THE 15th CHESAPEAKE SAILING YACHT SYMPOSIUM

The BASILISCUS Project - Return of the Cruising Hydrofoil Sailboat

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ABSTRACT

Basiliscus will be a cruising hydrofoil sailboat, much along the lines of David Keiper's *Williwaw*, but incorporating experience that has been gained in multihull design in the thirty years since *Williwaw*'s construction. This paper covers the development plan for the entire project and the technical results of design studies performed to date.

Topics covered include scaling laws for model hydrofoils, the baseline design, and preliminary CFD modeling of the hydrofoils.

NOTATION

A	aspect ratio, b^2/S
CAD	computer aided design
C_D	drag coefficient
C_{Dj}	junction drag coefficient
C_{DLE}	leading edge drag coefficient
C_{Ds}	spray drag coefficient
C_{Dw}	wave drag coefficient
C_f	skin friction coefficient
CFD	computational fluid dynamics
C_L	lift coefficient
Cp	prismatic coefficient
D	drag, lb
Fr	Froude number
F_Y	side force, lb
K	scale factor
L	lift, lb
LCB	longitudinal center of buoyancy
L_{wl}	length of waterline, ft
L/D	lift/drag ratio
N_j	number of junctions
N_r	number of rungs in ladder foil
N_s	number of surface piercing surfaces
OLE	object linking and embedding
RTM	resin transfer molding
S	area, generally, ft^2
S	hull wetted cross sectional area
S	hydrofoil projected planform area
S_D	drag area, ft^2
S_{Di}	induced drag area, ft^2
S_L	lift area, ft^2
S_Y	side force area, ft^2
SMP	ship motion program
V	speed, generally
V, V_1, V_2	boat speed, ft/sec
VPP	velocity prediction program
W	weight, lb
X	longitudinal distance, ft
X_{CB}	position of LCB forward of amidships
a_0	sectional lift curve slope, deg^{-1}
aka	crossbeam between hulls
ama	outer hull
b, b_1, b_2	span, ft
b_e	effective span, ft
c, c_1,c_2	chord, ft
g	gravitational acceleration, ft/sec^2
n	chord scaling exponent
p	velocity scaling exponent
l_{cb}	X_{CB} / L_{wl}
t	foil thickness, ft
a	angle of attack, deg.
a_0	angle of attack for zero lift, deg.
∇	displaced volume, ft^3
Γ	dihedral angle, degrees
γ	course angle to the true wind, degrees
ρ	density, $slug/ft^3$
ξ	independent parameter

INTRODUCTION

In the Spring of 1968, David Keiper's *Williwaw* made her first flight. *Williwaw* was a 31 ft plywood trimaran equipped with aluminum ladder foils (Figure 1). Over the next decade, Keiper sailed her extensively in the Pacific, ranging from San Francisco to Hawaii and New Zealand. She was destroyed at anchor in Hawaii in 1977 (Keiper, 1996). Although several foil-assisted trimarans have been sailed and raced offshore, to date, *Williwaw* is the only full-flying hydrofoil to have proven herself in transoceanic sailing.

Correspondence with Keiper regarding two-dimensional foil sections led to starting on the design of a complete boat - the *Basiliscus* Project . This is a report on the early stages of a work-in-progress. It will concentrate on the planning aspects of the project and design requirements.

Fig. 1, *Williwaw* sailing at Pacific Multihull Association speed trials, 1975

The basic concept is moderate risk - it's been done before. However, it's only been done once, and the concept is not mature enough to be considered low risk. There are very little empirical data available, and none at all for sailing hydrofoils of this size. The budget is also very limited, which rules out tank testing or wind tunnel testing to base the design on experimental data.

So the plan of attack is to depend a great deal on modeling and simulation to explore the basic design parameters and to create a good performing, robust design. However, computer modeling alone is not expected to be accurate or reliable enough, so a subscale, manned prototype will be used to validate the predictions, gain practical experience with sailing hydrofoils, and to serve as a test bed for investigating various foil arrangements.

Despite the limited budget, money will be spent where it can have the most leverage on the total cost. Consulting by a professional boat designer or naval architect will bring in offshore experience and structures expertise and serve as a cross check on the engineering analyses.

Finally, the method for constructing the boat will be factored in as early in the design as possible, and considerable effort will be made to ensure that the fabrication will be efficient and as inexpensive as possible.

REQUIREMENTS

The process for developing the boat starts with defining clear requirements and priorities. The usage of the boat will evolve in three overlapping phases. Phase I is the experimental phase. During this period, the boat will be day-sailed to develop the hydrofoils and rig, and to gain experience in sailing a boat of this type. Phase II will consist of club racing on Puget Sound and coastal cruising, primarily in the San Juan Islands and along Vancouver Island. Phase III will consist of cruising in the Pacific. Although the anticipated operating area is the Pacific Ocean, nothing in the design should preclude being able to operate world wide, except for the Southern Ocean.

There is no intention at this time of doing long distance racing, other than coastal races like the Swiftsure Classic or the VanIsle 360, and racing requirements will not be a design driver. Given the unusual nature of the boat, it will require special treatment in handicapping, so there is little point in warping the design to optimize its rating.

There are only three hard requirements:

- It must fly,
- It must cruise,
- It must be affordable.

Everything else will be traded off if it means one of these will not be met.

It Must Fly

The ability to fly is the only performance requirement. There is no specification for how fast the boat has to go. However, it is expected that if the performance is sufficient to fly in a wide variety of conditions, that her performance will be satisfactory for cruising and racing.

The purpose of the hydrofoils is to raise the average speed of the boat, not necessarily the top speed, with the philosophy that, "It's not how fast you go, it's how much you go fast that counts." Until the velocity prediction program (VPP) is operational, it is not possible to guess as to what kind of speeds will be obtained and under what conditions. Although the VPP will be used to maximize the performance of the boat, the object is not to build a 30 knot sailboat. The object of *Basiliscus* is to make 20 knots as boring as possible.

The performance goal is to be able to fly to windward. Keiper's *Williwaw* did not have the stability and her second-hand sails were not efficient enough to allow her to fly on courses other than a reach. Being able to fly to windward will significantly improve the comfort when beating into a seaway and the ability to fly closehauled will improve her performance when sailing off the wind with the apparent wind well forward.

Speed is not the only reason for hydrofoils. They improve seaworthiness, too. "Amazingly, the hydrofoils help to cure most of the bad habits associated with multihulls, such as: pounding, quick motion, snap-rolling in beam seas, difficulty in self-steering, the shaking of wind out of the sails, lee-bow burying, and pitchpoling or capsizing in freak waves." (Keiper, 1996). These attributes are due to raising the hulls out of the water and away from wave disturbances, by the increased dampening provided by the hydrofoils, and through the increased stability afforded by widely spaced foil units. The latter arises from the fact that hydrodynamic forces increase with the square of the speed, while forces from buoyancy are independent of speed. Thus the boat acquires additional stability when it needs it most as it is driven hard or surfing down waves.

Hydrofoils also allow tailoring of the motions in waves through their heave stiffness. For fully submerged foils this is done through the design of the feedback control system and for surface piercing foils by the choice of chord and dihedral, which dictate the rate at which the wetted area of the foils change with height.

Against these advantages must be balanced some severe drawbacks for hydrofoils. Hydrofoils add weight and complexity. It is important that they be retractable when hullborne to reduce the considerable added drag due to their wetted area. When retracted, the hydrofoils add windage and may occupy deck space.

However, the most severe drawback is their propensity for collision. Even small debris or seaweed can cause damage or significantly degrade performance. And whereas the chances are a collision with a modest size object and a hull will be a glancing blow, the hydrofoil leading edge meets everything head on. This is a severe liability for a coastal cruiser where the chances of encountering debris is high. Finally, grounding of a foilborne hydrofoil can be a catastrophic event.

In major collisions, such as with a semi-submerged shipping container, the craft has a good chance of escaping severe damage because the hydrofoils can be made to be sacrificial, breaking away and allowing the craft to decelerate more slowly while the hull passes over top of the object. The hydrofoils may be destroyed, but the boat has a better chance of avoiding catastrophic damage.

Therefore, the hydrofoil cruiser may be a niche vehicle, best suited to offshore passage making, where the chances of minor collisions are reduced, the avoidance of catastrophic damage is most needed, and where the hydrofoil's speed and seaworthiness can be a greater asset.

The need to fly exerts a powerful influence on the rest of the design, particularly with respect to the need to keep weight to a minimum, have a powerful efficient rig, to have a structure which is stiff and capable of handling the large loads at concentrated points from the hydrofoil attachments, and a hull shape which is compatible with stable transition to foil borne operation on takeoff. These factors argue for a boat that is designed from the outset to be a hydrofoil, rather than adding hydrofoils to an existing boat.

It Must Cruise

The purpose of *Basiliscus* is to travel long distances offshore with a crew of one or more. This is not to be a stripped-down racer nor a day-sailer like the two current production hydrofoil sailboats, the Hobie Trifoiler and the Windrider Rave. Nor is it to be an extreme ocean racing machine in the vein of the Open 60 trimarans.

It is to provide simple but "female friendly" accommodations for extended passages. Firm requirements include standup headroom and an enclosed head. The interior must be habitable when capsized, and hard points will be built into the cabin sole for hanging hammocks when inverted. Each cabin must also be equipped with an escape hatch.

Another firm requirement is shoal draft. All foils should be retractable to allow mooring in shallow water and beaching.

Crew size will typically be two to four for cruising. The boat must be capable of being cruised single handed. Crews larger than four will only be used when day-sailing or round-the-buoys racing.

Based on boats with comparable requirements, such as the Brown *Searunner* 37, Farrier F-36, Hughes 37C, Shuttleworth *Damiana*, or Grainger TR40, the length will be between 35 and 40 ft. Also based on similar boats, the empty weight, with hydrofoils, will be approximately 4000 lb. With cruising payload, including sails and crew, of around 3000 lb., the maximum displacement is targeted at 7,000 lb.

Height of the mast will be limited to 65 ft so as to clear the fixed bridges on the Intracoastal Waterway.

Cruising requirements will also dictate much of the required equipment. The boat will comply with offshore racing regulations as a guide to the minimum safety requirements.

It Must Be Affordable

The earliest decisions tend to have the largest impact on the final cost. For example, the decision to fly costs $100,000, since this dictates building a new boat as opposed to purchasing an existing one. Therefore, a significant effort is being placed on doing analyses and planning at an early stage while delaying the start of construction as long as possible. The object is to spend time and money wisely at the start of the project so as to get the greatest leverage to reduce the total cost.

Farrier estimates that an F-36 can be built for $90K - $130K (Farrier 1997), and a Contour 44 (40 ft Lwl) production trimaran has a sailaway price around $335K (Chiodi 1998). Assuming that the price scales as length^3 or by the pound, scaling the Contour to 36 ft provides a production trimaran price of $250K. It appears that if *Basiliscus* can be built for $200K in today's dollars over approximately seven years its acquisition costs will be affordable. This will require considerable home-building.

Development of the hydrofoils can be expected to incur additional costs which are difficult forecast at this time. A factor of three will be applied to the estimated costs of the hydrofoils to handle these contingencies. Additional foil stock will also be purchased or built at the outset to improve the economy of scale and provide for spares and configuration changes.

Maintenance, mooring, and other operational costs must also be factored into the design. The hydrofoil offers some significant savings in maintenance costs, because the boat can be allowed to dry out on its foils, making the bottom accessible for routine cleaning or repair without hauling out. Wider beam makes mooring more difficult to find, and more expensive, and may dictate the maximum beam of the boat. The length is being held to less than 40 feet to keep berthing costs in check. The use of exotic materials will be limited, both to reduce building costs and to ensure the boat is repairable outside of the U.S.

ENGINEERING ANALYSES

The engineering analyses are designed to answer the questions,

"How fast will it go?"
"Will the ride minimize seasickness?"
"What are good shapes for the hulls?"
"How strong does it have to be?"
"Will it fly?"
"Will it be stable in flight?"
"How much wind is required to fly?"
"Will it be well balanced directionally?"
"How much wind does it take to capsize?"
"Is it susceptible to wave-induced capsize?"

