where winds average 30-40 kts[19]. The Graf Zeppelin class of dirigibles, to 700' and flown in the 1920s and 30s, powered through all normal storms and maintained their schedules. KiteTugs' control systems will need to be capable of reducing the Tug's coefficient of lift to low levels, while maintaining stability and control. While this is a challenge for human controlled kites, it will be within the computer controlled and sensored KiteTug's ability.

Last, we need to consider damage or catastrophic deflation to the canopy and emergency landing and/or self rescue at sea. First, the crewed nacelle will be on the order of 60-80 feet long. It will be a watertight, boat-shaped unit, capable of operating on its own at sea. It will have decent handling characteristics, and include effective sea anchors, or other position maintaining devices. These will be needed to re-launch the kite, if repair is practical. Large inflated kites, when tethered by their trailing edges, are relatively docile and will lay on the surface unattended for long periods. Thus, an emergency procedure would entail reducing altitude (by any of several means) until the nacelle is waterborne, then cutting away (or more practically, quickly lengthening) all forward lines of the bridle, leaving the kite tethered by its rear lines. It may then be deflated and retrieved, or abandoned. If repairable, and for initial launch, the kite will be re-inflated and re-launched by reversing the procedure. If the canopy is not repairable, a second, much smaller "jury-rig" kite is deployed, and the nacelle may be sailed back to harbour as a kite-rigged boat herself.

COSTS AND CASH FLOWS FOR A 30,000 SQ. FT. KITETUG

Here we'll consider two scenarios and make a number of assumptions. Scenario one considers a KiteTug of 30,000 sq. ft. Its dimensions might be: 350' span × 100' chord, by 22' thickness of canopy. The manned nacelle might be suspended 300-350 ft. below the kite itself. Scenario 2 considers a KiteTug of 15,000 sq. ft. This kite might span 240' × 70' × 15'.

The 30,000 sq. ft. kite is expected to cost $3 million in prototype[4], which is in line, on a per-pound basis, with other large high tech prototypical structures (experimental aircraft, wingsails, etc.). It has been estimated that offshore (Far East) sub-contracting of such a structure may save 35% of this cost, and that mass production (on the order of ten units/run) will save approx. 20%. These savings are cumulative, i.e. foreign production units might be 52% (65% of 80%) of a US domestic prototype's costs[1].

This kite is well sized for crewed commercial flight. Taking the nacelle, its instrumentation, crew, supplies, and auxiliary engines and fuel into account, plus the weight of the canopy itself, a structure this size will contain a sufficient volume of helium to achieve positive buoyancy. Some of the volume of the kite will be filled with air, in order to maintain near-neutral buoyancy. The kite's altitude will vary from zero to perhaps 1500 ft, so some provision must be made for expansion of the helium.

We shall assume that the KiteTug spends 250 days/year at sea. This is a fairly widely accepted average for commercial ships. At first blush, this seems too few for the KiteTug, as commercial vessels typically spend 4 days of every 14 at the dock, loading and unloading. Since the KiteTug does not need to stand by while the vessel loads, she ought to be able to spend more days at sea, and probably will. With ships, however, general maintenance takes place at these docked times also, with one 2-4 week overhaul/year. The KiteTug will need maintenance as well. For purposes of this study, we'll stick with industry averages.

Of the 250 days at sea, we'll assume that half the total mileage will be dead-headed, and half will be under paying tows. This is probably conservative, given an efficient dispatch service and a bias for routes with favourable wind conditions. Ref 1 finds that approximately $^1/_3$ of all winds at sea are less than 14 kts. In addition, by definition, $^1/_3$ of all courses are less than 60 degrees from the eye of the wind. Assuming a KiteTug will consider light winds and courses close to the wind unprofitable, approximately one half of all ship voyage/hours will have favourable wind directions and true wind velocities more than 14 kts. This figure is without regard for actual course sailed, and is a composite of all possible vessel courses. We will further assume that the KiteTug's speed while deadheading will be 50% faster than while under tow, so we shall budget 100 days/year for deadheading, and 150 days under paid tow.

Of the days under paid tow, we will assume 65% of the time we are able to act as "pure" sail, providing all the ship's motive power, and 35% of the time we will be "sail assisting," while the towed ship runs her engines concurrently. This will be during times of reduced wind, and thus reduced ship speed. We will assume that a kite of this size and power will be able to maintain 80-110% of the ship's normal cruising speed for 65% of the time chosen for KiteTug assist. We'll use 90% of full cruise speed as an average for calculations. It is assumed that at some threshold speed (80% of cruise speed?), the ship's master will decide to re-start his engines. Since marine engines do not generally do well at low power settings[(3)], we'll assume that, under all "sail assist" scenarios, the ship run her engines at half power settings, and thus will burn half of the fuel she normally burns under her sole power; thus towing rates will need to be reduced by half for these times, in order to remain economically viable. These numbers are completely arbitrary and may appear optimistic. They will, in fact, vary greatly with the size of vessel under tow. The KiteTug, however, has the ability to "pick" its tows, and to abandon uneconomic tows for better ones elsewhere.

Market forces, in the persona of the ship's and KiteTugs' captains, will determine at what point a tow becomes "uneconomical." Physical distance to a more lucrative tow will be a factor as well. A ship's captain might be willing to accept a slower boat speed in order to entice a KiteTug to remain on station. Similarly, the Tug's captain might accept the reduced per diem income stream to avoid a long deadhead to another tow. A computerised matrix, constantly updated by the Tug's dispatch, will assist in making these decisions.

A KiteTug this size is capable of economically towing ships from about 25,000 tons to about 50,000 tons. It is estimated that a 30,000 sq. ft. kite, pulling a vessel at 14 kts in a 20 kt crosswind, might generate 200-400,000 pounds of towing force.

This equates to 10-20,000 thrust horsepower (Shaft horsepower is multiplied by gear and propeller efficiency, typically 75-80%, to yield thrust horsepower) [4]. This implies that, at 30,000 tons, the KiteTug/ship combination might split "pure" sailing and "sail assist" in the $^{2}/_{3}$: $^{1}/_{3}$ ratio envisioned above. At 50,000 tons, the ratios will perhaps be reversed, only $^{1}/_{3}$ of the time will the vessel sail "pure." However, the larger vessel's much higher fuel consumption, and thus potential fuel savings, will result in higher average tow rates chargeable, and the KiteTug will favour large vessels over small. Below, we will assume a vessel of 30,000 tons, burning approximately 36 long tons of diesel oil, at $320/ton per day. A 50,000 ton ship might burn closer to 50 tons. Even larger vessels may also be towed, but likely only in "sail assist" mode. Expected net fuel savings, and thus maximum tow rates chargeable, will be the only deciding factor in choosing vessel size and type.

Finally, we will assume that a ship owner will pay 80% of the cost of his actual fuel saved, as a towing rate. As the industry matures and KiteTugs become accepted, this number will likely rise (current conventional sail assist schemes offer to provide as little as 10% average fuel savings, with the ship owner absorbing the cost of the retrofit, to boot).

Thus, we have 100 days/year in which the KiteTug replaces 90% of 36 tons of diesel fuel burned per day. At 80% of 90% of $320/ton, this would lead to average fees charged of $8,550/day, or $855,000 on an annual basis. In addition, the tug will have 50 days in which it can only charge an average of half normal fuel costs, so will add another $237,500 annual income. This gives a total annual income stream of $1,092,500.

LIKELY ANNUAL COSTS OF OPERATION:

Maintenance, helium and repairs (this is 50% more than expected maintenance costs of other modern sail assist rigs, on a per sq. ft. basis)[1]	$100,000
Fuel for auxiliary power, manoeuvring, and free flying. Average of 200 gals/day × 250 days @ sea. (This would be zero if solar powered.)	50,000
Crew salaries (three crew at $50k, $35k and $35k)	$120,000
Total annual operating costs	$270,000

Profitability

We'll look at profitability two ways; gross profit model, with the KiteTug leased, and simple payback model, with the KiteTug purchased for all cash.

Gross Profit Approach:

We assume that the KiteTug is 100% leased, on a seven year schedule. We assume the interest to be 9%/year, with a salvage value of 30% after 7 years. This will result in:

Annual lease payments of	$487,000
Grand total cost of operation	$757,000
Annual income stream	$1,092,500
For a gross annual profit of	$335,500

Simple Payback Approach:

Gross operating costs	$270,000
Gross income stream	$1,092,500
Gross profit	$822,500

Industry expectations for capital payback are of the order of three years[1] $3.0 million, divided by $822,500 gives a payback of 3.65 years.

OPTIONS FOR INCREASING PROFITABILITY

Option 1: Assume that the prototype is built in Asia

Then assume that production KiteTugs are built there as well. This presumes a capital cost for the prototype of $2.0 million, and $1.6 million for production Tugs.

This brings the gross annual profit on the prototype (under the gross profit approach) to $497,500, and the gross annual profit for the production model to $563,500.

Under the simple payback model, paybacks are:

Asian prototype	2.43 years
Asian production model	1.95 years

These figures are well within acceptable ranges, indeed they are far better than virtually any sailing retrofit system envisioned so far[1]. Even presuming wide variations in actual revenue streams, an average payback period under 2 years is perfectly acceptable to investors.

Option 2: Factor in the income from salvage towing.

Under current standards of practice, deep-sea tugboats charge from $100-500/mile run, both out to a disabled ship, and back to harbour[26]. Thus, a 30,000 ton vessel, stranded 500 miles offshore, might pay $400,000 for a tow to harbour. Such a trip, under KiteTug, would take less than a week, both out and back (24 kts out, 8 kts back = 3.5 days). One single such salvage per year would dramatically change the financial outlook for a KiteTug:

Gross profit approach:

US prototype gross profit:	\$735,500
Asian prototype gross profit:	\$897,500
Asian production gross profit:	\$963,000

Simple payback approach:

US prototype	2.45 years
Asian prototype	1.64 years
Asian production	1.31 years

This activity is obviously very profitable and KiteTug dispatch services will seek such commissions for their Tugs.

Option 3: Add 20% to paying days at sea

(This presumes "pure" sailed days, which generate \$8,550/day in fees) This may be done by reducing deadhead days (through finding closer "back tows"), reducing "at harbour" days, reducing "sail assist" days, towing larger ships, or any combination of all four. It only needs to add 20 average days/year to the mix.

Gross profit approach:

Domestic prototype gross profit	\$506,500
Asian-built prototype gross profit	\$668,500
Asian-built production Tug	\$734,000

Simple payback approach:

Domestic Prototype	3.02 years
Asian prototype	2.01 years
Asian production	1.61 years

Fairly small increases in utility of the system can make dramatic differences in profitability.

Option 4: Fuel doubles in cost:

Gross profit approach:

Domestic Prototype profit	\$1,378,000
Asian Prototype profit	\$1,540,000

Asian production unit	$1,615,500

Simple payback approach:

Domestic prototype	1.61 years
Asian prototype	1.07 years
Asian production	0.86 years

Here we see that a doubling in fuel prices (a likely scenario within the foreseeable future) brings payback of a production KiteTug to less than one year. While materials costs for the Tug itself will likely also rise, its raw materials, though petroleum based, are a relatively small proportion of its all-up cost. Perhaps a 10-15% increase is foreseeable, which will still keep paybacks under one year.

