An Autonomous Wing-Sailed Catamaran
Ph.D.Thesis by Gabriel H. Elkaim

The following information has been extracted from the thesis submitted by Dr. Gabriel Elkaim to Stanford University, and for which he was awarded his Ph.D. The full thesis, which can be viewed at http://www.soe.ucsc.edu/~elkaim/Documents/GabrielElkaimThesis01.pdf *(and an extract published in the AYRS's Journal 'Catalyst' which can be found at* http://www.soe.ucsc.edu/~elkaim/Documents/Catalyst_BoatArticle.pdf), *describes the Atlantis project, whose aim was the design, development, and experimental testing of an autonomous wind-propelled marine craft. The parts printed here are the ones which may be of interest to members of the JRA*

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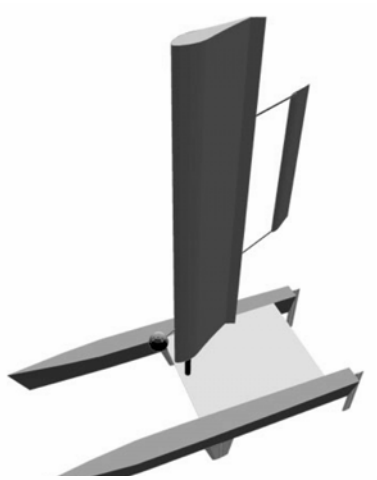
Please note that the figures are numbered as in the original document.

The Wingsail

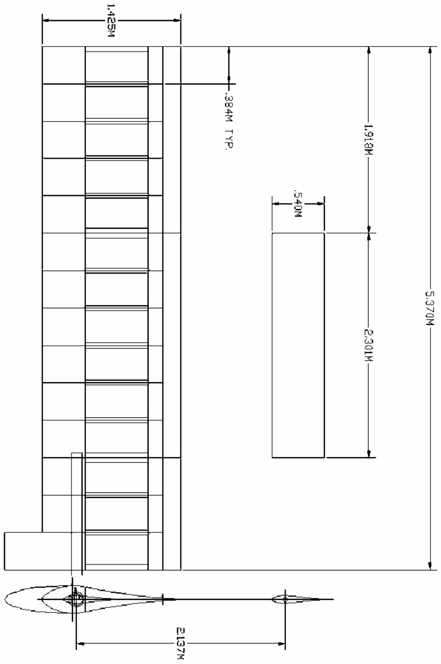
The most visibly unique aspect of the Atlantis project is the wingsail propulsion system, as shown in Figure 5-1. The design considerations and goals are: equivalent performance to the original sail system, low actuation force, and the ability to precisely control the resulting system.

A sloop rig sail can achieve a maximum lift coefficient of 0.8 if the jib and sail are perfectly trimmed. Realistically, an operating maximum lift coefficient is 0.6. The design goal of the Atlantis wing is to achieve a maximum lift coefficient of 1.8. Since this allows the wing to generate three times the force of an equivalently sized sail, the wing area is reduced to one third of the area of the original sails. Because the drag characteristics of the wing are much improved, the performance of the wingsailed catamaran should be superior to the original configuration.
At worst, the wing will yield equivalent performance.



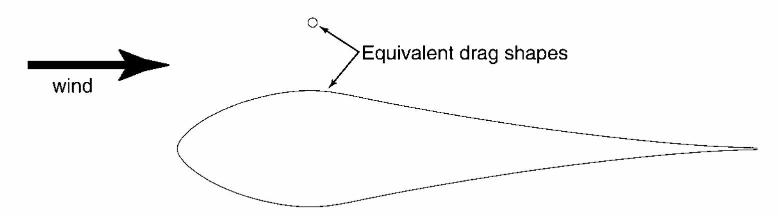
Wingsail Description

The chosen wingsail is 5.37 meters tall and has a chord of 1.45 meters. ------ The wingsail is built entirely of marine grade plywood covered in polyester fabric and is suspended by a spherical roller bearing at the top of the stub-mast. It is stabilized by a needle roller bearing around the stub-mast at the bottom of the wing. This allows the wing to rotate freely through 360 degrees without significant resistance. An engineering diagram of the wing is shown in Figure 5-3.



Wing Versus Sail

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



Airfoil Section Design

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

It is desirable for the section to achieve a maximum lift coefficient of 1.8 at a Reynolds number range of 200,000 to 250,000. This can be aided by a simple plain flap of constant flap/chord ratio. -------------- First, in order to achieve the high lift coefficients at low Reynolds numbers, a very thick section is required, where the entire lift is generated on the forward section, typical of the Liebeck “rooftop” sections. The boundary layer requires a trip-strip that will force the transition from laminar to turbulent, placed symmetrically on the top and bottom surfaces. Typically, these trip-strips are a thick material with a zig-zag leading edge that is affixed to the surface at the desired location. The zig-zag causes a small-scale vortex to form which pulls in the higher energy flow outside of the boundary layer, and though viscous drag increases, separation (and thus form drag) is delayed.