Several key computer programs are being used to answer these questions.

Multisurf, by Aerohydro, was selected as the primary computer-aided design (CAD) geometry engine (Aerohydro, 1998). This program was selected for its relational geometry (which makes it highly parametric), its ability to support object linking and embedding (OLE), its built-in hydrostatics capability, and its affordability. The OLE capability, in particular, makes it possible to link Multisurf to other engineering tools so as to integrate and automate many of the design and analysis processes.

Several computational fluid dynamics (CFD) programs are being used. Michlet, written by Leo Lazauskas, is a Mitchell integral wave drag code, capable of calculating the wave and viscous drag of slender symmetrical multihulls. It is being used to estimate the hull-borne resistance. It is not capable of handling leeway or heel effects. However, the hull forms are well rounded, heel angles will be less than fifteen degrees, and leeway angles should be small with adequate lateral plane area, resulting in very little of the side force being carried by the hulls and thus little induced drag being produced as a consequence. So the Michlet results are expected to be applicable when heel angles are accounted for by the relative immersion of the hulls.

The workhorse CFD program is CMARC, a variation by Aerologic of the NASA Ames panel code, PMARC (Garrison, 1997). CMARC is a low-order Morino method panel code. It is used to calculate forces and moments on the hydrofoils and will be used to investigate rig designs. The principal drawback of CMARC is that it does not have a free-surface capability. However, the program was modified at the author's request to include the linear surface boundary condition corresponding to the infinite Froude number approximation. This is adequate for the hydrofoils.

Hydrofoil sections are designed and analyzed using the Eppler code (Eppler, 1990), which was for several decades the state-of-the-art in the aerospace industry for two-dimensional flow around subsonic airfoils. It has been highly validated by comparison with wind tunnel and flight tests. Selected H105 Eppler results have also been validated with XFOIL - today's state-of-the-art.

Finally, the US Navy's Standard Ship Motion Program, SMP, will be modified to compute the dynamic derivatives and added mass for the seakeeping analysis.

The primary tool for performing simulations and analyzing the dynamics will be Scilab (Drakos, 1998). This is a public domain program, modeled after Matlab, available from INRIA in France.

Yet to be determined are the tools for structural design and analysis. Programs needed will include a composite laminate properties code and a finite element code.

Velocity Prediction Program

The velocity prediction program (VPP) is the starting point for most of the engineering studies. It will be used to calculate the yacht's performance and to provide a steady-state trim solution for the dynamic simulations.

The principal difference between the VPP being developed and conventional programs is that the *Basiliscus* VPP solves for the full six-degrees-of-freedom motion equilibrium. This is necessary to properly trim the forces and moments from the hydrofoils.

Time Domain Simulation

The quasi-steady force modules from the VPP will be used in a time-domain simulation to analyze the stability in flight and the takeoff characteristics. The simulation differs from the VPP in that the VPP requires the state of the craft to be iterated until a static equilibrium is reached, while the simulation simply integrates the accelerations resulting from any unbalanced forces to compute the resulting motion.

The simulation will be hosted on Scilab. In addition to being able to create time histories of the motion, this will make it possible to generate linear models to compute the eigenvalues and modes of the motion and perform frequency responses as a prelude to the seakeeping analysis.

Seakeeping Dynamics

The boat will platform small waves but contour large ones. There will be no switching of modes as a function of wave height; instead the dynamics will be tuned to the wave spectra for ocean waves to achieve this behavior. Small, high frequency waves should pass under the boat with minimal response. So a key question is how high does the craft have to fly, given its natural frequencies and the sea state? Or put another way, at what sea state is it likely that it will have to transition from flying to hullborne operation and what are the probable operational limits of the craft? How should the foilborne frequencies and amplitudes be tuned to minimize seasickness? These questions have to be answered with a seakeeping analysis.

Surface piercing foils do well in headseas because the orbital motion helps them up and over the waves. As the wave approaches, the orbital motion increases the relative velocity of the foil, creating more lift and raising the boat. The bow encounters the increased orbital motion first, so the boat tends to pitch up to fly over the wave as well.

But surface piercing foils have a problem when overtaking following seas. As the boat approaches a wave crest, it experiences a drop in relative velocity due to the orbital motion. This causes the boat to tend to pitch down and descend into the wave crest. These trends are resisted by the heave stiffness of the surface piercing foil. So how much heave stiffness is needed for stability in larger waves vs. the desire to be insensitive to smaller waves is an important consideration to be answered by the seakeeping analysis.

The dynamic coefficients for the seakeeping analysis differ from the time-domain simulation because they will be a function of the frequency of motion. These will be estimated for the hulls using SMP. Added mass and dynamic coefficients for the hydrofoils will be estimated using handbook methods (Martin, 1963).

The key stumbling block to the seakeeping analysis at present is the transformation of the coefficients to the center of gravity. Transforming the forces and moments to a new reference center is straightforward, but due to their lateral displacement, the outer hulls and hydrofoils are located at different phases in the wave motion than the main hull. How to handle this phase information in the transformation remains to be worked out.

Once the ensemble coefficients for the whole boat are assembled, they can be substituted into the equations of motion and the transfer functions of the boat's response determined. Multiplying the transfer functions times the input spectra for the waves yields the response of the craft to regular waves. The response of the craft in a random seaway will be obtained by superimposing the responses for regular waves of different directions (Hirsch, 1968).

Unique to this seakeeping analysis compared to that for ships is the inclusion of aerodynamic forces. The motion of the craft in waves will include the aerodynamic damping provided by the sails. Aeronautical models for low level turbulence will be used to determine the motion in flat water due to random gusts in a similar manner to the seakeeping analysis. This motion can be further superimposed on the boat's response in a seaway to obtain the complete motion spectrum.

Capsize Dynamics

Some conventional multihull strategies for extreme conditions may not be available to the cruising hydrofoil. One example is the strategy of retracting the centerboard or dagger boards to minimize the lateral plane area and allow the craft to slide sideways like a raft if struck by a breaking wave, and avoid the rolling moments that would result from the board resisting the lateral force of the wave.

The hydrofoil boat can be expected to progress from foilborne operation to hullborne with the foils down for damping when conditions worsen. As the situation deteriorates farther, it is doubtful whether the hydrofoils can be safely retracted. Therefore, the hydrofoil must be capable of surviving extreme conditions with the foils down.

Keiper found the motion of a hydrofoil in large waves to be considerably different from the motion of a conventional multihull sailboat, due to the increased damping and dynamic stability. So the wave-induced capsize dynamics will be analyzed to assess the relative susceptibility of the boat with foils up and down, and to develop possible strategies for coping with extreme conditions that are compatible with the unique characteristics of the hydrofoil.

The time domain simulation will be modified to do this analysis. The modeling of the wave-induced capsize will follow that of (Meyers and Krushkov, 1984).

Structural Loads

One result of the extensive modeling planned for the performance and dynamics of the boat is that these models should provide considerable information on the applied loads. The VPP will provide the static loads on hulls, rig and foils, while the seakeeping analysis will provide the acceleration spectrum for any point on the boat for determination of dynamic loads.

The initial structural analysis will be based on (Reichard, 1985). More detailed structural analyses will be contracted out to experts with multihull structural design experience.

Weight Estimation

The preliminary design is based on statistical weights for similar craft.

In addition to the top level requirements, a detailed requirements document is being maintained. This is an outline which breaks the requirements down to the level of individual features or equipment. From this will be derived a spreadsheet containing a bottoms-up weight and mass properties estimate.

As the bottoms-up weight estimate is established, each piece will have an estimate of its moment of inertia, and the mass properties of the boat will also be built up in detail, including moments of inertia.

HALF SCALE PROTOYPE

The state of the art in CFD today still does not allow accurate estimates to be made in all cases without calibrating the calculations with empirical data. Tow tank testing would be useful, but would consume the entire project budget. Instead, a half scale sailing model of the cruiser will be built as a prototype.

The purpose of the prototype is to serve as a hydrofoil test bed and to validate performance predictions. It may also serve to validate handling qualities and balance. The performance predictions will be validated by predicting the performance of the prototype configuration in order to validate the prediction process. The same methodology will then be applied to the full scale article. Strict similarity to the cruiser configuration is not required, however the closer the test bed is to the cruiser configuration the better, because the results themselves may be scaled up to be a cross check on the cruiser computations.

An additional purpose of the prototype is to gain experience in boat building and to experiment with different materials and fabrication methods. The experience gained in building the prototype is expected to pay for itself in improved detailed design of the cruiser and a shorter learning curve in its construction. It is desirable that the prototype use like materials for the hull and similar hardware for such items as foil attachment points.

The cheapest and fastest way to produce a half scale prototype is to purchase a used beach cat and modify it to represent the cruiser configuration. The beach cat will be turned into a half scale prototype by building a scaled model of the center hull and extending the akas. The beach cat's rig will be retained, but may be relocated to match the cruiser's balance. Lateral resistance will come from a centerboard or dagger board in the main hull rather than the dagger boards of the beach cat when hullborne. The hydrofoils will provide the lateral resistance and steering when deployed.

Prototype Scaling

The cruiser has a sail area of 800 ft^2, a length of 36 ft, and displacements of 5000 lb to 7,000 lb. This gives it a displacement/length ratio of 47 to 66 and a Bruce number of 1.65 to 1.47. A candidate prototype would be a Hobie 18, which has a weight of 400 lb and a sail area of 240 ft^2. Assuming a new 20 ft hull and beams weigh 300 lb, with a single crew weight of 200 lb, the prototype would have a displacement of 900 lb for a displacement/length ratio of 50 and a Bruce number of 1.60. This is a good match for the cruiser at light weight. Placing another 200 lb crew aboard results in a displacement/length ratio of 61 and a Bruce number of 1.50, which is representative of the cruiser at a mid to heavy weight.

Hydrofoil Scaling

Hydrofoils for the prototype are more problematic. There are two promising avenues for scaling the hydrofoils: Froude scaling and equal foil loading.

The first, Froude scaling, results in hydrofoils that are geometrically similar to the cruiser's foils and takeoff speed of the prototype is 70% of the full scale cruiser's. Equal Froude numbers mean that the wave drag characteristics of the two boats will be as similar as possible and the scaled spanloading results in the same induced drag/weight ratio as the full scale boat. Thus the hump speed behavior may be similar. However, the subscale foils will be more lightly loaded than the full scale foils and less susceptible to cavitation. This makes the prototype more robust, but may not uncover problems with the full scale configuration.

The second, equal foil loading, results in the chord of the half-scale model being only one quarter of the chord of the cruiser, but the model has to operate at the same speeds as the big boat. Since the speeds are the same and the lift coefficients are the same, the absolute pressures on the foils will be the same. These hydrofoils would have the same susceptibility to cavitation and ventilation as the full scale foils. Naturally, it will be more difficult for the prototype to take off, since its Bruce number is similar to the cruiser's and it has to sail to a higher Froude number.

The major factor that makes this option attractive is that it would allow the use of aluminum foil extrusions already on hand, purchased from the Keiper estate. For a half scale prototype, the foil chord will be one quarter of the cruiser's chord. Preliminary estimates indicate that the cruiser's foil chord will be on the order of one foot, which makes this a good match to the three inch foil extrusions. Unfortunately, the section shape on the extrusions, approximately a Clark Y, is quite different from the custom foil shapes, such as the author's H105, that will be used on the cruiser. This limits the utility of the existing extrusions.

The plan for the prototype will be to start with hydrofoils made from the existing aluminum extrusions, so as to gain experience in building and sailing a hydrofoil. Since ladder foils are being used, it may be possible to double the number of rungs to gain the extra area needed to match the Froude scaling speeds. As time and money permit, Froude scaled hydrofoils will be fabricated and tested on the prototype. This will provide experience in fabricating custom hydrofoil units and offer the opportunity to experiment with candidate materials and processes, which will also be relevant to the full scale boat.