COSTS AND CASH FLOWS OF SMALLER 15,000 SQ. FT. KITETUG

This kite is likely to be on the smaller size for manned commercial flight. Taking the nacelle, plus the weight of the canopy, a structure this size will just contain sufficient volume of helium to achieve positive buoyancy. Less efficient kite shapes may be envisioned at smaller sizes (thicker airfoils, or lower aspect ratios), to gain sufficient volume, but here we're optimising aerodynamic shape to gain as wide a performance envelope as possible.

For the 15,000 sq. ft. kite, all of the sailing assumptions are the same. We'll assume that a KiteTug this size is capable of economically towing ships from about 8,000 tons, up to 25,000 tons. Kite power/displacement ratios for these vessel sizes suggest that, at 10,000 tons, the KiteTug/ship combination might split "pure" sailing and "sail assist" in the $^2/_3$: $^1/_3$ ratio envisioned earlier. At 25,000 tons, the ratios will perhaps be reversed, only $^1/_3$ of the time will the vessel sail "pure." However, the larger vessel's much higher fuel consumption, and thus potential fuel savings, will result in higher average tow rates chargeable, and the KiteTug will again favour large vessels over small. Below, we will assume a vessel of 10,000 tons, burning approximately 12 long tons of diesel oil, at $320/ton per day. A 25,000 ton ship might burn twice that.

Thus, we have 100 days/year in which the KiteTug replaces 90% of 12 ton of diesel fuel burned per day. At 80% of 90% of $320/ton, this would lead to average fees charged of: $2,850/day, or $285,000 on an annual basis. In addition, the tug will have 50 days in which it can only charge an average of ½ normal fuel costs, so will add another $79,000 annual income. This gives a total annual income stream of $364,000.

LIKELY ANNUAL COSTS OF OPERATION:

Maintenance, helium and repairs (this is	$50,000

considerably higher than projected maintenance costs of other modern sail assist rigs, on a per sq. ft. basis)	
Fuel for aux. power, manoeuvring, and free flying. Average 100 gals/day × 250 days @ sea. (This would be zero if solar powered)	25,000
Crew salaries (two crew at \$45k and \$35k)	80,000
Total annual operating costs	\$155,000

Profitability

Again, we'll look at profitably two ways; gross profit model with the KiteTug leased, and simple payback period, with the KiteTug purchased for all cash.

Gross Profit Approach

We assume that the KiteTug is 100% leased, again for seven years. We assume the interest to be 9%/year, with a salvage value of 30% after 7 years. This will result in:

Annual lease payments of	\$244,000
Grand total cost of operation	\$399,000
Grand total income stream	\$364,000

This results in a loss of \$35,000/year, with current assumptions.

Simple Payback Approach

Gross operating costs	\$155,000
Gross income stream	\$364,000
Gross profit	\$209,000

\$1.5 million, divided by \$209,000 gives a payback of 7.18 years - still probably unacceptable.

OPTIONS FOR INCREASING PROFITABILITY

Option 1: The prototype is built in Asia

Production KiteTugs are built there also. This presumes a capital cost for the prototype of \$1.0 million, and \$0.8 million for production Tugs.

This brings the gross profit on the prototype, under the gross profit approach to \$25,000, and the gross profit for the production model to \$49,000.

Under the simple payback model, paybacks are:

Asian prototype	4.67 years
Asian production model	3.74 years

Option 2: Factor in possible income from salvage towing.

Under current standards of practice, deep-sea tugboats charge from $100-500/mile run, both out and back to a disabled ship. Thus, a 10,000 ton vessel, stranded 500 miles offshore, might pay $200,000 for a tow to harbour[26]. Such a trip under KiteTug would take less than a week, both out and back (24 kts out, 8 kts back = 3.5 days). One single such rescue per year would dramatically change the financial outlook for a KiteTug:

Gross profit approach

US prototype gross profit	$170,500
Asian prototype gross profit	$225,000
Asian production gross profit	$249,000

Simple payback approach:

US prototype	3.62 years
Asian prototype	2.42 years
Asian production	1.93 years

Salvage is the single most profitable activity for this size KiteTug. Such work will be sought and prioritised.

Option 3: Add 20% to paying days at sea

(This presumes "pure" sailed days, which generate $2,850/day in fees) This may be done by reducing deadhead days, reducing "at harbour" days, reducing "sail assist" days, towing larger ships, or any combination of all four. It only needs to add 20 average days/year to the mix

Gross profit approach:

US prototype gross profit	$27,000
Asian-built prototype gross profit to	$86,500
Asian-built production Tug to	$110,500

Simple payback approach:

US Prototype	5.54 years
Asian prototype	3.69 years
Asian production	2.95 years

It is clear we're getting somewhere.

Option 4: Fuel doubles in cost:

Gross profit approach:

Domestic Prototype profit	\$320,000
Asian Prototype profit	\$370,000
Asian production unit	\$409,000

Simple payback approach:

Domestic prototype	2.74 years
Asian prototype	1.82 years
Asian production	1.46 years

These numbers are much more acceptable, and await a simple doubling of current fuel oil prices.

WILL IT HAPPEN?

The largest free flying inflated flying wing built to date is 7,340 sq.ft.[20]. Materials technology, in the form of Spectra and Kevlar reinforced Mylar fabrics and films, Spectra cordage, computerised controls and autopilots and telemetry devices are taken directly "off the shelf."[4,15] The US government stockpiles hundreds of millions of cubic feet of helium and indeed, is considering disposing of it. Unmanned Aeronautical Vehicle (UAV) technology, fly-by-wire, and computer modelling presumptions are state of the art and require no break-through innovation[17,21]. Costs for these systems are in the $\$10^3$-$10^4$ range, and are tumbling fast. The KiteTug dispatch service envisioned is a straightforward exercise in computer database generation, weather reporting and communication.

This concept is not a "dream awaiting technology," nor a technology awaiting a shift in world market conditions. Included cash-flow projections, with the exception of Option 4, presume 1997 dollars and current world wide fuel costs and vessel usages. While further development work is needed, enabling technology and fully operational kite powered boats[4,8,22,23,24,25] exist today. An interesting exercise would be to computer model present-day world shipping, overlay it with average wind patterns and flows, and then simulate a virtual KiteTug's capabilities and utility on an artificially accelerated timeline. Such an exercise should be well within the capacity of fast desktop computers, and would go far towards verifying or refuting the assumptions in this study.

There are no economic issues preventing the KiteTug's inception. Whether KiteTugs will be accepted by the world's shipping industry, or by investors, is beyond the scope of this study. Current data suggests that such a concept is economically viable today. Future increases in fuel costs, or world-wide shortages in petroleum supplies, may render it imperative.

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An Odd-Ball Wind-speed Meter or A Reynolds Number Demonstration

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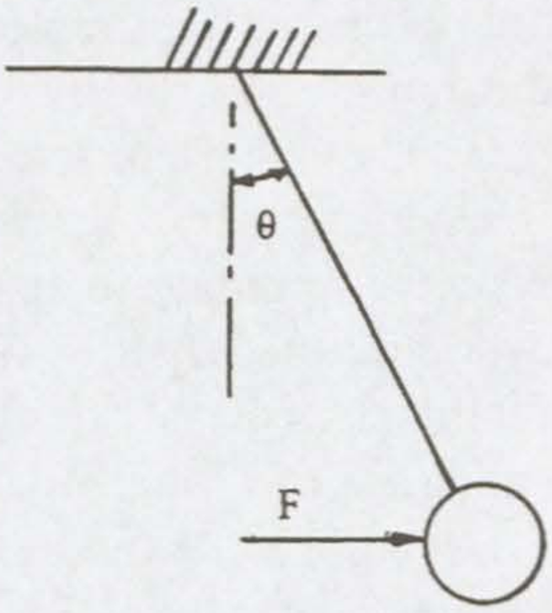
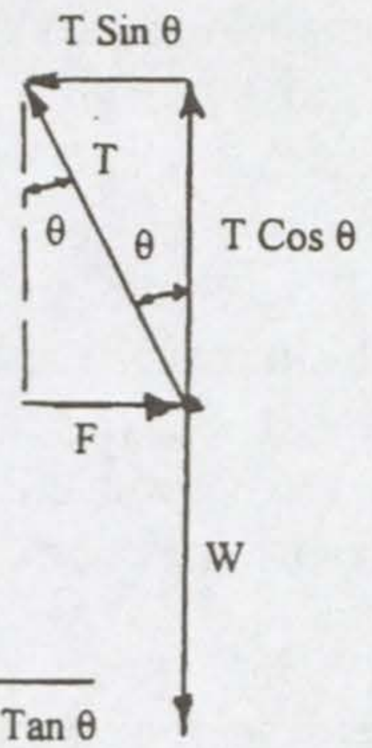
The following exercise, in futility perhaps, was carried out because it was thought possible a low cost, accurate, wind-speed meter for low wind speeds could be constructed using low technology but relatively high science and also trying to avoid intricate and uncertain calibration. The meter was to be used for measuring air-speeds in a small home made wind tunnel. When the exercise was finished, it was decided that perhaps the experimental set-up finally arrived at would be an aid to a good demonstration for those unfamiliar with the Reynolds number, which is basically a combination of a speed, a length, and a measurement of the viscosity of the air. Why one should be interested in the Reynolds number is that things like sails and boat hulls can act differently at different Reynolds numbers.

At present there are many methods of measuring wind speeds. With the advent of computer chips and micro circuits, I believe the methods have increased in number significantly. However, as the intricacies of the meters have multiplied I also suggest that the difficulty of calibrating them accurately has also multiplied. Consider the fact that if you could see a chunk of moving air and you could record the time it took to cover a known distance, you would be pretty certain of its speed because what you needed to measure that speed was a standard length and a standard stop watch, the accuracy of both of which could be easily verified. I posit that, beyond this, the picture starts to get very sticky. So, is there a simple method using only simple, basic measurements? The answer is both yes and no depending on your viewpoint. The following description of the test apparatus may answer this question.

