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An Autonomous Wing-Sailed Catamaran - Construction of the Wingsail

Gabriel H. Elkaim
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Is it a boat, a plane, something in between?

This presentation details [some of the work on] the Atlantis project, whose aim is the design, development, and experimental testing of an autonomous wind-propelled marine craft. Functionally, such a vehicle is the marine equivalent of an unmanned aerial vehicle (UAV), and would serve similar purposes. The Atlantis project has been able to demonstrate an advance in control precision of a wind-propelled marine vehicle from typical commercial autopilot accuracy of 100 meters to an accuracy of better than one meter with a prototype based on a modified Prindle-19 light catamaran. The project involves substantial innovations in three areas: windpropulsion system, overall system architecture, and sensors.

The wind-propulsion system is a rigid wing-sail mounted vertically on bearings, mass balanced to allow free rotation in azimuth about a stub-mast. Aerodynamic torque about the stub-mast is trimmed using a flying tail mounted on booms aft of the wing. This arrangement allows the wing-sail to automatically attain the optimum angle to the wind, and weathervane into gusts without inducing large heeling moments.

The concept of using a wing upon a sailboat has been around almost as long as aircraft themselves. Many previous designers have come to the false conclusion that adequate lift coefficient could only be achieved with an asymmetric (cambered) wing. [The analysis carried out for the Atlantis project showed that this was not necessarily so, and that adequate performance could be achieved by a symmetrical wingsail.] The design choices for the wingsail were presented in a previous article. This article describes the sail construction.

STRUCTURAL DESIGN

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

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

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

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

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

CONSTRUCTION

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

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

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

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

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

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

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

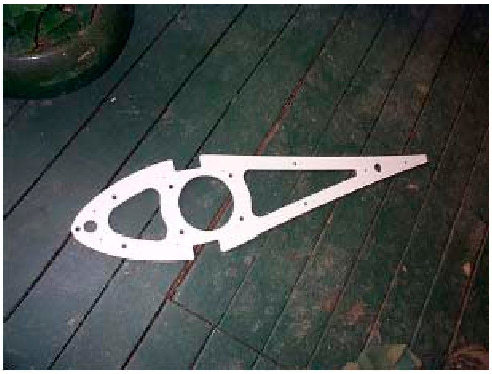

Figure 5-44 Master main wing rib template used to fabricate all wing ribs from marine grade plywood. The large holes are to lighten the ribs. The two medium sized holes forward and back are for a assembly onto a jib made of electrical conduit. The eleven small holes are for threaded rods that secure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

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

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

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

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

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

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

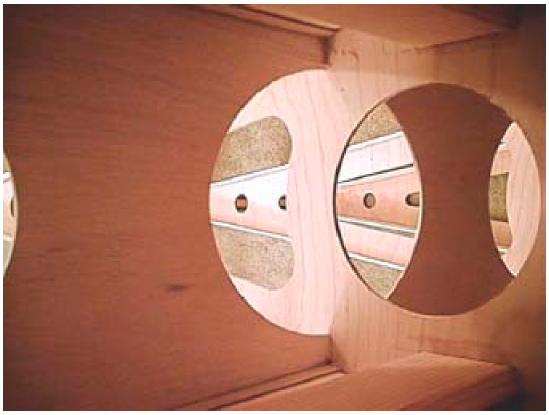

Figure 5-47 Plywood sheer webs join the leading edge skin and upper and lower spar caps. Lightening holes are cut in the sheer webs. Note the distance between the rear of the spar cap and the sheer web. This is because this is the lower section, and the stub-mast will fit just inside the circular opening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

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

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

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

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

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

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

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

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

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

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

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

Future Work: Experimental Measurement of the Wing Sail Performance

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

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

Future Ocean Crossing

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

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

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

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

References

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

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

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