Instrumentation of the prototype will be consistent with its low cost nature. A hand held anemometer and GPS would provide the means to measure windspeed-boatspeed ratio as well as absolute boat speed. It may be worthwhile to invest in commercial electronic instrumentation, since it could later be installed on the cruiser itself.

Testing of the prototype will include general handling, and stabilized speed measurements on a variety of headings. Particular attention will be paid to the behavior of the hydrofoils, liftoff speeds under various conditions, and the difference between foil borne and hull borne speeds. Results will be compared to predictions for the prototype configuration. An attempt will be made to resolve differences between prediction and test data so as to obtain factors that can be applied to correct the modeling of the cruiser performance.

CONSULTING SUPPORT

The consulting effort will be divided into two phases; a review of the preliminary design, and detailed design support.

Phase I: Preliminary Design Review.

The purpose of the first phase is to critique the preliminary design and to establish a plan for the rest of the development effort. The ideal time for this review will be after the VPP is working and some initial trade studies have been done. At that point, the design should have some credibility and its general characteristics be known.

The tasks for the initial consulting effort are:

- evaluate the feasibility of the design,
- determine the preliminary material selection and scantlings,
- define the initial equipment list,
- establish common tools, such as CAD system, for future collaboration,
- estimate probable cost of the boat,
- evaluate the development plan and determine necessary revisions.

This phase of the consulting effort is intended to be short, and focused on determining the tasks which must be completed before the second consulting phase. It is also intended to inject realism into the design and focus it on practical matters.

Phase II: Detailed design & building plan.

The purpose of the second consulting phase is to complete all the engineering necessary to begin construction. The bulk of the consulting effort will occur in this phase. At this point, the performance and dynamics analyses will be complete, the design will have gone through several trade studies, and been tested on the subscale prototype. Static and dynamic loads will be available. Most of the drawings will exist in a digital format.

The tasks for the second consulting effort are:

- check the design calculations,
- perform structural analysis using a finite element analysis,
- revise scantlings,
- establish composite layup schedule,
- determine fabrication methods and procedures,
- generate full size plans and other drawings for construction.

The finite element analysis will require the lion's share of the resources for this phase. The ability to do such an analysis will likely drive the choice of consultants. The choice of consultant will depend on the ability to do the desired analysis, multihull background, interest in the project, and price.

In addition to the naval architecture consulting, potential builders will be identified at this time and brought into the discussions. Considerable design changes may be required in order to reduce the costs of building the boat. The objective of the extensive design analyses is to produce a firm design for which changes during building will be minimal.

CONSTRUCTION

Planning for the yacht's construction is broken up into the supporting logistics and the actual fabrication process itself.

Logistics

The purpose of the logistics effort is to address the affordability of the yacht.

Make-Buy Breakdown. The biggest question regarding whether to make the part or purchase it is the hull structure itself. The current plan is to have the hulls and akas (cross beams) professionally built, then fitted out at home. This uses the skill of the builder where it counts most; capitalizes on the builder's facility with its space, tools, and hazardous waste handling (spray booth and the like); and avoids paying shop time and labor for the time consuming but simpler task of installing the hardware.

Secondary structure, such as interior joinery, can be constructed at home. This will primarily consist of flat composite sandwich panels, which can be formed and vacuum bagged on a flat table.

The mast will be handled the same way as the hulls - professional construction of the mast itself, and home installation of the hardware.

For the hydrofoils, one possibility is filament winding. It appears that it may be possible to build all the foils using one cambered section and one symmetrical section, or possibly just one cambered section, allowing limited series production. Putrusions were investigated and found to be too expensive.

After filament winding, the next most likely method of fabricating the foils will be composite hand layup in female molds. This can be done entirely at home. All the foil segments are less than 10 feet long, and there are many similar pieces, making it feasible to construct the tooling for limited series production. The plugs will be machined professionally using numerically controlled machinery to ensure a high degree of accuracy.

A more expensive but better controlled variation on hand layup is resin transfer molding (RTM). This requires steel tooling for the molds which would have to be cut using numerically controlled machining. Once the molds are in hand, the equipment for doing RTM is only a few thousand dollars. The high accuracy of the resulting foil shape and the limited amount of hand work needed to finish the foils makes this approach attractive.

If the foils are to be made of aluminum, they will have to be professionally fabricated. It may be possible to have dies made for custom extrusions. As a last resort, the foils will be made of rolled, welded aluminum plate. However, this is not likely to yield the desired accuracy in the section profile, and *Williwaw* continually experienced problems with fatigue cracking of her welds. In general, composite construction is preferred over aluminum.

Metal fittings will be avoided throughout where the function can be provided by composites. Chainplates are a good example. Maximum use of composites will help to minimize both weight and cost.

Facilities. Under the current plan, the builder's facility will be used for construction of the hulls. These will be transported home individually for fitting out under a bow frame & plastic enclosure. Once the hulls are complete, they will be transported individually back to the boatyard for final assembly and launching. This solves the problem of getting a 28 ft wide boat out from behind the house and transported through the half mile of city to the nearest marina.

Tools. Tooling will be simplified due to the use of a professional builder and his facility for the major construction. A flat table with vacuum bagging equipment, basic hand tools, composite material handling (resin pumps and the like), and a table saw and band saw for cutting composite core and wood joinery will be needed. Inexpensive laser pointers or home-construction type laser tools will be used as references for alignment.

Transportation. Transportation of the boat will be eased by transporting the hulls individually. These can be moved on an ordinary flat bed truck or trailer.

Berthing Location. Berthing of a multihull in Puget Sound will take some advance planning, since all the marinas have waiting lists that are years long. Waiting lists will be joined as soon as construction actually begins. It may be necessary to find a moorage on Vashon or Bainbridge Islands while waiting for a more convenient berth on the mainland.

Fabrication

The construction planning has two purposes. The first is to determine what aspects of the design drive the costs, so that the design can be modified at the early stages where construction considerations can have the biggest impact on the cost. The second purpose is to plan the construction process for execution.

Part Fabrication. The design of the boat will be accomplished using CAD, which opens up some possibilities over traditional boat building. Shops with numerical machining capability will be used to cut parts for the boat, including tooling and composite cores. This may make it possible to provide the builder with precut pieces, like a kit, with the labor savings making the added expense worthwhile. The labor savings are expected to come from having the pieces readily available for assembly, reduced fitting and rework, and a more accurate hull shape requiring less fairing effort.

Hulls. The builder will be consulted extensively and a great deal of design time spent on the construction process itself. Features in the hull design which are difficult to build will be modified or eliminated. Once construction starts, changes to the design will be limited to those which are absolutely necessary to remove obstacles to getting the boat built, or those which result in a net reduction of the cost of building.

The materials to be used for the hulls, and thus the construction process, will be determined as part of the structural design and analysis. For planning purposes, the baseline construction will be of Corcel™ foam core with s-glass skin and local carbon fiber reinforcement. Although cold molded wood, or even wood skinned sandwich construction is not ruled out. Plywood is unlikely due to the rounded contours. Wood core, such as Western Red Cedar, is attractive in cost, but may be excessively heavy. Cylinder mold and constant camber methods are also unlikely due to their inability to accurately achieve the desired shape. Accuracy in building is important to realize the performance benefits of the engineering and to minimize the labor involved in constructing the hulls through the use of CAD/CAM.

Resin infusion will be investigated to see if it is cost effective for this one-off boat. There should be considerable progress in this area by the time the boat is built, and a closed molding process of some kind is highly probable.

Interior. Interior joinery will be sandwich panels for lightness. A thin wood veneer may be used on one surface for aesthetics, with fiberglass for the facing skin.

The current design lends itself to having the center section of the boat interior, including the centerboard trunk, flammables locker/cockpit sole, cockpit seats, bulkheads, and berths all constructed as a unitary piece using flat panels. If male molds are used, this center section could be constructed as a unit and used as a major part of the mold. If female molds are used, this unit could be dropped into place once the inside skin of the shell is laid up.

Spars. A rotating spar will be used unless there is an overwhelming advantage shown for a fixed spar. The spar will have a custom section of moderate size, determined by its use as a storm sail. By the time the boat is built, it is likely that carbon fiber costs will have dropped to the point where carbon will be the only real choice for the spar. This will undoubtedly require professional fabrication. The spar hardware will be installed at home, although the stays will be fabricated by a professional rigger.

Hydrofoils. Assuming that the foils are made of composites, either filament wound or laid up, constructing the hydrofoil units will be largely a matter of trimming the prefabricated sections to length and gluing them together. Fairings at the intersections will both reduce the interference drag and reinforce the joints. A key requirement for the hydrofoil assembly is high accuracy in aligning the foil elements during assembly. This will require extensive jigging.

Fitting Out. The vast majority of the hardware installation will be done at home using hand tools, and the author's own semi-skilled labor.

Final Assembly & Launching. Final assembly is another area where the builder's skill in ensuring accurate alignment, and the equipment necessary to handle large awkward hulls, will be of benefit. Depending on the builder's facilities, this may be a different boatyard from the one where the hulls were originally constructed.

Weight Management

A weight management program will be in place before construction begins. The purpose of the weight management program will be to monitor the construction processes for any unanticipated weight growth, to ensure that the mass properties remain suitable for stable flight, and to maintain an awareness in all participants of the importance of minimizing weight. This will include weighing each article as it is finished to compare with the predicted weight. Excessive deviations will be cause for modifying the processes so as to check the growth before it accumulates. If necessary, design analyses will be redone and parts changed to ensure that the boat will still meet the three cardinal requirements - to fly, to cruise, and to be affordable.

SCHEDULE

The *Basiliscus* Project is a long term effort, and it is expected that it will take ten years to produce a mature, ocean-going craft. There is no set deadline for its completion. The approximate duration for the tasks discussed above is shown in the program schedule, Figure 2.

BASELINE DESIGN

The baseline design is a starting point for the engineering analyses. At this time, the emphasis is on developing the design processes and not on exploring

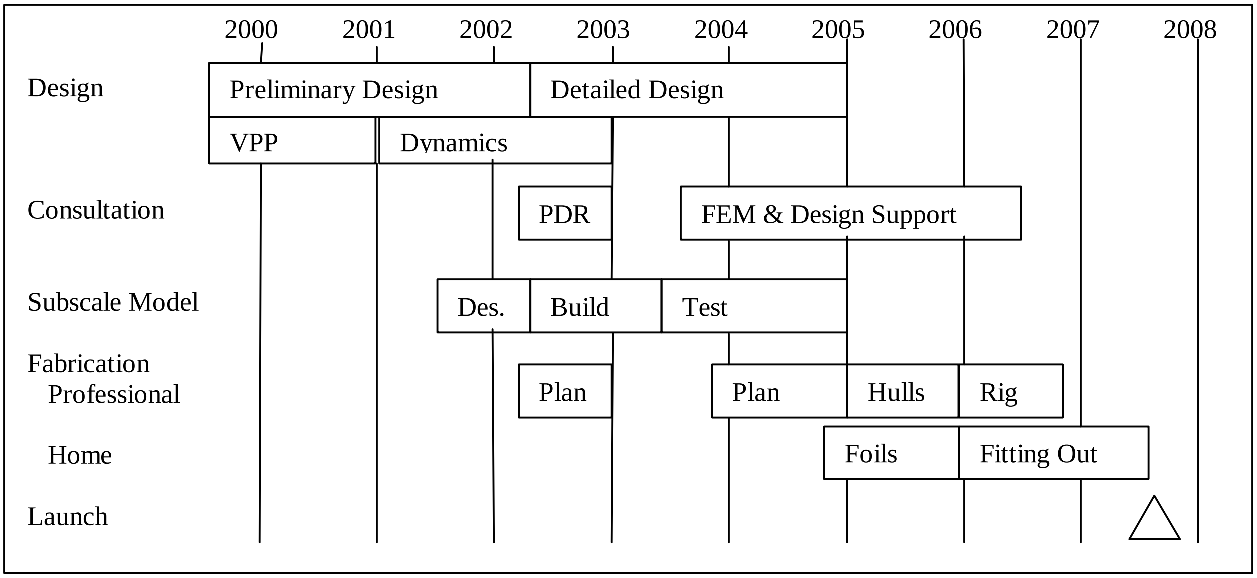

Fig. 2, Program Schedule

alternatives for the design itself. The final design will undoubtedly be quite different.