Consider a small sphere, such as a ping-pong ball or a hollow plastic fishing float. Hang it on a short thread and put it in a constant speed air stream. Measure the angle the string makes with the zero wind-speed condition and from geometry and some physical constants, compute the air-speed. This "Basic Arrangement" is shown in the accompanying sketch. Listed on the sheet are the physical quantities involved. W is the weight of the ball. The angle can be either measured directly using an angle scale or figured from two measured lengths. The Diameter of the ball is easily measured so the cross sectional area of the ball can be computed. The mass density of the air can be obtained from any handbook. The Reynolds number can be computed. One of its components is the viscosity of the air, which also can be obtained from a handbook. The only factor not available, and this is the sticking point in this whole exercise, is the drag coefficient on the ball. Handbooks can give you a close approximation to this number for use in this exercise. Using all of the above, with appropriate formulas, the speed of the air can be computed

Basic Arrangement: Odd-Ball Wind Speed Meter





$F = T \sin\theta$

$T = F/\sin\theta$

$W = T \cos\theta$

$W = \dfrac{F}{\sin\theta} \cos\theta$

$F = W \tan\theta$

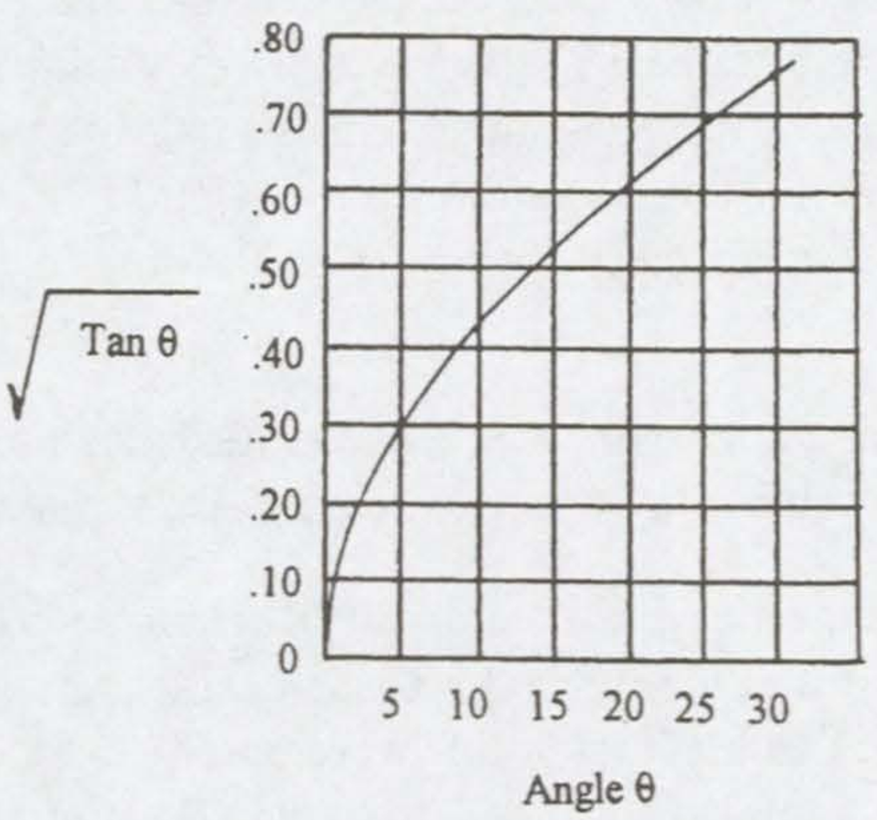
$F = C_d\, A\, P\, V^2/2$

$$V = \sqrt{\frac{2F}{C_d\, A\, P}} = \sqrt{\frac{2W \tan\theta}{C_d\, A\, P}}$$

$$V \cong \sqrt{K \tan\theta}$$

K is closely constant

F = wind force on ball, lbs.
C_d = Drag coefficient, no units
A = Cross-sectional area of ball, sq. ft.
P = mass density of air, .00237, lbs. sec^2/ft^4
V = Velocity, ft./sec.
R = Reynolds number, no units
D = diameter of ball. ft.
v = kinematic viscosity of air, 1.58×10^{-4}, $ft.^2$/s



relatively easily. You might ask, why not have a calibrated meter and compare the different angles obtained at different air-speeds and thus make a calibration curve and thus dispense with all of this nonsense, but then you would not have participated in the mysfique of the Reynolds number. Let it be said the experimental set-up was tested against a commercial meter. Let it also be said, I suspect some of the inaccuracies of the ultimate calibration were due to variations in temperature and pressure, which were not taken into account. From looking at the sheet called the Basic Arrangement, you can see the theoretical calibration curve is basically related to the square root of the tangent of the angle the ball makes with the vertical, and it is concave downward. Using basic, simple statics, it is not too hard to set down the derivation of the force F on the ball which is necessary to hold it at any small angle. The force F on the ball tends toward infinity as the angle approaches 90 degrees. This is the same force which a constant air-speed would cause the ball to move to the appropriate angle. This formula is the basic drag formula which should be familiar to us all by now. It is made up of the drag coefficient, the area of the ball, the mass density of the air, and the square of the velocity. Substituting for and getting rid of F and solving for V, we get the final formula shown for the velocity. If you are more interested in the Reynolds number than the velocity, you could solve the formulas for the drag coefficient and then check it against handbook values.

When the actual experiment was done, it was found that the ball oscillated back and forth in line with the air-speed so it was considered necessary to add another weight, W2, as shown in the Final Arrangement drawing. This is called a longitudinal dampening weight and added stability to the system. It also made it easier to measure the angles, since when the lengths of the threads are appropriate, angle A is always larger than angle B so easier to read. Unfortunately, the geometry is more complex and the only way to get the value of angle A is to use the formula shown. This causes some extra calculator work, but is no big deal. Lateral stability was fairly good but an appropriate finger here and there sometimes held the ball quite steady. The results were plotted as shown. Although the results at first glance are a bit disappointing, you must remember what you have done is measure some forces which are small multiples of 1/1000 of a pound ! The following paragraphs are a further discussion of some points to be considered in reviewing this exercise.

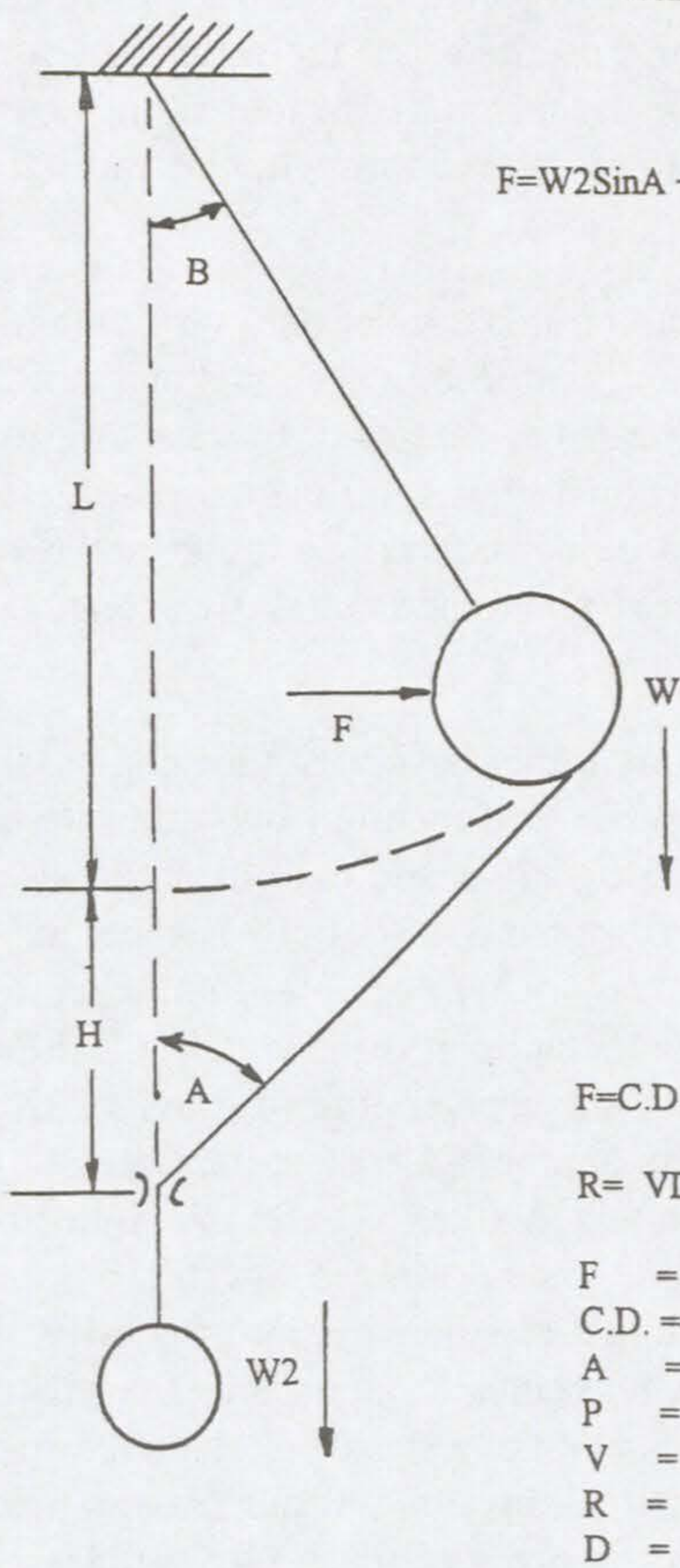
The master meter used in this experiment was a Davis Instruments Turbo Meter. It is of the windmill type and accuracy is supposed to be in the range of ±3%.

Using the Final Arrangement, an unknown amount of friction was introduced into the system. However, it was assumed that the small oscillations of the ball might minimise this friction. The calculated velocities were, in any event, greater than the actual meter readings. It was also assumed that any drag on the threads was minimal.

For those of you very unfamiliar with the Reynolds number, it is basically a number to help organise experimental drag data on a graphical plot of drag coefficient versus R Number. Its components are such that it has no dimensions. A bit more on this below.