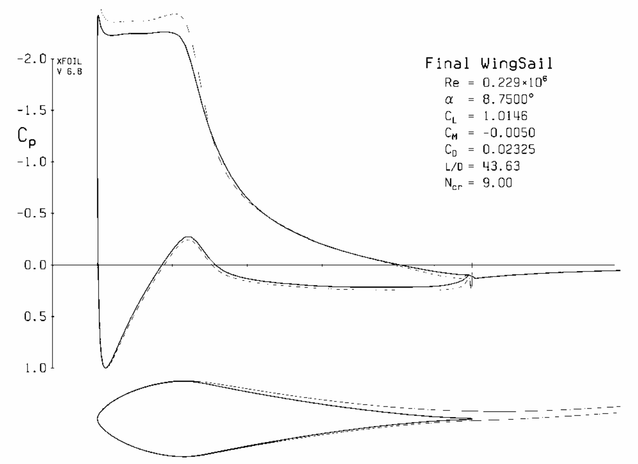
In addition to the short, flat pressure distribution on the section, the entire aft portion of the section is given to pressure recovery of the flow preventing flow separation from the section surface. Thus the back three quarters of the section do not contribute at all to the lift, but merely ensure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

For space reasons it was considered necessary to leave out the section on Reynolds Number Effects, which indicated the shortage of data available. It also referred to the relationship between model aircraft and sails, and their requirement for high lift/drag ratios. Using modern airfoil design techniques a symmetrical section and a simple plain flap was designed to achieve a maximum C_L *very close to that of an asymmetrical section.*

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

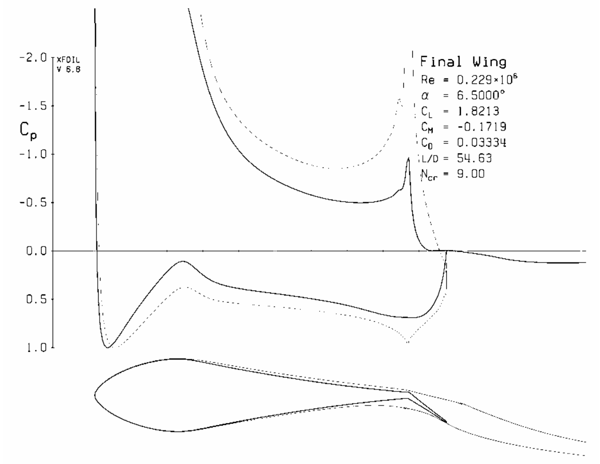
Close inspection of the section will show that the post boundary trip curvature is in fact concave. -------.

Again, it is important to point out the salient features of the pressure distribution shown in Figure 5-10. Observe the flat top of the pressure distribution, corresponding to a uniform suction on the



upper front surface. The pressure begins its recovery just after the trip strip located at the 22% chord point and very smoothly recovers back to free stream pressure without separation. Note that the flow is actually accelerating on the lower surface below the stagnation point. This causes the upward slope of the lower line in the pressure distribution, indicating some suction existing at the maximum chord point of the final wing section. Also, just after the trip-strip lies a very smooth pressure recovery all the way to the rear point of the airfoil section. Reemphasizing, there are no laminar separation bubbles and no turbulent separation. This airfoil section is not close to stall but will stall gently from the rear progressing forward, resulting in a very gradual loss of lift and increase in drag. This is important due to the varying nature of the wind. When the wind is highly variable, a conventional section like the NACA 0015 will often abruptly stall and lose lift.

Flap/Chord Ratio



In order to increase the coefficient of lift of the main wing section a simple plain flap is used to increase the camber of the wing. Figure 5-13 shows the pressure distribution with the flap deployed at 45 degrees. Note that the flow separates off the back of the flap causing an increase in drag. Unfortunately, at these low Reynolds numbers, the flow cannot negotiate the curvature of the flap hinge regardless of where it is placed on the airfoil section. This means that the flow on the low pressure side of the flap will separate as soon as it is deflected more than a degree or so. With this constraint, the issue becomes one of trading the separated flow and subsequent drag for increased effective camber of the section and increased lift. Thus, the low Reynolds number pushes the design toward a very small flap/chord ratio and large deflection. In other words, a small trailing edge tab deflected a great deal will turn the flow enough to give effective camber, while giving the flow only the smallest area from which to separate.

After investigation, and remembering that for the special requirement of this project a small flap is desirable to keep the control forces from the drive motors small------ the optimum is found to be at 13%. The final shape for the main wing section is presented in Figure 5-13, with the flap-deflected 45 degrees.

R & D Secretary's comments.

I must apologize profusely to Dr. Elkaim for chopping up his most excellent thesis so brutally, but there are restrictions on the column inches available for R & D. I strongly recommend viewing the web sites mentioned at the beginning of the extract. The aim of printing these extracts is to highlight *a number of very interesting points.*

1. *Note the large wingsail section with the same drag as the tiny cylindrical mast. Using a double-sided sail which enclosed the mast and running rigging can significantly reduce the overall drag, and have a very significant effect on windward ability.*
2. *To achieve a high lift/ drag ratio the camber is concentrated in the front 20% of the section, with the rear 75% being only used for pressure recovery.*
3. *The Lift/Drag (L/D) ratio of the Atlantis wingsail is in the 10 - 30 range, whereas the L/D of the conventional sail is in the 3 - 5 range.*