Basiliscus will be a trimaran configuration because this was the best fit for the hydrofoil arrangement, a trimaran has the most interior space among multihulls this size and smaller, and because a trimaran has the best performance in light winds.

The philosophy behind the design is to have a craft that is a good sailing boat, fully competent to make ocean passages in all conditions without the hydrofoils. Previous hydrofoil designers have often paid little attention to the hullborne capabilities and suffered from a lack of stability and poor performance. For example, Keiper capsized *Williwaw* three times due to a lack of buoyancy in the amas. She also had poor performance going to windward when hullborne with the foils down, and was eventually fitted with a leeboard to provide lateral resistance with lower drag than the hydrofoils.

Figure 3 shows the baseline configuration. It is 36 feet long on the waterline, 38.9 feet in length overall with the foils retracted, with a design displacement of 7000 lb. Beam between the centerlines of the amas is 25 feet. Beam overall is 27.6 feet with the foils retracted and 45.8 feet with the foils down. Maximum draft is 1.8 feet with all foils retracted, 6.2 feet hullborne with the flying foils down, and 7.6 feet with the centerboard down. The amas are 32 feet on the waterline at a design displacement of 4000 lb, 32.7 feet length overall, and displace 9460 lb fully submerged, or 135% of the design displacement.

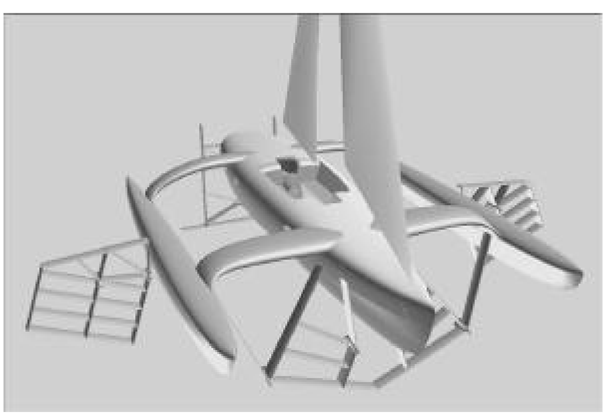

Fig. 3, Trimaran, Foils Down

The baseline rig is an 80% fractional sloop. Sail area is 800 square feet, with 500 ft^2 allocated to the main and 300 ft^2 to the jib. The head of the main is at 61 feet above the water.

Hull Design

The hull lines are shown in Figure 4. The main hull has a prismatic coefficient of 0.6, with an underwater length/beam ratio of 10. The prismatic is somewhat lower and the stern finer and more rounded than many modern trimarans, reflecting a hull optimized for performance in light winds.

The design cross sectional area distribution is given by:

1) $$X=\left[\frac{-1}{2}\cdot\cos(\xi)-l_{cb}\cdot(1-\cos(2\cdot\xi))\right]\cdot L_{wl}$$

2) $$S=\frac{D}{\rho\cdot g\cdot L_{wl}}\cdot\left[\frac{4}{\pi}\cdot\sin(\xi)+\left[\frac{2}{\pi}-\frac{5}{(8\cdot Cp)}\right]\cdot\sin(3\cdot\xi)\ \ldots+\left[\frac{-2}{\pi}+\frac{3}{(8\cdot Cp)}\right]\cdot\sin(5\cdot\xi)\right]$$

$$0\le\xi\le\pi$$

Where X is the longitudinal distance along the hull, and S is the cross sectional area. D is the design displacement, L_{wl} the design length of the waterline, Cp the prismatic coefficient, and l_{cb} the position of the center of buoyancy as a fraction of L_{wl} forward of amidships.

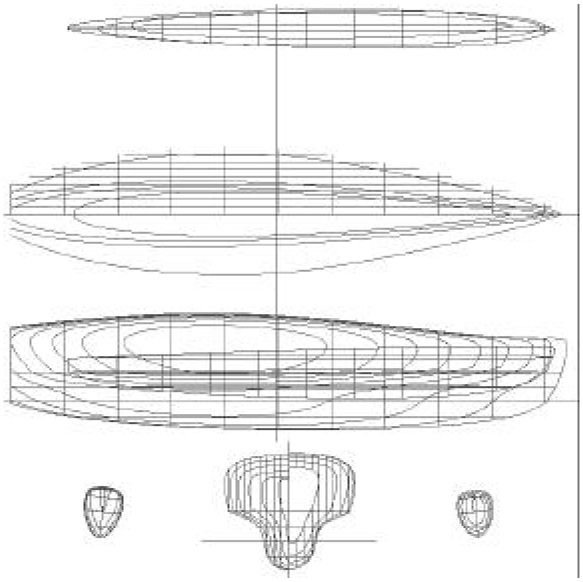

Fig. 4, Hull Lines

The fine entry is a result of the cross sectional area distribution (Figure 5) and a beam/depth ratio of 0.5 at the bow. The beam/depth ratio is 1.8 amidships and the sections are very rounded to minimize wetted area. Center of buoyancy is 1% aft of amidships, and the maximum cross sectional area is located 2% aft. There is little flare at the waterline to minimize added drag in a seaway.

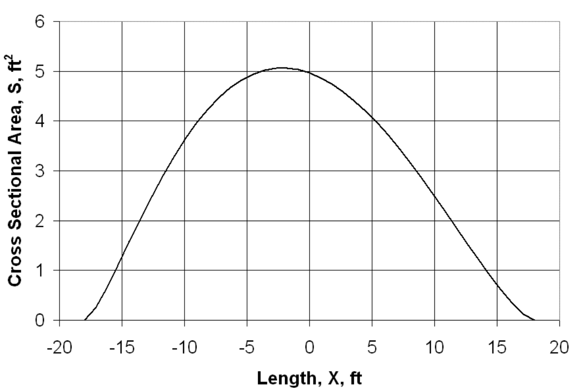

Fig. 5, Main Hull Cross Sectional Area Distribution

The narrow stern is a compromise between the need to provide pitch damping while hullborne, minimizing wetted area and wave drag when sailing below hull speed in lighter winds, and stability on takeoff. Low rocker and flat, planing sections aft can contribute to unstable pitch-heave coupling. This arises when the support provided by the aft sections of the hull drops off rapidly as the boat rises up on the hydrofoils. This causes the boat to pitch up, increasing the lift on the hydrofoils and accelerating the heave. The result is a boat that shoots up out of the water and then crashes back down. Keeping the hull support centered allows the hydrofoils to lift the boat in trim, providing a smooth transition from hullborne to foilborne operation.

Pitching while hullborne is controlled by the movement of the center of buoyancy in the amas and the main hull, as recommended by Shuttleworth (Shuttleworth, 1998). In addition, the stern foil can be deployed by itself if needed to provide damping when conditions warrant, at the cost of some increase in wetted area

Lateral plane area when hullborne is provided by a centerboard and twin rudders are used for control (Figure 6). The rudders are vertical extensions of the stern foil struts which are immersed when the stern foil is retracted.

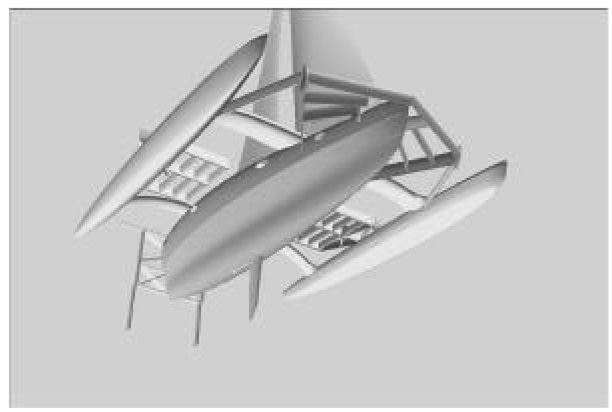

Fig. 6, Trimaran, Bottom View

The topsides are flared above the waterline to provide interior space. From the chines at the edge of the flare section, the topsides sweep up and across the deck in a continuous curve. The rounded shape of the sheer is designed to reduce windage. However, a bluff body realizes most of the possible drag benefit when the corner radius reaches 20% of the height (Hoerner, 1965). So extremely rounded decks are not necessary. Crown of the foredeck is modest and only a small portion of the available walking area is sacrificed to the radius at the edges.

The topsides of the amas are similarly shaped so as to provide an area suitable for good footing while being sufficiently rounded to minimize the windage (Figure 4).

The amas can be expected to be out of the water in moderate conditions, since the boat will be flying then. But they must still provide the necessary stability and seaworthiness under heavy conditions when the boat will be operated hullborne. Therefore it is not prudent to reduce their size very much relative to a non-flying trimaran. The emphasis on their design can be shifted more to robust behavior in heavy conditions without being too concerned about reducing their drag for performance in moderate conditions. However, they still need to allow the boat to efficiently reach its takeoff speed.

The bottoms of the ama sections are wedge shaped forward. This provides considerable reserve buoyancy and results in the center of buoyancy moving strongly forward as the ama is immersed so as to reduce sensitivity to pitchpoling. This is shown by the middle curve in Figure 7, which is the difference between the cross sectional area distribution for full immersion (9460 lb) and the design area distribution (4000 lb). Also evident in this figure is the precision to which the actual area distribution meets the design distribution.

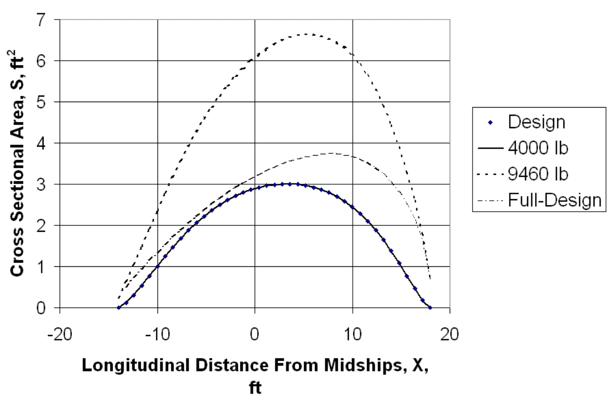

Fig. 7, Ama Cross Sectional Area Distribution

The middle sections of the ama are a V'd egg-shape to reduce wetted area while not being so blunt as to promote pounding and excessively quick roll motions. The aft sections of the amas are wall-sided. This maintains a long waterline for moderate immersions while not picking up much buoyancy aft when the amas are heavily loaded. Any buoyancy aft under those conditions only helps to push the bows down. The aft sections of the amas are also rounded to minimize side force, vortex formation and boundary layer separation with leeway.

The ama lines are designed in a similar manner to the main hull's. A design displacement of 4000 lb was selected to represent the "catamaran" condition in which both hulls are nearly evenly loaded. The prismatic coefficient was set at 0.65, reflecting the amas' higher design speed, and a similar cross sectional area distribution was used.

The akas are one-piece beams extending into the amas nearly to the bottom skin. The center section of the amas are cylindrical to facilitate construction and alignment, and the ends are straight tapers that fit into molded sockets in the amas. This provides a stiff, accurately aligned connection. The akas' shape is wide and flat on the top to form a wide walkway between the hulls. Their cross sectional shape is that of an airfoil with a rounded trailing edge to minimize windage. They are placed high in the hull to minimize their interference with the interior space and to help the hull float out of the water when capsized.

Interior Arrangement

The interior arrangement is patterned after that of the Brown Searunner series (Brown, 1979). The key features of this configuration are the central cockpit over the deep centerboard trunk with the mast stepped in the cockpit. Berths are located on each side, fore and aft (Figure 8). The saloon is located in the stern with the galley just behind the aft companionway.