The largest unknown in the formulas is, of course, the value for the drag coefficient of the spheres. Values were taken from Hunter Rouse's book "Elementary Mechanics of Fluids". It is to be noted these values plotted on his curve of drag coefficients versus Reynolds numbers were derived from spheres in wind tunnels and also from very small spheres of steel, lead, etc., dropped in water and oil. There was essentially very good agreement between the two but the curve was very difficult to

Final Arrangement of Odd-Ball Windspeed Meter
With Longitudinal Dampening



$$F = W2 \, SinA + \left[\frac{W2 \, CosA + W1}{CosB} \right] SinB$$

$$TanA = \frac{SinB}{1 - CosB + H/L}$$

$$F = C.D. \, A \, P \, V^2/2$$

$$R = VD/v$$

F = wind force on ball, lbs.
C.D. = Drag coefficient, no units.
A = Cross sectional area of ball, $ft.^2$
P = mass density of air, .00237, lbs. $sec^2/ft.^4$
V = Velocity, ft./sec.
R = Reynolds number. no units.
D = Diameter of ball, ft.
v = kinematic viscosity, 1.58×10^{-4}, $ft.^2/sec$

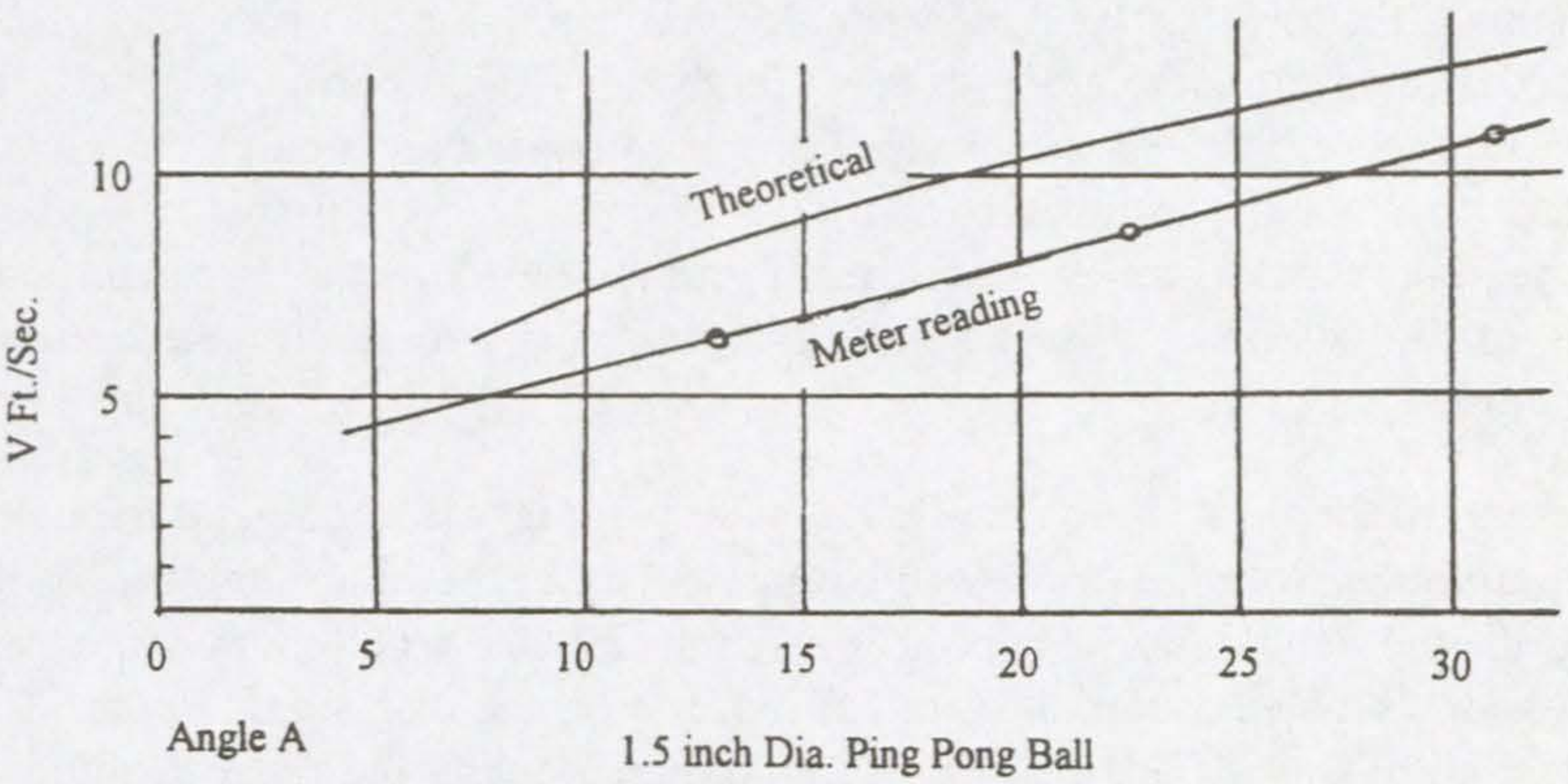
read due to its published smallness and there was spread of points from the mean line. Values of the drag coefficient used in the formulas varied between .40 and .46. At the most difference, this would give a discrepancy of 7% but could be closer to half that or 3%.

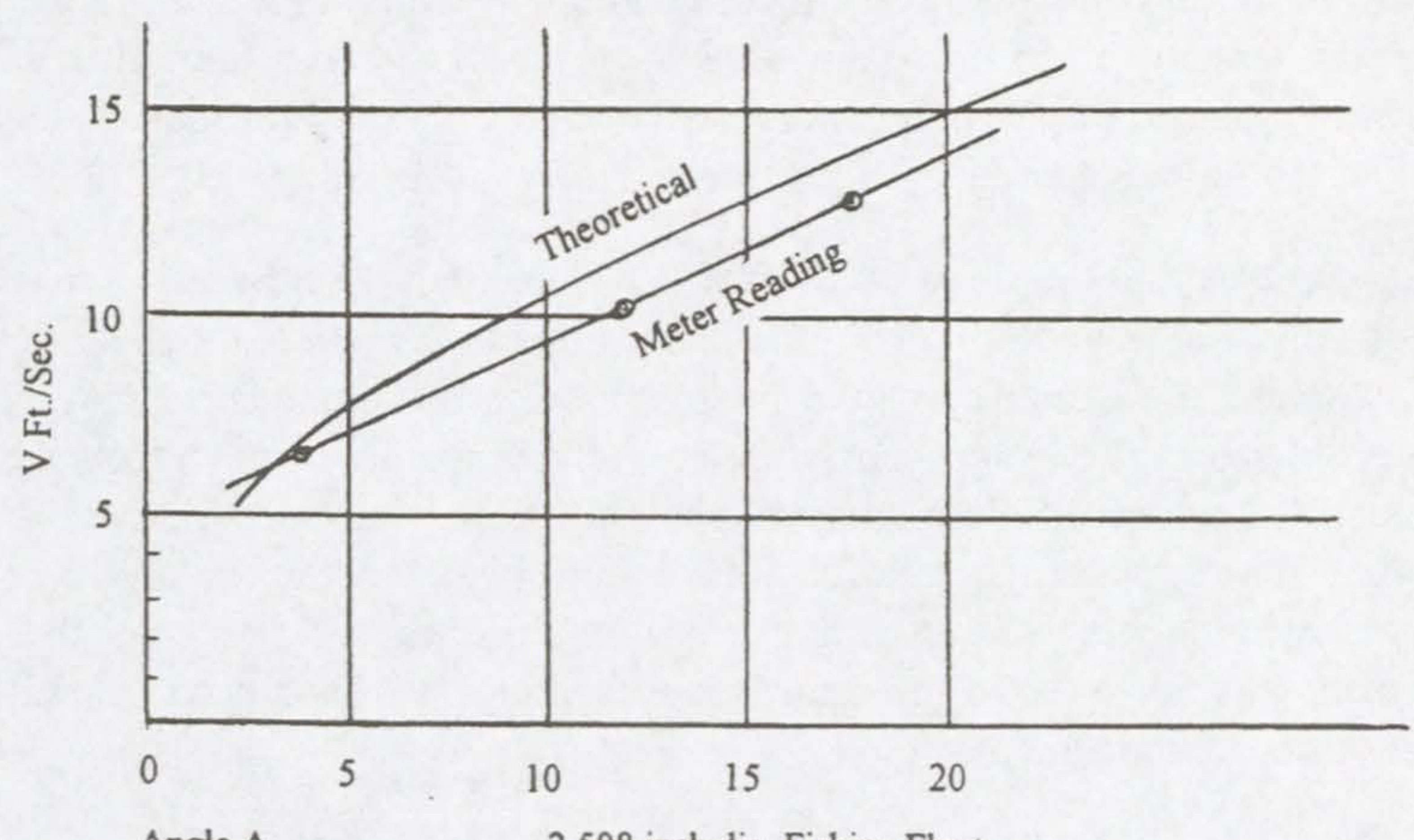
Taking of actual temperature and pressure readings during the gathering of data was not done. Note that for the values of the kinetic viscosity and mass density of the air, handbook values were taken at more or less standard temperatures and pressures. A 20°F difference in temperature can change the viscosity about 7% and the mass density about 4%. Further, considering the factors that go into the makeup of the density figure, temperature, pressure and humidity, there can easily be a difference of 10% when all three of these items go the right, or wrong, way, also considering that the humidity effect is rather small. More readings could have been taken and averaged but when a front moves through, the sailing is great around here and off I go.

Some enterprising person might, after reading this article, on a very calm day, take some small, light-weight spheres and drop them from a second story building, and with a stop watch and tape measure gather some data, and, by cranking it into the appropriate formulae, come up with their own drag coefficients. Estimates of the start of terminal velocity would have to be considered. I found nowhere in the handbooks the smoothness of the spheres mentioned but I suspect this is very important to the value of the drag coefficient.

Most of the values used in the formulas are rather basic: lengths, angles, time, and weights. But I will now get on my soap box and mention two other items which enter into these calculations, the mass density of air and the kinematic viscosity of air. Both of these values can be picked from handbooks but I suspect the average reader of these AYRS journals does not know what goes into the makeup of these two items. The mass density of air is rather simple: it is the weight of (in US units) a cubic foot of air divided by the value of the acceleration of gravity (32.2 ft. per sec per sec). The kinematic viscosity is another sort of animal and a bit more complex to explain but it too comes down to a mixture of basic things like distance, time, velocity, and mass density. Some future articles for these journals or newsletters might be short resumes of things like density, mass density, dynamic viscosity, and kinematic viscosity and how these values are arrived at. The mathematics involved is still rather elementary and a simple explanation of some of these terms would go a long way towards making some of our readers much more comfortable with some of the mathematics in many of the AYRS articles. Is it too daunting a task for us to understand the following statement and any of its implications for yacht research: "The viscosity of a true fluid is independent of the rate of shear." (Hunter Rouse, page 151, Elementary Mechanics of Fluids", and most any other book on hydraulics.)

Another thing which might help our readers better understand the numbers we play with is to emphasise what "units" go into the makeup of the numbers. By "units" I mean things like feet, seconds, pounds, mass, force, and, yes, velocity and speed. I am not extremely rigorous here when I mention speed and velocity. Everything moving without acceleration has velocity but when you sometimes show this on paper, the velocity can turn into speed — a philosophical view pointed out to me by one M Rowe. (Thanks, Mike.)





Actual results using a Sport Craft Ping-Pong ball and a plastic Fishing Float

A brief example to explain what I am talking about here is the following: Velocity is a distance, feet, divided by time, seconds. So velocity has the units feet/sec. All other items we talk about are variants or different combinations of actually a very few more "units." The units are handled like simple algebra, they multiply and divide each other, cancel each other, etc. and end up with some units or no units, which is interesting also. The Reynolds number has no units which I find rather amazing.

The Reynolds number is explained in most any handbook or elementary textbook. For the calculations in this exercise, it was necessary to make several approximations before the drag factor and its related velocity jived with the Davis meter, but, with a pocket calculator, this was no problem. The procedure went something like this: estimate the Reynolds number; using this number, pick off the drag coefficient from the graph of R number versus drag coefficient. Put this value into your theoretical formula for velocity and compute the velocity. If this value is greatly off from the estimated value you used for the R Number, revise your R Number and pick off a new drag coefficient value and recalculate the theoretical value of the velocity. With no more than two approximations, the values come very close.