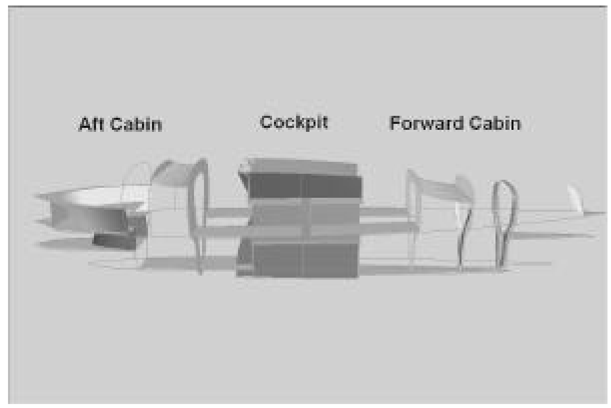

Fig. 8, Interior Structure

The aft cabin (Figure 9), is the social center of the boat. It has the saloon in the stern with the galley immediately forward. The aft aka intrudes into the galley, but there is six feet of headroom beneath it and the area of the galley between the aka and the saloon has over 6.5 feet of headroom. A well insulated icebox will be built under the saloon sole, with the contents in a drawer that pulls out into the galley.

Berths are located port and starboard, extending under the cockpit seats. The berths are located near the center of gravity to minimize their motion in a seaway. All berths are seven feet long, with the aft berths being 31 inches wide and the forward berths 28 inches wide. The aft berths are well suited for lounging, with approximately four feet of sitting headroom. Each person has stowage area for their personal gear located under their berth.

Heavy stores are located to each side of the centerboard trunk low in the boat and close to the center of gravity. This maximizes the stability, minimizes the moments of inertia, and limits the range of travel of the center of gravity to help ensure stability while flying. The taper of the hull makes the forward end of this area the preferred location for water tanks, since the opening to the forward cabin is narrower than the region inside.

The reverse is true aft, and the stores are more likely to be needed in the galley than the forward cabin.

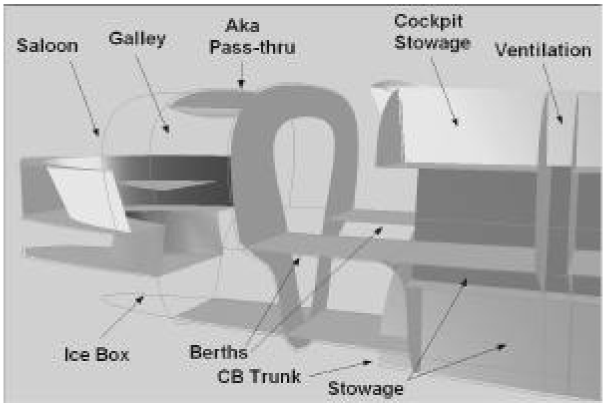

Fig. 9, Aft Cabin

A double bulkhead divides the aft berths from the forward berths. This will be vented with a hooded slot located on the side of the hull outboard of the cockpit and baffled to form a dorade box. Each berth will have an inspection port opening into this space so that the occupants can control the ventilation to their own space. The slots are located in a region that has high pressure on one side of the boat and low pressure on the other side when the wind is blowing across the boat, promoting a crossflow through the cabin in addition to the flow through the companion-ways, forward and aft hatches, and the saloon's aft port. The inspection ports also provide access to the sheaves for the steering cables which will be routed under the berths and through the ventilation space to the cockpit.

The forward cabin (Figure 10) is the quiet section of the boat, isolated from the social center and designed to allow the off-watch crew to rest undisturbed. The arrangement of the berths is similar to the aft berths, but with less headroom - not quite three feet of sitting headroom is available at the forward bulkhead - although more sitting headroom is available at the cockpit bulkhead. Forward of the aka is the head/wet room, under the forward hatch. The sail locker is in the peak forward of the head. Additional sail stowage is available in the amas.

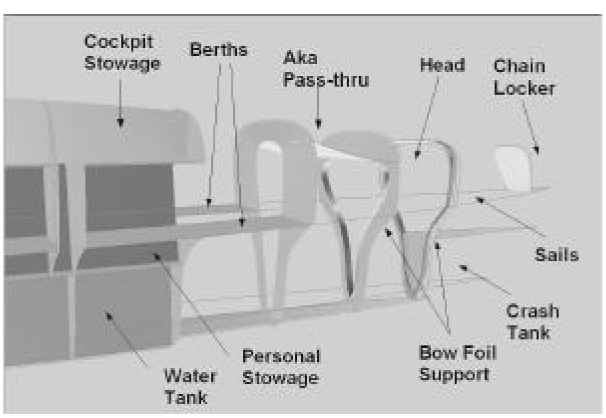

Fig. 10, Forward Cabin

The frame at the forward edge of the aka is a major load point, taking the loads of the aka attachment and the pivot for the bow foil. The current scheme for the aka attachment has transverse bolts going through ears on the akas to the forward bulkhead on each side. At the aft center of the aka, horizontal and vertical links connect the aka to the hull, with their bolts running fore and aft. This results in a statically determinant connection to the hull, avoiding internal stresses and facilitating alignment of the hulls. A tray-like structure is inset into the deck to form a notch for the aka, and the web forming the aft side of the tray stiffens the structure to take the loads of the vertical link. The frame forward of the head picks up the remaining bow foil attachment point.

The forestay attaches to the aft bulkhead of the chain locker rather than to the stemhead. This bulkhead distributes the load into the hull. In conjunction with a folding bow pulpit, this results in a less obstructed entry and exit to the boat when tied bow-on to a quay. Mooring stern-on is not suitable due to the presence of the stern foil and its supporting structure.

The center cockpit configuration assures the crew weight will be kept near the center of gravity, since most of the time is spent in the cockpit rather than inside. The proximity of the cockpit-stepped mast means that all of the sheets and halyards plus the steering is close at hand. There is little need for a single-handed sailor to have to leave the cockpit, and as pointed out by Brown (Brown, 1979), this is especially true as conditions get worse, ensuring that the crew remains safe and protected in the cockpit.

Not visible in the pictures is the flammables locker. The cockpit sole is a grate and underneath on either side of the centerboard trunk is a well where propane and gasoline will be stored. Fuel for the stove and outboard will be close at hand but isolated from the living areas of the boat.

Generously sized tubular scuppers, molded into the bottom of the under berth storage areas, will run from the wells outboard to the hull. In addition, openings in the side of the centerboard trunk will allow the cockpit to drain into the trunk. This arrangement ensures that the cockpit will stay dry and will empty quickly when pooped.

Hydrofoil Arrangement

The hydrofoils are shown extended in Figure 3 and retracted in Figure 11. The "diamond" arrangement consisting of a bow foil, two lateral foils, and a stern foil was pioneered by Keiper and is ideally suited for a sailing hydrofoil. When flying, the windward lateral foil is completely out of the water.

Figure 12 shows a concept used by Nord Embroden (Embroden, 1987) to analyze the static stability of landyacht planforms. The idea is to sum up the total

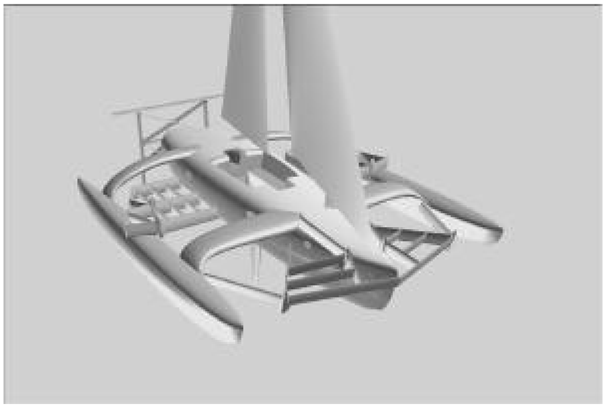

Fig. 11, Trimaran, Foils Retracted

moments in roll or pitch and then represent them as an equivalent movement of the center of gravity (c.g.) in the horizontal plane. The equivalent c.g. arm is obtained by dividing the moment by the weight. This provides an intuitive measure of stability because capsize occurs when the equivalent c.g. reaches the extremes of the vehicle's range of centers of buoyancy, such as the outer hull. The concept is especially useful for examining the sideways capsize vs. pitchpole stability of multihulls.

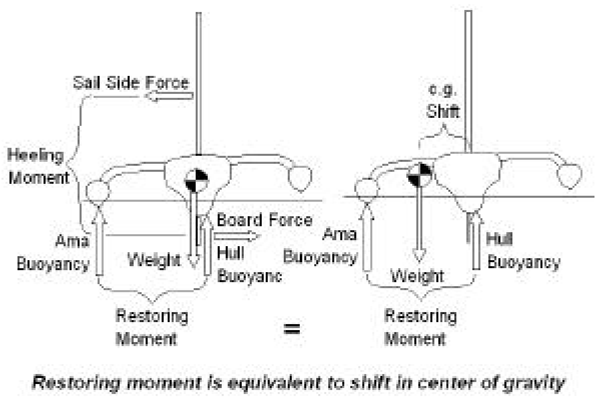

Fig. 12, Equivalent CG Concept

Figure 13 illustrates the concept applied repeatedly to the *Basiliscus* configuration and the results overlaid to integrate stability and performance information. The nominal center of gravity is indicated by the symbol located near amidships. Since three foils are in the water, the support is statically determinant and the relative loading of the foils can be estimated for any location of the equivalent center of gravity. This is indicated by the grid of straight lines, representing the linearly dependent nature of the foil loads.

The heavy black curves represent the moments due to the sail forces at all apparent wind directions and at apparent wind speeds ranging from 10 kt to 30 kt, based on 800 ft^2 of sail area. These curves are based on the Milgram sail force model as presented in (Larsson and Eliason, 1994). The 25 kt curve just reaches the ama, indicating that when hullborne this is the maximum wind that can be sustained with full sail without capsizing. The 30 kt curve just reaches the center of the lateral foil, indicating that the boat would be just balanced on the lateral foil under at that condition.

The final set of curves superimposed on the picture corresponds to hydrofoil performance. The hydrofoil side and resistance forces must equal the forces applied by the sail. A certain amount of drag is incurred just supporting the weight of the craft. This is represented by a lift/drag ratio. An additional drag is incurred as the foils generate side force, and the incremental drag for each pound of side force was arbitrarily assumed to be twice that due to a pound of vertical lift on the basis that the depth of the hydrofoil is typically less than the span. With these assumptions, the dashed lines representing the moments due to sail forces required to overcome the hydrofoil drag and side force were plotted for a range of hydrofoil lift/drag ratios.

The resulting picture establishes an excellent idea of the hydrofoil requirements. For example, it is clear that the craft is not likely to fly in apparent winds much less than 15 kt, no matter how efficient the hydrofoils are. If the hydrofoils have a lift/drag ratio (L/D) of at least 12:1, the craft could fly at 15 kt, but only with the net sail force pointing straight ahead, which would probably correspond to sailing off the wind a little below a beam reach. With 20 kt of apparent wind, the craft could fly with hydrofoils with an 8:1 L/D, and could fly to windward if the hydrofoils had an L/D of 12 or above.

In terms of pitchpole stability, the 30 kt curve just reaches the line for zero load on the stern foil. Any additional moment results in the stern foil carrying a down load. It is important, therefore, that the stern foil be designed for negative lift coefficients as well as positive lift. It is also apparent that the stern foil is unlikely to carry more than one third of the weight. However, it must be able to do so at the comparatively low speeds corresponding to takeoff in marginal conditions.

Finally, this analysis makes certain design optimizations straightforward. The diamond hydrofoil arrangement is seen to decouple the pitch and heave characteristics from the roll balance. The longitudinal location of the lateral foil was chosen to maximize the roll stability in high winds, and it is also positioned so that the relative proportion of the loads carried by the bow and stern foils remains about the same as the heeling moment increases. When hullborne at low angles of heel, both lateral foils are in the water and contributing lift. However, this lift is near and ahead of the physical center of gravity so the effect of a change in support from the lateral foils as the vehicle rises up is a small but stabilizing (bow down) change in the pitching moment.

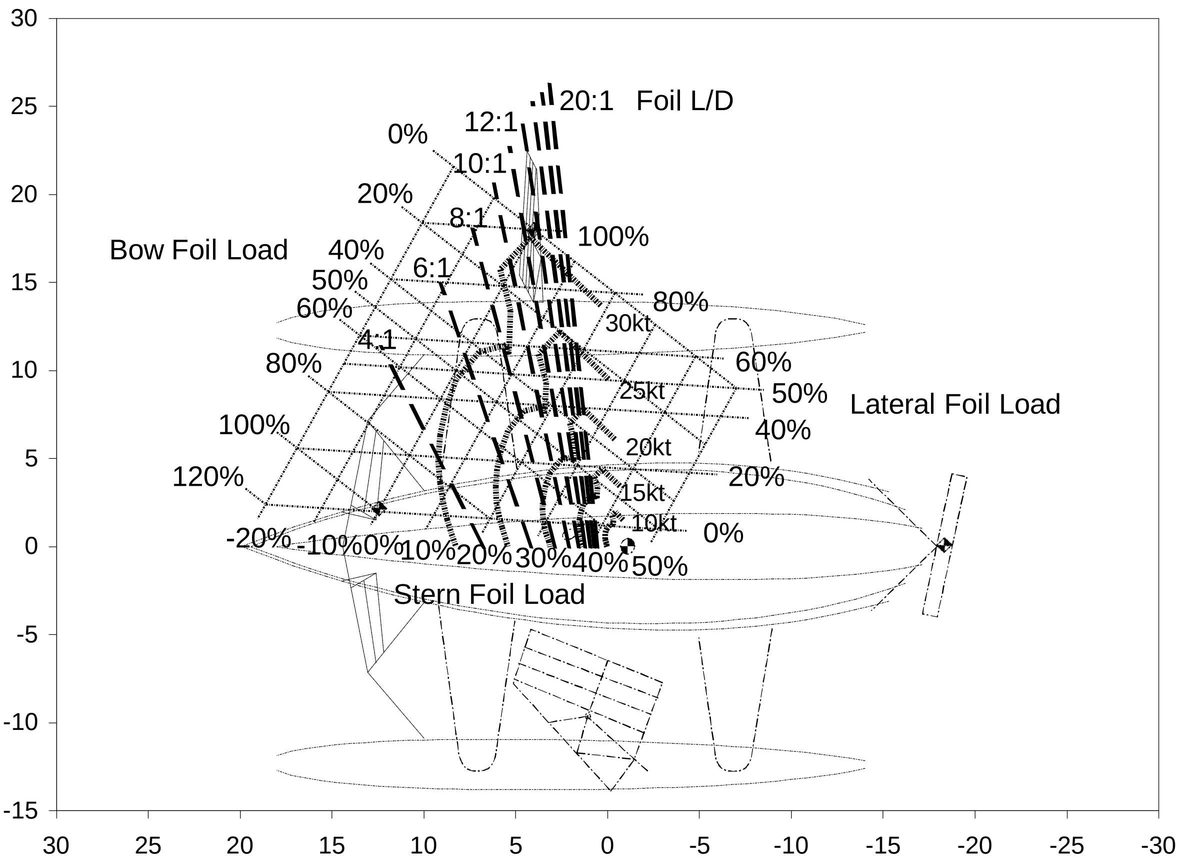

Fig. 13, Hydrofoil Balance

The most unsatisfactory aspect of the baseline design is the stern foil (Figure 14). The stern foil must rotate about the vertical axis for steering and a horizontal axis for retraction. The transverse axis is currently selected for retracting the foil, allowing the foil to rotate forward and aft. Besides retracting the foil, this freedom of motion also allows the pitch of the stern foil to be adjusted.

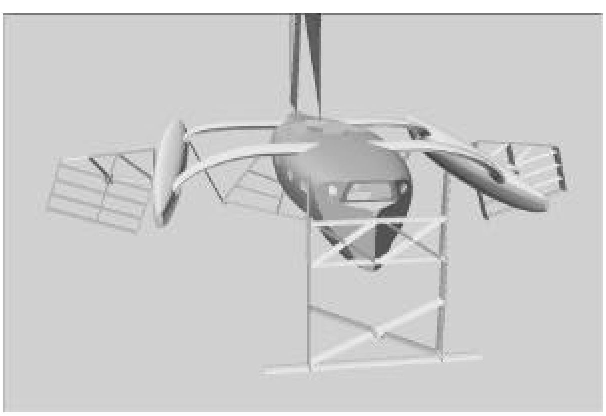

Fig. 14, Stern View

A fully submerged foil provides the most stability. Such a foil would be the sole determinant of the pitch of the craft when flying because pitch is the only degree of freedom available for the stern foil to reach equilibrium with its applied loads. The heave of the main hull would then be determined by the bow foil. So it is more important that the stern foil incidence angle be adjustable than it is for any other foil.

To avoid interference with the hull, the vertical support has been divided into two struts, forming an inverted "π" foil. Preliminary calculations indicated that the required area could not be practically achieved with a single element of the same chord as used for the bow and lateral foil ladders, requiring the addition of two more elements. These have been arranged in an "X" configuration to provide for a smooth variation in area as they broach the surface and to brace the struts diagonally to stiffen them against side loads. Horizontal ladder rungs could lead to a limit cycle oscillation as the lift on the stern foil changed in discrete steps unless the rungs were closely spaced so that the heel angle alone was sufficient to cause successive rungs to overlap.

These design aspects drive the stern foil support to be a large truss. The truss is heavy, ugly, produces windage, and could be susceptible to large loads when being pooped. This was the configuration Keiper used on *Williwaw* and the author has tried unsuccessfully to find a suitable alternative configuration. The truss will be much wider and more unwieldy on *Basiliscus* compared to *Williwaw* because of the wider aft cabin.

In addition, the cross elements do not allow the stern foil to rotate forward of the retracted position, which inhibits the rudders from kicking back when grounded. So shoal waters will have to be negotiated with the stern foil down - not a very palatable prospect. Shoal draft can be obtained by shortening the rudders, as was done on *Williwaw*. Keiper found his shallow rudders lacked adequate control under some conditions. Other alternatives are being investigated, including the possibility of a fixed (but retractable) stern foil and separate steering or using kick-up rudders in the amas.

HYDROFOIL DESIGN TRADE STUDIES

Hydrofoil Section Design

Three two-dimensional hydrofoil sections have been investigated. These are the NACA 63-209, Eppler E817, and the author's H105 design. These are shown in Figure 15. The NACA 63-209 has a thickness of 9% of the chord, the Eppler E817 11%, and the H105 12.5%.

The NACA 63-209 is one of the 6-series laminar flow airfoil sections designed by the National Advisory Committee on Aeronautics during World War II. The 6-series airfoils were designed to produce a uniform velocity from the leading edge back to a specified location (given by the second number in the designation), and then a linear decrease in velocity to the trailing edge - the recovery region. This flat "rooftop" velocity distribution can be seen in the upper surface velocities at three degrees angle of attack (relative to the zero lift line) and in the lower surface velocities at one degree angle of attack (Figure 16).

In between these limits, the section has a favorable pressure gradient back to the beginning of the recovery region, promoting laminar flow and creating the low drag "bucket" characteristic of its drag polar. A constant velocity distribution is also of value in a hydrofoil because cavitation occurs when the local pressure falls below a limiting value, and the constant velocity distribution minimizes the maximum velocity and thus the potential for cavitation.

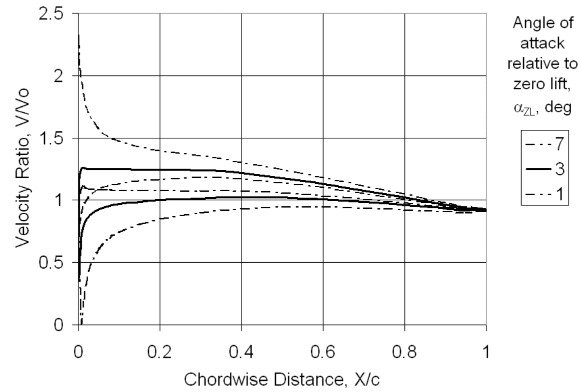

Fig. 16, NACA 63-209 Velocity Distribution

Bringing the constant velocity clear to the leading edge creates a problem, however, because at angles of attack above the design condition the velocity peaks very strongly at the leading edge, as can be seen by the distribution for 7 degrees angle of attack (Figure 16), where the local velocity is more than double the freestream velocity. The rapid deceleration following this peak promotes boundary layer separation. And the high velocities themselves promote cavitation.

The Eppler E817 section was specifically designed for use as a hydrofoil (Eppler, 1990). Preventing cavitation over as wide a range of operation as possible was the key design requirement. This section also has a very long flat rooftop velocity distribution, as can be seen at its upper surface design condition of 5 degrees angle of attack and lower surface design condition of 1 degree angle of attack (relative to the zero lift line). The velocity distribution is rounded somewhat at the

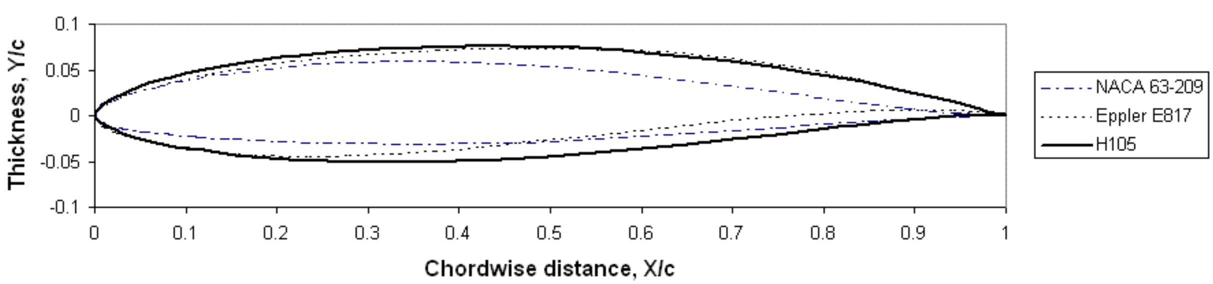

Fig. 15, Hydrofoil Section Shapes

leading edge which reduces the formation of the leading edge suction peak compared to the NACA 63-209 (Figure 17). The slightly concave recovery region is much shorter and steeper than that of the NACA 63-209 and the section has a significant amount of aft loading. This results in a hooked, under-cambered trailing edge.

The Eppler E817 was not intended for use at low Reynolds numbers, such as might be experienced by the subscale prototype, where laminar separation must be considered. At 12 kt, a three-inch wide hydrofoil would be operating at a Reynolds number of 360,000, while a one-foot chord operating at 17 kt would have a Reynolds number of 2,000,000. So a new section was designed to perform well at Reynolds numbers as low as 250,000 while still having low drag and minimal susceptibility to cavitation.

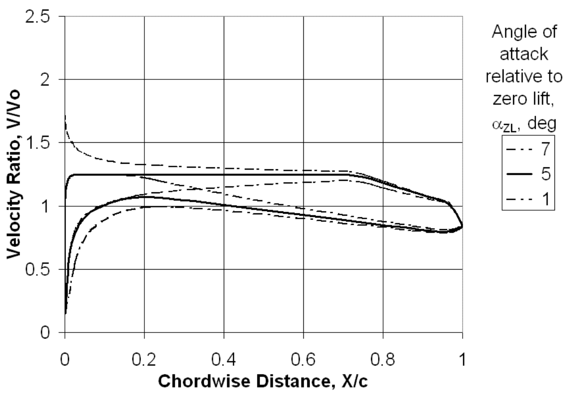

Fig. 17, Eppler E817 Velocity Distribution

The new section was designated the H105, the H indicating it was designed for use as a hydrofoil and the number being arbitrary. It takes a completely different approach to either the E817 or NACA 63-209. Instead of a flat roof-top followed by an abrupt transition to the recovery region, the upper surface velocity distribution has a shallow adverse pressure gradient to a well rounded transition, turning the entire surface into a boundary layer transition ramp (Figure 18). Since laminar separation is unavoidable at low Reynolds numbers, this velocity distribution ensures that the laminar separation region will reattach in a short distance as a turbulent boundary layer, and that the position of this separation bubble will move smoothly forward as the angle of attack increases, providing a turbulent boundary layer for a robust pressure recovery. The velocity distribution is also more rounded at the leading edge than the E817, reducing the leading edge suction peak even more and making for a more forgiving section. The H105 has less aft loading than the E817, resulting in a front-loaded section with a near-constant load over much of the chord.