Referring to the final plot of the Davis meter reading, the angle, and the calculated value of the air-speed, it appears in both cases, using the ping-pong ball or the fish float, the theoretical results appear to be about 29% and 11% high respectively — not good. We cannot pin all of this difference on the drag coefficients. I cannot explain all of this difference. I also cannot explain why the meter reading plots a straight line when compared to the theoretical curve which is related to the square root of the tangent of an angle and thus a curve. The wind tunnel used in this experiment was extremely rudimentary with at best only three air-speeds available. However, the points recorded seemed to group themselves very well.

Another point is that the point on the bottom of the ball where the lower thread is attached appeared to be in line with the upper thread. Why this is so I do not know but if it wasn't, the geometry would be horrific to work out. There may be other subtle problems in the basic theory that are not yet visible to me. However, I do not intend to make a lifetime study of the Odd-Ball wind-speed meter. Perhaps more time taken to get more points, and recording temperatures and barometric pressures would bring the two curves into closer agreement but the whole experiment was done just to see what would develop. Perhaps it is a miracle there is even this close agreement.

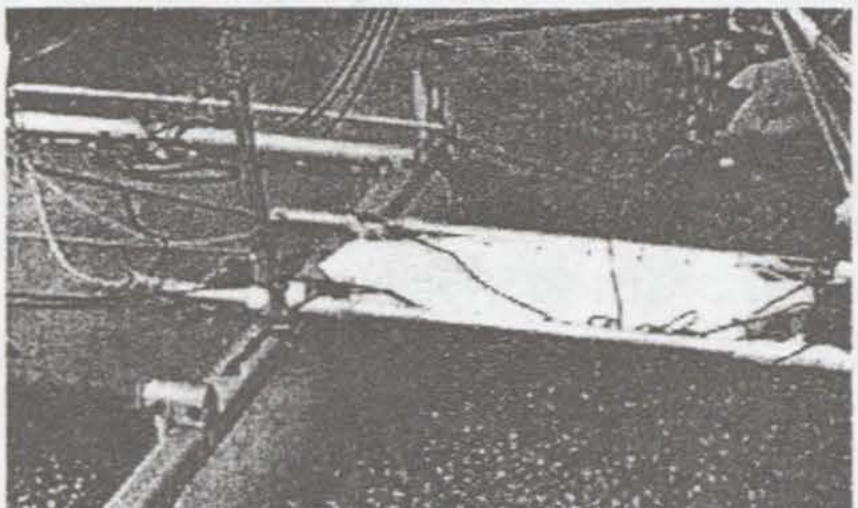
All in all, it appears philosophically, and basically, impossible to measure wind-speeds from simple basic physical units, unless you actually move the air over a measured straight distance in a measured time or whatever that entails. All in all, the above was an interesting experiment.

Midweek evening seminar - Speed Week '97

Report from John Perry

The midweek evening seminar has become a regular and popular feature of Weymouth Speed Week. The seminar allows all willing competitors, organisers and spectators to each give a brief exposition on any relevant topic. Fred Ball took the chair and ruthlessly kept the speakers to schedule which made for a fast moving meeting in which a lot of ground was covered with some finer points remaining for later discussion at the bar. It should be noted that this year many of the competitors attended only the beginning or end of the week and so the competitors able to talk at this seminar were just a small selection of the total. As before, the meeting was at the Royal Dorset Yacht Club. This club has challenged for the America's Cup and I was amused to see an obviously fake version of the cup already on display in the bar - presumably this is just to check that the real one is going to fit in all right with the art nouveau décor. The talks, in order of presentation, were as follows:

SLADE PENOYRE Slade had brought his Catapult inflatable catamaran to Weymouth equipped with a sitting-out/trapezeing aid in the form of a fabric covered rectangular frame of aluminium tubing looking something like a stretcher. He explained that he is developing a device to give enhanced righting moment and speed in strong winds and to be suitable for use with a wide variety of beach cat designs. The aluminium frame can be fixed to project outboard from either hull and a crew member can either lie on the canvas covering, which is possibly more comfortable than using a trapeze, or one could possibly trapeze from the outer end. Slade's first prototype for this device appeared at Weymouth three years ago and caused some amusement being nothing more than a full length heavy duty wooden roofing ladder lashed to the foot of the mast.



Slade also put forward suggestions for improving the performance of monohull racing yachts. He argued that old racing yachts have a poor resale value because they need excessively large number of crew on the rail in order to perform as designed and hence there is a need for some device to enhance the righting moment of such yachts when they are short handed. His suggestions included a water ballast tank extended to windward on a pole, e.g. a spinnaker pole, or an underwater kite (hapa) towed on the windward side. He had made a small prototype hapa and during this speed week we tried this out on board the author's sailing dinghy. After experimenting with different arrangements of wires between the mast of the dinghy and the hapa we got the hapa to fly underwater in a stable manner (we called this a happy hapa situation). However, at this stage of development there was no improvement in performance and indeed there was noticeable acceleration of the boat as the hapa was removed from the sea and brought back on board!

DIDIER COSTES. Didier Costes has attended many Weymouth Speed Weeks but was unable to be present this year since he is very busy experimenting elsewhere as explained in the following letter (slightly paraphrased) which was read out at the meeting by Roger Glencross. Note that the Seadogs are underwater kites, or paravanes, which can be towed though the water on lines to produce side force (referred to as lift) perpendicular to the direction of motion. The 'Floaters' are small streamlined floats made from expanded polystyrene with fibreglass covering.

> In August, I went with a friend for a week at the Nantua Lake (in Jura, near the Swiss border). The wind was weak and only at some times sufficient for inflating the Paraglider. We towed it twice, lifting a pilot with a 30HP motor boat, the pilot releasing the rope to land. This towing was easy. We did not attempt to associate Paraglider and Seadog, due to the lack of wind, but performed some towing tests on 3 Seadogs. Back in Paris, I made some improvements.
>
> One of these Seadogs has a long tube with two floaters, one at each end, and self inclining aluminium plates for hydroplaning. It worked better than the model brought to Weymouth last year. I modified the floater shape, reaching a lift to drag ratio of about 6.
>
> The bigger Seadog has an underwater tail, terminating with a vertical fin and a transverse fin. Its lift to drag ratio is better than 10, but the tail must be rotated end for end when tacking. In Nantua, I began to construct an orientating system driven by a looped towing rope on two pulleys. It was finished in Paris.
>
> Last week I went to the Serre-Poncon Lake in the south French Alps. I had constructed 3 floaters for a hang glider so transforming it into a sea-plane with the pilot clear of the water when on the surface. A two-man hang glider was used with a single professional pilot. It took off towed by a powerful motor boat with 100-metre rope. It flew well after rope release, and water landing was quite smooth. Again, the wind was weak and only on the last day did we succeed in hooking the Seadog into the water for wind propulsion. For a short time it worked properly but the hang glider was loosing height in this weak wind and it was necessary to release the Seadog and land before any tack. The boat towed the rotating tail Seadog and the tacking system appears to work, but it is slower than for the first Seadog (the one with floaters at each end of a long tube). This seems inconvenient for tacking with a hang glider but the system could be good for use with an airship. I hope to reach a larger lift to drag ratio with the 2 floater system, on which I shall work this week.

Several French people are now interested in such ideas. On the week of 22nd-27th September, I intend to go again to the South Alps for new tests and if successful I could attend the 'Festival du Vent' in Corsica in October.

- Didier Costes.

JEAN HURTADO Jean and his cheerful team arrived from France with two craft. One is basically a monohull but it has outriggers carrying two very small floats which are mounted high enough to allow the craft to roll though 90 degrees as it tacks. This rolling moves the inclined rig from one side of the craft to the other so that in principle it remains non-heeling as wind load increases. The second craft is a catamaran with a single square sail. The innovative monohull had been to Weymouth before and so his talk concentrated on the new catamaran which is called *DRAK*. This has sleek hulls, which appear conventional above the waterline but are very asymmetric below the waterline. The outward facing surfaces of the asymmetric underwater forms have large flat areas to resist leeway. The rig of this catamaran is very simple, just a large low aspect ratio square sail a bit like the Vikings used, except that there is a yard at both the top and the bottom. Jean explained that the lower yard is intended to blow out to leeward, restrained by lines to the lee hull, and this means that the sail is steeply inclined so as to reduce the heeling moment. Both of Jean's craft share a distinctive style of construction with lots of robust and nicely welded aluminium fabrication, including large diameter tubes with flanged and bolted joints. It looks very heavy but perhaps it is not as bad as it looks if the tubes are thin walled. The craft have relatively small sail area and are clearly designed for use in strong winds, so Jean will have to try again next year!

V. RADHAKRISHNAN Although "Rad" was a spectator at this Speed Week he took this opportunity to tell us how much he had enjoyed his 30 year membership of AYRS and to make some suggestions for the future. He also presented a glossy booklet based on the inaugural lecture which he gave on recently taking the chair of Professor of High Energy Astro-Physics at Amsterdam University. This booklet is a short history of the development of sailing craft with numerous references to the work of AYRS members. As an example of the achievements of amateurs, Rad mentioned the English physicist Geoffrey Taylor who was also an amateur yacht researcher and the designer of the CQR anchor. Although Rad was lavish in his praise of the work of AYRS members he did lament that this work has received little recognition outside the society and particularly from the professionals in the yachting industry.

As for the future, Rad urged the AYRS committee to seize the opportunity to use the Internet to promote the society and to disseminate information more cheaply. As a member of this committee I have to say that I believe that AYRS is indeed using the Internet to good effect, but for the foreseeable future we also have to continue to serve the 85% (at our best estimate) of the membership which do not have Internet access. Internet access was available at a nearby member's house throughout Speed Week. It is also worth noting that four of the competitors who participated this year heard of the event only through the Internet.

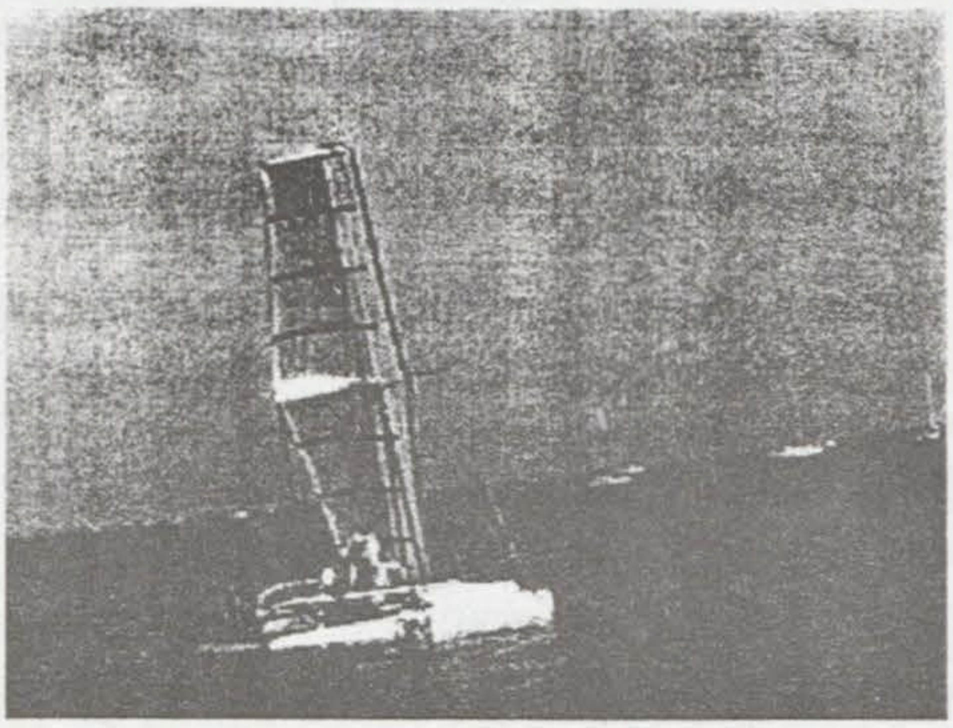
MARK TINGLEY Mark Tingley was also a spectator at this Speed Week. Like the author, Mark is interested in dinghy cruising. By dinghy cruising we mean using small road trailable sailing craft for relatively long distance cruising, a canvas shelter providing overnight accommodation. Mark is planning his next boat to be a small trimaran and after several years of discussing specifications with multihull designers and sketching on envelopes he now has a detailed model which he displayed after the meeting. This model is not lacking in unusual features. Indeed, without meaning to be over critical I am just a bit worried that there may be rather too many gadgets for a craft which is intended to be robust and exceptionally light in weight.

The outer hulls can be moved up and down relative to the ends of the amas, so as to prevent tipping from side to side when dried out, and to be able to reduce the draft to the absolute minimum when required. If this minimum draft is still too deep, then wheels can be fitted to the floats for skimming across shallows and up and down slipways. The outer hulls fold in or out independently of their vertical movement, and this allows rowing with the oars over the floats, as well as being for road trailing, for narrow marina berths, and for righting from a capsize.

The rig is a kind of gunter rig with a wing mast, a wishbone gaff and a vertical yard supporting a quadrilateral mainsail. It was inspired by a drawing in Dixon Kemp, 1880. The wing mast tapers towards the bottom, not the top, the taper giving extra buoyancy to avoid a complete capsize. The rig can be quickly folded down for shooting bridges under sail.

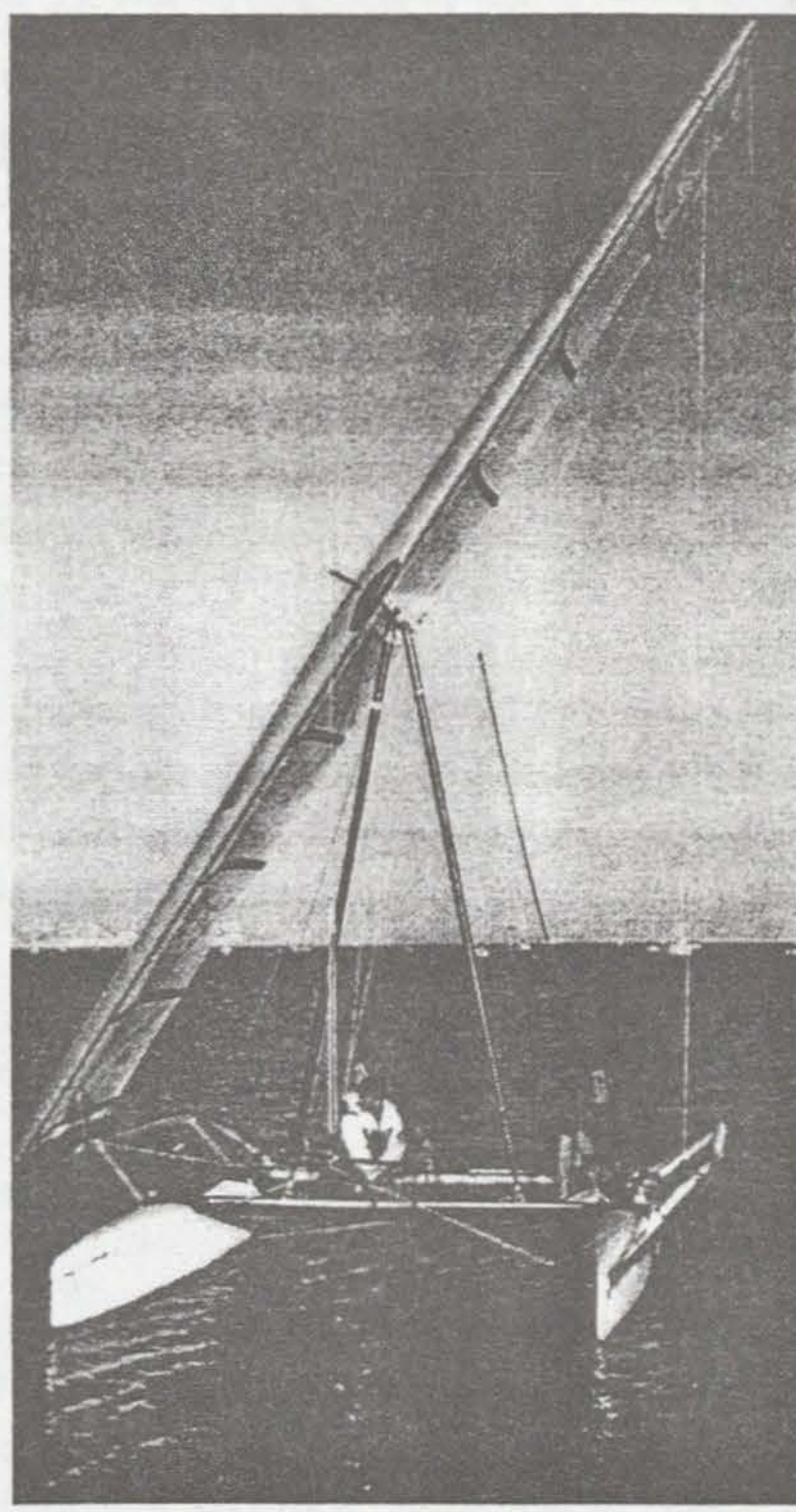
Leeboards on the main hull can slide fore and aft on very long slides so that perfect balance is certain to be achievable and presumably the designer does not even need to think about centres of effort and lateral resistance. Rudders are on the sterns of the outer hulls and can be controlled from anywhere in the boat using a portable remote control box connected to the rudders by Bowden cable. The structural members which span the main hull between the attachments for the amas are removable to make more space for living on-board. Platforms extend from the side of the main hull to make space to set a large tent overnight.

ALAN TANNER - BRISTOL SPEED SAILING TEAM The Speedweek talks given by members of this team are memorable for dry humour rather than technical content. Are they trying to offer light relief from the very serious matter of speed sailing, or are they just trying to avoid having to spend too long talking about their trade secrets? Serious comment this year was limited to a mention of the large detachable planing surface which has been seen on the lee bow of their craft [*'Connection'*, formerly *'Gamma'*] This was intended to prevent bow burying but



has been a failure due to large drag. Apart from that, we were left somewhat bemused by stories about the deadly quick sands at their test site in the Bristol Channel together with increasingly fantastical concepts for future speed craft. For example, how about a helium filled plastic bag, just floating on the water surface with the crew inside (with breathing apparatus?) suspended from a central transverse axle. Steer by shifting sideways along the axle. Lots of little sails on the outside make it whirl round and these sails become keels when they go underneath. Then I heard that the Bristol Speed Sailing Team actually is in possession of a couple of very large plastic bags! I soon got worried when I realised that the silly sails were probably just a smokescreen and that they really might have a horribly effective, albeit highly unsporting, record breaker for hurricane strength winds.

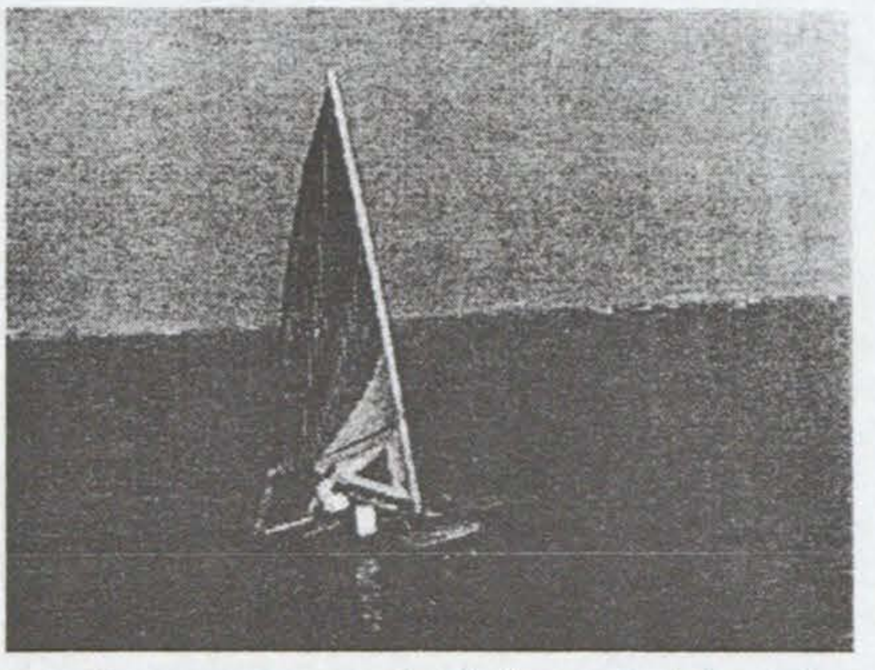
NIELS HAABOSCH - In contrast to the previous talk, this was a more serious talk from a member of a seriously well organised team from Holland. They have put three years of hard work into developing the craft *'Aeroskimmer'* which they brought to Weymouth behind a huge camper-van cum mobile boat-building workshop. The craft is a carefully detailed and well made catamaran having an asymmetric 20m^2 wing sail which tilts over the top of an 'A' frame mast so as to present the correct camber to the wind and perhaps also to gain a little aerodynamic lift. Niels explained that the ability to move the wing quickly into a horizontal position had also proved useful for braking and for coping with gusts. The wing is controlled by various lines leading to blocks on aluminium frames which extend from stem to stern outboard of each hull. These frames are also used for sitting out or trapezing and being elegantly curved tubes they do not look ugly. The hulls are fairly



conventional but with flattish bottoms for planing. Normal crew is three persons.

The overall beam to length ratio is at least what one would expect of a trimaran rather than a cat.

The wing sail has the main structure and the surface of the leading edge female moulded in aramid, epoxy and foam sandwich, and similar construction is used for the hulls. The rest of the wing surfaces are reinforced flexible film stretched on composite battens. Spars, crossbeams, rudders and dagger boards are pure carbon fibre and epoxy. Sponsorship is from 3M and other companies but the eventual aim is to make the project self supporting by selling production versions of this and other craft. This was generally the fastest of the non-sailboard competitors and in light winds was sometimes faster than the boards. It would be interesting to compare it with a more conventional cat of similar size and sail area, or with the *'Bootiful'* cat which Simon Sanderson brought to Speedweek in '95.