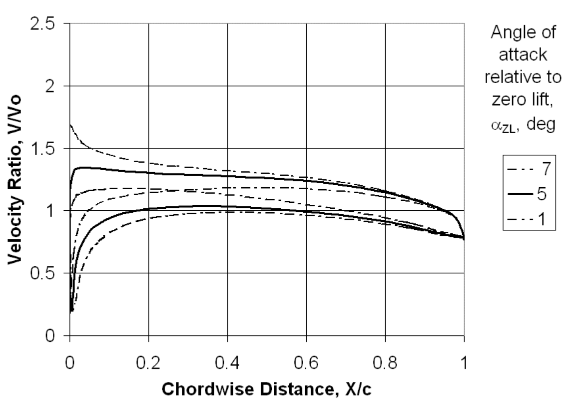

Fig. 18, H105 Velocity Distribution

Figure 19 shows the lift curves predicted by the Eppler airfoil analysis code for the three sections a three Reynolds numbers: 250,000, 1,000,000 and 3,000,000. All of the sections have a sharp stall, indicative of leading edge separation. The H105 high lift characteristics were intentionally traded off in favor of cavitation resistance, however, it still has a higher maximum lift than the other two.

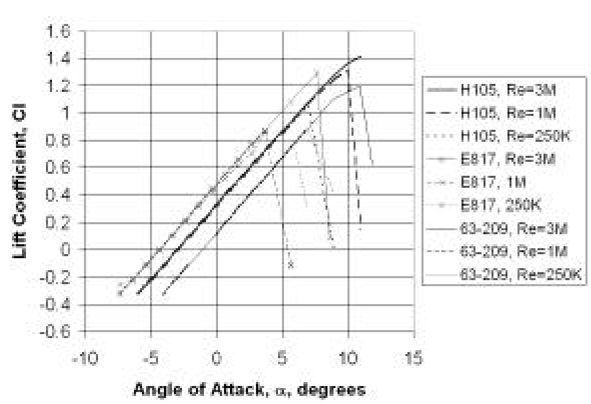

Fig. 19, Section Lift Curves

The drag polars for the same three Reynolds numbers and all three foils are shown in Figure 20. Compared to the NACA section, the low drag bucket of the modern sections is nearly doubled in width. At the highest Reynolds numbers, all three sections have essentially the same drag at a lift coefficient of 0.2, and the Eppler section's profile drag actually decreases towards its upper design range. The H105 section has a more rounded drag bucket but with near constant profile drag across the center as a result of the laminar to turbulent transition point moving forward on the upper surface while simultaneously moving aft on the lower surface, thus maintaining nearly the same total amount of laminar flow.

Cavitation occurs when the local pressure on the foil surface drops below the vapor pressure of water, causing the water to boil and form bubbles in the flow. At the lowest speed at which this can occur, the incipient cavitation speed, the bubbles are microscopic and quickly collapse without effect. As the speed increases, the bubbles become larger and more persistent, causing flow separation and surface damage when they collapse next to the surface. The collapse is triggered by bubbles passing from the region of low pressure in which they formed to one of higher pressure, and the damage is caused by extremely high pressures from the impact of tiny high velocity jets of water formed as the bubbles collapse.

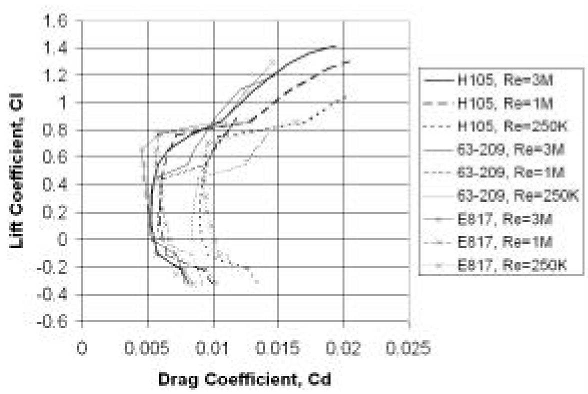

Fig. 20, Section Drag Polars

The key to controlling cavitation is to keep the maximum velocity that occurs on the hydrofoil below the limit at which cavitation can occur, or at least below the level at which cavitation has a significant effect. The maximum velocity, as a ratio between the local velocity and the freestream, is plotted versus lift coefficient for the three sections in Figure 21. The NACA foil has the smallest envelope, due to its strong leading edge suction peak. The Eppler foil has the lowest maximum design velocity within its design envelope. At low lift coefficients the H105 is as good as or better than the Eppler section, but it trades a little velocity at the upper end of the design range. Above the design range, the H105 foil has less cavitation susceptibility than either the Eppler or the NACA sections.

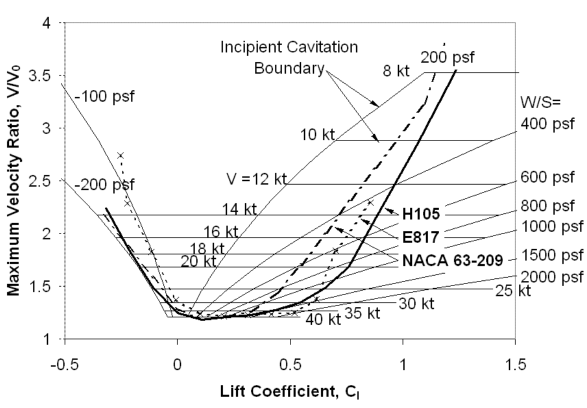

Fig. 21, Maximum Section Velocity

The significance of the velocity envelope can be judged with reference to the grid overlaid on the plot. These indicate the onset of cavitation - the incipient cavitation boundary. Cavitation cannot occur if the local velocity is below 27 kt at a given boat speed. The horizontal lines show the incipient cavitation boundary corresponding to a given freestream velocity. However, for steady flight the speed and the lift coefficient are linked. This is indicated by the lines of constant foil loading - the lift (or weight carried) divided by the planform area.

The vertical distance between the section's maximum velocity curve and the incipient cavitation lines represents a sort of cavitation margin. The velocities indicated by the section curves are the best that can be obtained. Actual velocities will be higher due to interference effects in areas such as the junction between foil and strut. This can cause local regions of cavitation, causing damage to the foils, added drag, and triggering ventilation leading to massive loss of lift.

A fully submerged foil cannot change its area and its lift must equal the weight it supports. Therefore, a fully submerged foil will experience its cavitation boundary closing in on it along one of the constant foil loading lines. Cavitation is normally thought of as a high speed phenomenon, but for heavily loaded foils the cavitation boundary actually intersects the section curve at two points. One is at low lift coefficients and high speed. The other is at high lift coefficients and low speed, where cavitation is caused by the leading edge suction peak. This can lead to separation and ventilation.

As the foil loading increases, the available cavitation-free range of operation shrinks. For the NACA 63-209, cavitation free operation is not possible above a foil loading of 450 pounds per square foot. The H105 has no cavitation-free zone much above 600 psf, while the Eppler E817 can go as high as 700 psf. However, the more likely region of operation is at lift coefficients of around 0.3 to 0.5, and in this range there is little difference between the H105 and E817. Completely cavitation free operation is also not possible above 22 knots for any of the foils, and there is only about a one knot difference in the cavitation speed over the design operating range.

A surface-piercing foil tends to operate at a constant lift coefficient if the craft maintains a level attitude, so the incipient cavitation boundary moves vertically downward with speed, as indicated by the horizontal grid lines. The foil loading is increasing all the while because of the reduction in area as more of the foil leaves the water. The surface piercing foil will not experience cavitation at low speed because it does not operate at high lift coefficients. Based on a combination of drag and cavitation considerations, a good operating point for an H105 surface piercing foil would be in the range of a lift coefficient of 0.3 to 0.4.

The H105 hydrofoil section is predicted to be an excellent all-round design for a hydrofoil. It has good thickness for structural strength, low minimum drag, a wide minimum drag range, good behavior outside the design range, is highly cavitation resistant, and can operate at low Reynolds numbers.

The other conclusion is that for a practical design having foil/strut junctions, etc., any speed above 18 - 20 kt will have some degree of cavitation present.

Baseline Hydrofoil CFD Studies

The general hydrofoil balance and system performance requirements were shown in Figure 13. The lateral foil must be designed to take from 0% to 100% of the total weight (7000 lb), and will operate in the vicinity of 50% of the weight for apparent wind speeds between 20 and 25 kt. The bow foil will generally carry 20% to 60% of the weight. The stern foil is more lightly loaded when flying, carrying approximately 20% of the weight, but must be capable of producing negative lift to avoid pitchpole. The foils in aggregate must have a lift/drag ratio of 12 or more to meet the goal of flying to windward. A generic hydrofoil trade study identified induced drag as the most important component for drag reduction, and established the ladder foil and inverted T foil as the most promising types.

The next step was to examine the baseline hydrofoil configuration. This was done using the Cmarc panel code. Multisurf was used to determine the intersections between the hydrofoil elements and the water surface, and patch files were output for each surface. These were assembled to create a Cmarc input deck for each combination of hydrofoil unit, heave, and roll. The panel code models varied from 500 panels to over 5000 panels, depending upon the degree of immersion. Straight wakes aligned with the freestream were used with no roll-up.

Each hydrofoil unit was evaluated at hull vertical displacements of one, three, and five feet and roll attitudes of zero, five, ten, and 16 degrees. Eight runs were made for each to establish the basic lift and drag and the derivatives with respect to angle of attack, sideslip, pitch rate, roll rate, and yaw rate. The basic coefficients and lift and drag derivatives will be used in the VPP. These data plus the angular rate derivatives will be used in the dynamic analyses.

Figure 22 shows some of the panel code models and the resultant local velocities. Quite visible are the regions of elevated velocity near the intersections. These are the areas which will be affected first by cavitation. Also evident is the highly nonuniform loading of the lateral foil elements, leading to unexpectedly high induced drag.

The highly variable geometry as a function of the operating condition has required a different approach to building the tables of aerodynamic coefficients. Instead of tables of lift, drag and sideforce coefficients, lift, drag and side force areas are used instead. These areas are defined as:

3) $$S_L = \frac{L}{q} = C_L \cdot S$$

4) $$S_D = \frac{D}{q} = C_D \cdot S$$

5) $$S_Y = \frac{F_Y}{q} = C_Y \cdot S$$

A similar approach is taken with moments, yielding effective volumes about each axis.

Although dimensional, with units of ft^2, they can be treated much like nondimensional coefficients. A good example is the estimation of the effective span, b_e from the slope of a plot of S_D vs. $S_L{}^2$:

6) $$C_{Di} = \frac{C_L{}^2}{\pi \ AE}$$

7) $$S_{Di} = \frac{S_L{}^2}{\left[\pi \cdot \left(b^2 \cdot E\right)\right]}$$

8) $$b_e = b \cdot \sqrt{E} = \sqrt{\frac{S_L{}^2}{\pi \cdot S_{Di}}} = \sqrt{\frac{S_{L2}{}^2 - S_{L1}{}^2}{\pi \cdot \left(S_{D2} - S_{D1}\right)}}$$

Once the effective areas and volumes are computed for a given configuration, they will be sized linearly with the chord to adjust them for best performance. More extensive geometry changes, such as changing the span or the number of elements will require fresh computation using the panel code.