TORIX BENNETT - Torix Bennett's craft *'Sea Spider'* has three small planing hulls and two fully battened sails set on rotating alloy masts with wishbones. Originally it was an asymmetrical craft with a good and bad tack, now it has been changed to be fully symmetrical to avoid cartwheel capsizes when on the bad tack. He has campaigned it doggedly for several years without yet managing to sail in suitably high winds whilst keeping the craft in one piece. Last year we had the wind but the craft pitch-poled in shallow water causing a big smash up. Earlier this year he had it more or less back together for trials at Weir Wood reservoir but then a mast broke, destroying a sail. For Weymouth this year he had rebuilt everything to a better than new standard only to be confronted with near calm conditions - the frustrations of a speed sailor.

One point Torix emphasised is that during the brief periods he has sailed his craft at speed it has given an extremely rough ride as the small wedge shaped hulls bounce across the waves. Torix said that the weight to sail area ratio of his craft worked out at 12.5kgs/m^2 and he wondered how this compared to other speed sailing craft. A quick calculation suggests that this figure is not much different to a typical sailboard with crew, so why does it not go as fast? - perhaps it will someday. Torix also asked for some advice. At present he uses three skegs side by side to resist leeway and he wondered what is a suitable spacing to chord ratio for such an arrangement.

MICHAEL ELLISON Michael can hardly describe himself as a speed sailor now that he owns a 20' ferro-concrete yacht, but he described how he has had a lot of fun fitting out this yacht. He has installed a new diesel engine and a new rudder which is 4" thick except where it had to be thinner in way of the propeller slipstream. The echo-sounder transducer was fitted to the rudder to avoid new holes in the concrete hull. A triangular portion was sliced off the top of a large second hand genoa to make the quadrilateral gaff mainsail. Michael said that this sets well and is a good method of obtaining a mainsail cheaply.

Finally Michael passed on a most interesting point which he gleaned from competitors in the Vendée Globe Challenge. This point is that if a monohull yacht capsizes to 180 degrees it is more likely to right itself if the rig remains intact than if it is dismasted. This is because the rig grips the water and provides a tripping effect so that large seas can right the yacht. I must say that it is not what I would have expected although I can see that a buoyant mast should certainly aid righting.

BOB DOWNHILL Bob Downhill talked about some of the inevitable trials and tribulations he endures to keep Speed Week running year after year and then continued to tell us a bit about the craft he would like to campaign if he were not too busy organising Speed Week. I suspect that like the Bristol Speed Sailing Team he was relying on humour to hide some of his secrets, but the general idea seems to be a large, say 3m x 6m, slab of sheet material which floats on the water with four surface piercing hydrofoils underneath. Horizontal motion is initiated by taking a run up and leaping aboard (he said the crew will be fit) but there was little mention of the details of the rig which will then further accelerate the craft to the normal cruising speed of 50 knots. The first prototype has been made from an 8' x 4' sheet of plywood and this has proved stable when floated on a canal. Bricks piled on top have been used to simulate crew weight. The canal is getting a bit shallow due to the number of bricks which have fallen off.

BOB SPAGNOLETTI Another more serious talk, this time about the electronic speed measuring system which Bob has been developing for use at Weymouth and other events. The idea is that the course start and finish lines are defined by infra-red beams and each craft carries a small box with a detector which senses when it passes through these beams. When the box crosses a beam it transmits a radio signal to a central computer and this signal is coded to indicate the identity of the craft and whether it is starting or finishing a run. The system should work automatically once set up, and should be more accurate than our existing system as well as being more reliable when numerous craft are using the course simultaneously. The boxes to be carried by the craft are about 100mm x 100mm x 70mm and can be fitted with webbing straps so that a sailboarder can wear one over the shoulders. Bob has put a lot of work into this over the last few years and it now looks very promising. At present he is working on improving the range of the beams a bit and the system should then be about ready to use in earnest.

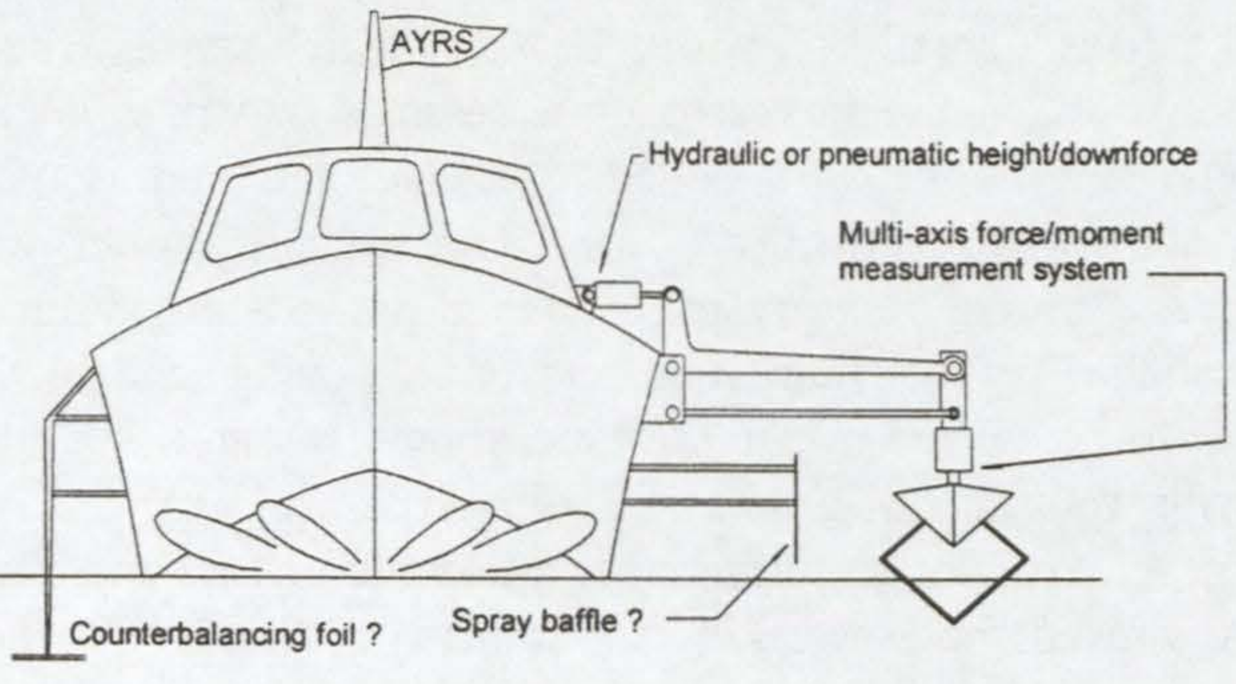
Suggestions for Projects

John Perry

Following from Publication No 123 "Computers Afloat", these ideas for three different projects are included as examples of the possible use of data acquisition in yacht research and may also be of use to anyone who would like to try some experimental work but cannot think of a suitable project.

1. MEASUREMENT OF FORCES ON HYDROFOILS AND SMALL PLANING HULLS.

It is interesting that within the last few years three very different types of craft have been in contention for the world sailing speed record, these being sail boards, a hydrofoil craft (*Longshot*) and a craft with three small planing hulls (*Yellow Pages Endeavour*). Although *Yellow Pages* now seems to have a clear lead, these three design options all seem to be well ahead of any other competition. Since these three types of craft have quite different rigs it is difficult to know for certain which has the best underwater configuration. Could it be, for example, that the *Yellow Pages* planing hulls are inferior to *Longshot's* hydrofoils but that the craft is faster because the rig is better? If hydrofoils are used, will cavitation become a problem in the near future and should the foils be fairly deeply immersed, as were those on *Longshot*, or should they be a shallower design to reduce wetted surface? How about letting the hydrofoils plane on the surface when full speed is reached? If, on the other hand, planing hulls are better, is the *Yellow Pages* arrangement of multiple tiny skegs the best and what is the optimum aspect ratio, angle of attack etc. for the planing surfaces? If I were building a speed record contender I would consider these to be crucial questions and if time and money were available I would certainly want to do some comparative experiments since I do not think that really relevant and reliable quantitative data has so far been obtained.



Force measurement on hydrofoils etc.

A suitable towing tank or water flume is unlikely to be available to the amateur experimenter and so I would suggest that the various hull/hydrofoils to be tested are attached to a powerboat. A powerboat is required which is large enough and fast enough to run smoothly and steadily at up to 50 knots plus while dragging the device under test. Such a vessel would be somewhat costly to buy and may not be all that easy to borrow, but it seems more feasible than the flume or towing tank approach.

Attachment behind the powerboat, that is a tow test, is probably not practical because of the powerboat wake. The other options are attachment ahead and attachment alongside, the later perhaps being preferable for observation and for minimum adverse affect on the manoeuvrability of the powerboat. Surface waves, ventilation and cavitation effects all play a part and so it would be difficult to correct for geometrical scale and best if the device under test is built full size. This should not be a problem since hulls and hydrofoils for speed record craft tend to be quite small. The device under test would be attached to the powerboat by a towing arm which would be long enough that water disturbance by the powerboat does not have too much effect. The connections between the towing arm and the device under test need to be adjustable, either manually or perhaps under electric servo control, so as to set the angle of attack of the device under test in both the vertical and horizontal planes. If it is required to measure these angles of attack then the pitch angle and side slip angle of the powerboat also needs to be measured although the side slip angle may be small enough to be ignored. Load cells would be built into the articulated arm to measure the forces transferred between the powerboat and the device under test. Depending on the arrangement of the load cells, it may be necessary to allow for the aerodynamic drag of the towing arm. The minimum requirement is to determine force in three orthogonal directions, e.g. lift, side force and drag, but it may also be useful to determine the corresponding moments which requires six degrees of freedom force measurement, similar to the force measurements applied to models in a wind tunnel. All forces could be measured by strain gauge load cells and the angles by servo potentiometers or optical encoders. To set the vertical force on the device under test the towing arm could pivot about a fore and aft axis at the point of connection between the towing arm and the power boat and the required vertical force could then be applied through the towing arm using an adjustable spring arrangement or preferably a pneumatic or hydraulic cylinder and pressure regulating valves. This way the device under test will take up a depth of immersion appropriate to balance the applied load and this applied load will be fairly independent of small changes in the roll, pitch and immersion depth of the powerboat. It may be necessary for the towing arm to be a parallelogram linkage to keep a constant roll angle for the device under test. If the device under test is not capable of maintaining its immersion depth to balance the applied load, for example a fully immersed hydrofoil with no incidence control is under test, then the articulation of the towing arm would need to be made rigid after adjustment and the vertical force determined by measurement rather than being pre-set. Roll stabilisation of the power boat may be necessary, perhaps by adjustable transom mounted trim tabs or a counterbalancing hydrofoil as shown. A catamaran power boat might be particularly suitable for this type of testing.

I would think it highly desirable to start these measurements in mirror calm water before moving on to study the effects of small waves. Larger waves will probably not be tolerable but are also probably not relevant to speed record attempts. Even small waves will cause large fluctuations in the readings due to the effect on both the power boat and the device under test. Computer data acquisition could be the key to taking sufficient readings at high speed so that there is a chance of obtaining meaningful results by averaging. All force readings need to be normalised with respect to the square of the water speed, that is all the force readings should be divided by the square of the water speed before making comparisons between results. To do this it is necessary to have accurate boat speed measurement and a good method would be by automatic timing over a known distance using optical start and stop gates as are being developed by AYRS member Bob Spagnoletti.

2. IMPROVED PRESENTATION OF DATA FROM INSTRUMENTS

Many well equipped yachts are already provided with instruments for the measurement of water speed, apparent wind speed and direction, water depth, GPS position, compass heading etc. All these instruments usually have their own individual displays which are sometimes duplicated at the chart table and in the cockpit. There is a trend towards more flexibility in selecting the formats for these displays, and in combining the measurements of various instruments so that calculated parameters such as VMG can be displayed. However, with conventional systems there is still only limited flexibility to customise the format of instrument displays to suit the users requirements and to include extra readings such as angle of heel, rigging loads, rudder angle and boom angle etc. There is scope for any AYRS member with some interest in computer programming to produce software to collect data from all the usual types of on-board instruments and perhaps a few extra sensors as well, and to display this information in novel and hopefully useful formats on a single computer monitor mounted at the chart table and/or cockpit. Although I have not done this for yacht instrumentation I have written this kind of software for various industrial systems and I would think it could make an interesting project for a gadget minded sailor.

A cockpit mounted monitor would need to be robust and waterproof and, as discussed above, a suitable unit based on solid state display technology currently costs around £1100. However this cost may be partly offset by the saving due to not needing to have the cockpit repeater displays which are used on many yachts. A single waterproof VGA monitor could replace almost any number of separate dials and it is neater and easier to remove from the yacht to avoid theft when not in use. Also it can be used at home or in the office when not on the yacht. It is relatively simple to produce software which will divide such a display into half a dozen or more 'windows' and draw a dial with a moving pointer in each of these windows. This may sound complicated to non-programmers but it is not really so difficult using a properly structured approach to writing the programme. A dial on a screen can be generated by a single function in C (or procedure in Pascal or subroutine in Fortran) and if you need ten such dials it takes very little program writing to produce clones of the first dial created and send a separate data stream to each one. If all the dials need to be different to each other you only need to program the differences, you do not need to create each one from scratch.

Here is a list of some of the features and effects which could be achieved. In general, these features would cost nothing except programming time:

- Digital and/or analogue displays.
- Prominence of display according to importance of information. E.g. If you run into shallow water the chart recorder display of water depth could automatically become prominent.
- Adjustable damping to filter rapid changes, that is a software reproduction of the effect of the viscous oil in a conventional magnetic compass.
- Visible and audible alarms when parameters move out of preferred limits.
- Moving charts to show how the various parameters are changing over time.
- Calculation and display of derived parameters such as VMG.
- Correction of readings for secondary effects e.g. correction of apparent wind direction and speed for angle of heel of the sensors, or correction of electronic compass for deviation and variation.
- Automatic cross checking of sensors. For example, a water speed log could be checked at intervals against GPS position and if there is a persistent error a warning could be indicated. If the tidal flow is known or small then the method could also be used for automatic log calibration.
- Logging of data on disc and automatic updating of a data base of performance under all sailing conditions.
- 'Grid' style magnetic compass display for steering off the wind and a similar display based on the direction for optimum VMG for when steering to windward. This means that when beating to windward the grid would no longer indicate the straight line direction to the next waypoint but would indicate the predicted optimum direction to steer for best VMG based on a database of historical performance.
- Indication of suitable time to tack when beating to windward. On a long beat it is often good to make shorter tacks as the destination gets closer. If the destination is a windward mark of a race course then the last tack should be exactly timed so that the yacht arrives just to windward of the mark without pinching or bearing away. The computer could determine this tacking point based on the data base of historical performance.
- Prediction of ETA etc. based on data base of historical performance.

- Real time display of polar graph of current performance with comparison against historical performance under similar conditions.

It is true that some marine instrument manufacturers are now including some of these features in their top of the range systems but I doubt whether any can provide all these features. A great advantage of using your own software rather than that built into a ready made system is that you know the assumptions and limitations on which the software is based and so can avoid the tendency to put more faith in it than is justified.

3. MEASUREMENT OF DYNAMIC FORCES ON TETHERED CRAFT.

If a wind tunnel is used to measure the forces on the rig of a full sized craft it will need to be a tunnel with an exceptionally large working section in order to accommodate even a small dinghy. For this reason wind tunnel tests on yacht rigs are usually applied to scale models. There are many disadvantages to the use of such scale models including the following:

- The cloth sails of a reduced scale model will probably not curve to the wind in quite the same way that full size sails do. For this reason wind tunnel models of rigs are often made from sheet metal rather than cloth and this means that camber, twist, wrinkles and surface texture are unlikely to be realistically modelled.
- The wind turbulence and gradient in a wind tunnel may not reproduce conditions on the water, although there are techniques which attempt to do this.
- If one is studying a rig design which has not yet been built at full size then there may be some financial saving in working with reduced scale models. If however one is trying to quantify or optimise the performance of an existing rig then a scale model is extra cost.
- The use of scale models requires attention to the effect of Reynolds number.

In view of the above there would seem to be a case for measuring the aerodynamic characteristics of full size craft by mooring them with sail set and measuring the forces in the mooring lines. In fact an AYRS member did do this about 25 years ago, in AYRS publication No. 40 (re-printed in No 82), Edmond Bruce describes this method for a 12 foot una rigged dinghy and shows the beneficial effect of increasing kicking strap tension. The measurements for these experiments were by manual reading of instruments such as spring balances and so error was almost certainly introduced by the continually changing speed and direction of the natural wind and the effect of small waves on the hull of the boat. The use of a computer data acquisition system should allow very large numbers of readings to be collected and processed in such a way as to eliminate or at least reduce such errors. I would hope that this would allow much more useful results to be obtained.

A couple of years ago I did a preliminary trial with my own boat, a 15 foot sailing dinghy, to see how easy it would be to hold the boat steady by mooring it with sail set. With two anchors, one fore and one aft, the boat was only stable at some angles of attack to the wind. Adding a third anchor to the forward attachment point made the mooring stable over the range of angle of attack and sail trim corresponding to sailing close hauled and reaching. To simulate running the third line may need to be attached aft.

The instrumentation could include load cells to measure the forces in the mooring lines, high quality wind instruments to measure wind angle and direction and servo potentiometers to measure the angles of the mooring lines. An alternative to measuring the angles of the mooring lines would be an arrangement of load cells which measures the force components in two horizontal planes so as to determine the magnitude and direction of the resultant. Another possibility is a load cell could be made along the lines of that shown in AYRS No 123, but using a small diameter thin walled tube in place of a leaf spring and having a ring of strain gauges at a section just above the fixed end. The gauges could be wired to form two bridges measuring the components of the applied force in two roughly orthogonal directions. This instrument could then be calibrated using known loads applied in known directions to produce calibration coefficients which would enable it to measure the magnitude and direction of the load in a cord or combination of cords attached to the free end of the tube.

The following should be considered:

- There should be no significant water current.
- Because the rig of a sailing craft has a marked affect on the airflow in proximity to it, the wind instruments should be kept well clear of the rig. A possible arrangement is to have the wind instruments on a pole extending well to windward of the rig, but probably it would be better to have wind instruments mounted on a floating platform(s) anchored nearby. In this case it is necessary to know the orientation of this platform relative to that of the boat. This may be possible by use of electronic compasses on both the boat and the platform or by a light but rigid pole linking between the boat and the platform. The connections at each end of this pole could be designed to allow two angular degrees of freedom whilst preventing rotation about the vertical axis.
- The measured forces will include aerodynamic effect of the hull as well as the rig. This is generally an advantage since both are important to overall performance. The hull and rig are thought to interact aerodynamically so that their performance as a combination cannot be accurately determined from measurements on the rig and hull separately.
- Depending on the load cell arrangement, it may be necessary to allow for the vertical angle of the mooring lines.

- Angle of heel is important and, depending on the object of the experiments, either the angle of heel should be allowed to correspond to the simulated sailing conditions or the angle of heel should be kept to zero by use of moveable ballast or perhaps an outrigger. A heel sensor will be needed and ideally would be connected to the data acquisition system.
- The heeling moment due to the rig is an important parameter in comparing alternative rigs or rig adjustments and this moment needs to be determined. It may be possible to determine the heeling moment from the heel angle and the measured hydrostatic characteristics of the hull, or from the ballast movement necessary to prevent heeling. An alternative approach is to use load cells in the rigging but this would be difficult with complex multi-stayed rigs. When quoting a heeling moment, it is also necessary to indicate the vertical height of the axis about which the moment is measured, for example the waterline or the deck level and this needs to be taken into account in comparing results.
- The results obtained will be dependant on the way the rig is adjusted and so important settings should be recorded, including, for example, the sheet and kicking strap adjustments.
- The most important parameter which can be derived from the results is probably the overall lift to drag ratio in the horizontal plane. Fortunately this parameter is relatively insensitive to small fluctuations in wind velocity and angle of attack.

It is questionable whether this type of experiment will be sensitive enough to show up the very small improvements possible by minor tweaking of the rig. It has been suggested that such improvements can only be evaluated by trials between two identical boats acting as 'sparing partners'. Although this may be true, the disadvantage of this method is that it is hard to isolate the effect of rig adjustments from the effect of other variables such as helming technique.

If a good instrumentation system is used, then it seems likely that this type of experiment would produce better aerodynamic data for yachts than has previously been obtained. Such data could be useful in improving the prediction of performance at the design stage. Although, as discussed above, it could be difficult to measure the effect of minor rig tweaking, it should be possible to quantify the effect of relatively major adjustments or design options. For example, I would find it very interesting to get better quantitative information regarding the following:

- Rotating versus non-rotating masts.
- How much does mast diameter matter?
- Full length sail battens versus short battens.
- Methods of coping with strong winds including reefing, increasing sail twist and bending the mast to reduce camber.
- The effect of airflow between the rig and the deck. Is it an improvement to attempt to block off the gap under the sails? If not, how large should the gap be?
- Is it worthwhile setting jibs/genoa as well as the spinnaker downwind?

About AYRS

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

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

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

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

AYRS Publications

Prices (for non-members) are correct for 1997. Prices to AYRS members are discounted - see AYRS Newsletter

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12	Amateur Research	1957	£5.50*	50	Catamarans 1964	1965	£5.50*
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20	Modern Boatbuilding	1958	£5.50*	58	Practical Hydrofoils	1966	£5.50*
21	Ocean Cruising	1958	£5.50*	59	Multihull Design/Cats	1967	£5.50*
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25	Fibreglass	1959	£5.50*	63	Multihull Capsizing	1966	£5.50*
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