Preliminary results of the panel code analysis are shown in Figures 23 through 28. The axis convention adopted throughout the *Basiliscus* project is X positive forward, Y positive starboard, and Z positive down, referenced to amidships, design waterplane centerline. So lift in the upward direction is a negative Z force and drag produces a negative force in the X direction.

The bow foil lift and drag as a function of roll and angle of attack at the takeoff height of one foot is shown in Figure 23. The straight lines on the drag area vs lift area-squared plot show that the induced drag follows the classical parabolic drag polar, as expected based on the linear aerodynamics of the panel code. Figure 24 shows the bow foil lift and drag for the bow foil at 10 degrees of heel as a function of height and angle of attack.

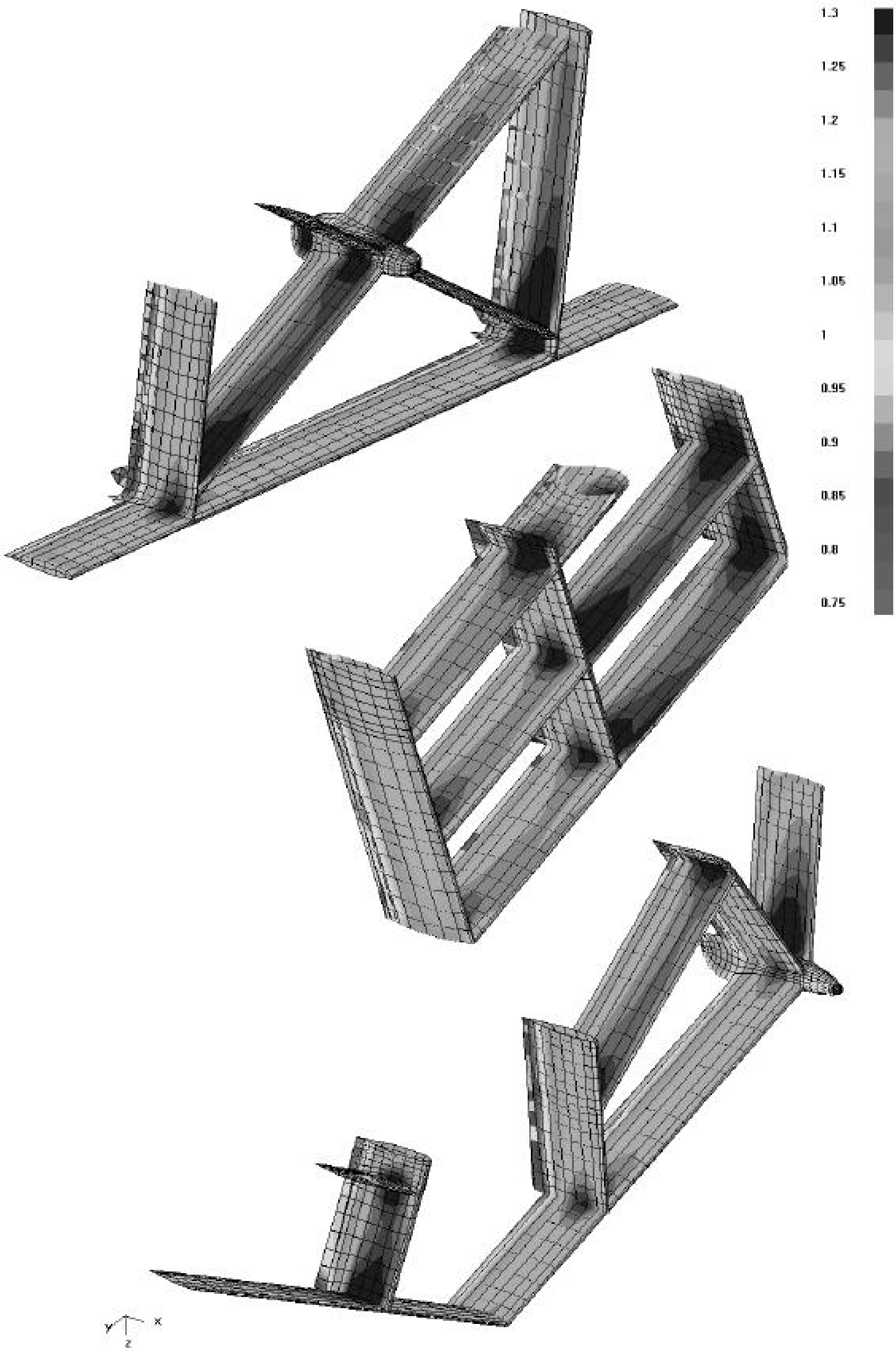

Fig. 22, Foil Surface Velocity Ratios
Z = -3 ft, Roll = -10 degrees, Alpha = 2 degrees

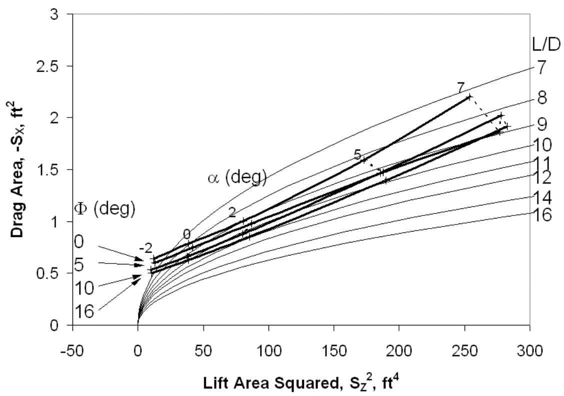

Fig 23, Bow Foil Drag Polar
Z = -1 ft

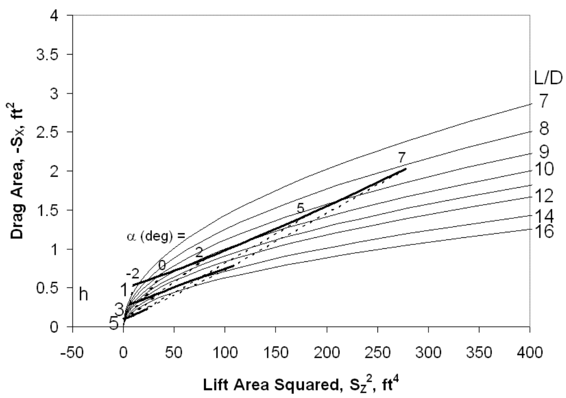

Fig 24, Bow Foil Drag Polar
Roll = -10 degrees

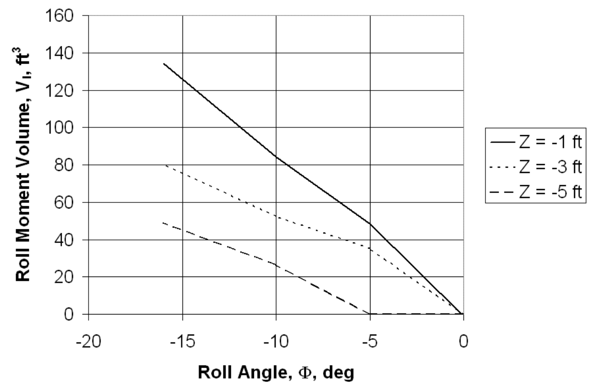

Fig 25, Lateral Foil Roll Moment Volume

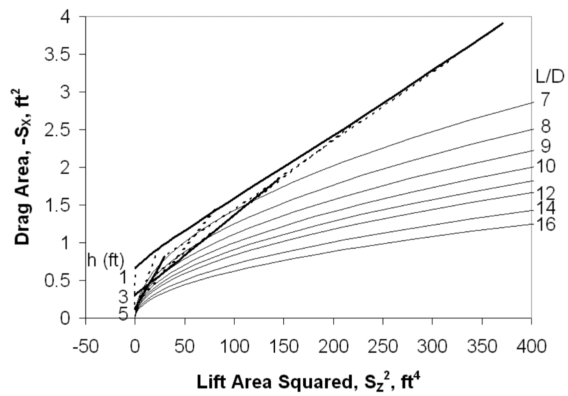

Fig 26, Lateral Foil Drag Polar
Roll = -10 degrees

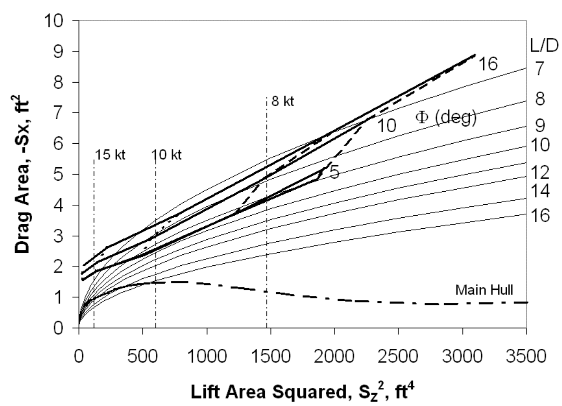

Fig 27, Total Drag Polar
Z = -1 ft

The bow foil does not quite meet its requirement for an L/D greater than 12 in the takeoff condition, but it does have adequate performance after takeoff. Optimum angle of attack is seen to be near two to three degrees at all heights.

Figure 25 shows the strong increase in rolling moment due to the lateral foil as a function of heel, as increasing amounts of lateral foil are immersed. The drag characteristics of the lateral foil, shown at 10 degrees of heel in Figure 26, are quite different from those of the bow foil. The lateral foil is seen to produce excessive drag at all heights. When deeply immersed, it has high profile drag due to its large wetted area. At shallow immersion it has high induced drag. The lateral foil falls well short of the performance requirement.

Total lift and drag for all three foils at the takeoff condition is shown in Figure 27. The stern foil incidence was set to trim the craft in pitch at a height of three feet and an angle of attack of two degrees. If the craft is allowed to pitch up to 5 degrees, it can take off at 8 kt. At two degrees angle of attack, 10 kt.

The drag of the main hull is shown as the dashed-dot line for comparison. The drag of the hydrofoils is several times that of the hull at the takeoff condition. At three feet elevation (Figure 28) the drag is still higher than the hull, but at five feet elevation, the drag is less than the hull. This implies that the foils have too much area, and should be designed with a smaller chord to take off at a higher speed with a higher angle of attack.

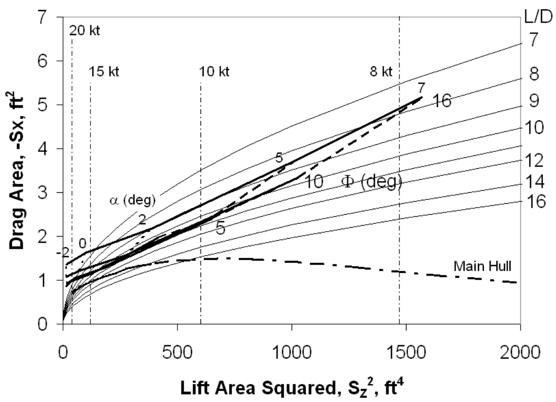

Fig 28, Total Drag Polar
Z = -3 ft

CONCLUSIONS

The *Basiliscus* project is well on the way to producing a cruising hydrofoil sailboat. The overall requirements have been defined, the basic program plan is in place, and preliminary design is underway.

The baseline design consists of a contemporary cruising trimaran configuration with ladder foils. The ladder foils were selected on the basis of their ability to produce adequate performance, their structural strength, mechanical simplicity, and insensitivity to ventilation.

CFD modeling of the foils has shown that the baseline design does not yet meet the requirements, but there are no fundamental obstacles. Additional work is needed to improve the lateral foil design. Takeoff for the baseline design requires 18 - 20 kt of wind (Force 5) and occurs at 9 - 10 kt of boat speed.

The design will be refined based on the VPP and dynamic analyses to produce a craft that will meet the three cardinal requirements: an affordable, flying cruiser.

ACKNOWLEDGEMENTS

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