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HYDROFOIL OCEAN VOYAGER "WILLIWAW"

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Abstract

The development, design, performance, and successful sea trials of the first hydrofoil sailing yacht are described. The 31-foot long hydrofoil trimaran "Williwaw" demonstrated outstanding all-around yacht performance in cruising to, in and around, and returning from, the Hawaiian Islands.

1. DEVELOPMENT

The sailing "bug" took hold of me in 1961, shortly after acquiring my first boat, a 20-foot keel-centerboard sloop. Its churning wake and difficulty in handling at its top speed of 7 knots led me to start thinking of better ways to utilize the power of the wind for moving across the water. My design efforts on hydrofoil multihulls began in 1962. During a South Pacific cruise in 1965 on my second boat, the 29-1/2 foot trimaran "Nimble #1" (formerly Art Piver's Transatlantic Trimaran), I was working on a hydrofoil trimaran design that promised the ultimate in sailing performance and comfort. Construction of my 31-foot prototype "Williwaw" began in May 1966 in my backyard along the Petaluma River at Black Point, California. Williwaw had a complete set of hydrofoils in November 1967, but the fickle winter winds made testing difficult. Williwaw first became fully foilborne in the Spring of 1968. In June 1968, we were managing to stay fully foilborne for a couple miles at a time averaging 18 knots while crossing San Francisco Bay.

The major problem encountered was not with the hydrofoils, but with the pontoons. At first, Williwaw's pontoons only had a useful buoyancy of 20% of the craft weight. While moving fast, the hydrofoils gave tremendous stability. However, while stopped or moving slowly with sheets hauled in, wind gusts had a habit of laying Williwaw over to extreme angles of heel. In early tests I generally had 4 or 5 crew members standing on the windward deck. After one capsize while stopped, pontoon buoyancy was increased to 40% of craft weight. Ballast weight in the main hull was tried, but it only led to the boat wallowing too much and having difficulty taking off. After a capsize while beating slowly to windward with gale gusts, a masthead float was installed. After a 500 mile shakedown cruise off the California coast in strong winds and heavy confused seas, pontoon buoyancy was increased to 70% of craft weight and the craft widened slightly. This made the craft much easier to handle in gusty winds and in beating to windward. It was no longer necessary to ease sheets in most gusts.

In September 1970, we (one crew member and myself) made a voyage from Sausalito to Kahului Harbor, Maui, Hawaii. Strong winds and 15 to 20 foot seas were encountered at the beginning. The idea of racing to Hawaii was abandoned at dusk the first day when we sighted heavy floating debris. Sail reduction halved our 15 knot speed average that night. Light variable winds and calms in midocean, and having only working sails, held us back further. Frequently we left the foils set in choppy seas when there were inadequate winds to fly, in order to gain comfort and self-steering (at the cost of some speed). The voyage took 16 days. We both would describe it as an easy voyage, for the hydrofoils helped Williwaw self-steer 90% of the time, and contributed considerably to comfort and control.

2. DESIGN

The design approach on Williwaw was to use a fixed, but retractable (see Figures 1 and 2), foil system. Dynamic stability was to be inherent in the foil configuration. Gadgetry and moving parts were avoided, because they would tend to wear out, corrode, and malfunction. It was desired that the person sailing the craft would have no more controls to operate than a conventional sailing craft.

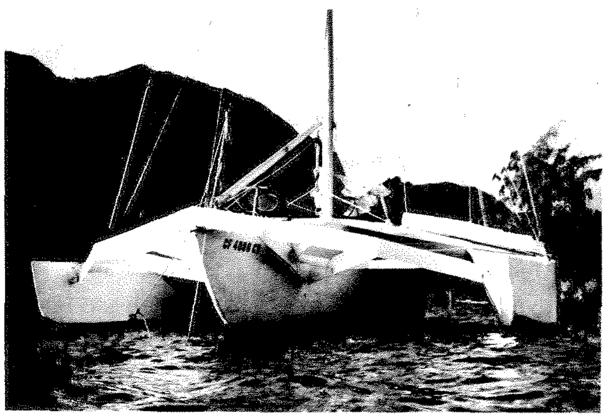

FIGURE 1

WILLIWAW ANCHORED IN NAWILIWILI BAY, KAUAI, WITH HYDROFOILS RETRACTED. BOW FOIL RETRACTS BY SWINGING 90 DEGREES FORWARD, UP TO THE BOW DECK. WHEN SET, IT IS SHEAR BOLTED TO A TRANSVERSE PLATE ON THE MAIN HULL JUST UNDER THE WATERLINE. LATERAL FOILS LAY DOWN ON THE DECK WHEN RETRACTED, THROUGH USE OF TWO PIVOT AXES AND A REMOVABLE PIN BOLT NEAR THE WATERLINE.

The trimaran hull form was chosen for a variety of reasons. Overall light weight was required for the craft to be able to take off in moderate winds. This also requires considerable craft width for stability. Appearing best was a configuration of four hydrofoil units, consisting of bow foil, steerable stern foil, and dihedral foils laterally of the center of effort of the sails on each side. It offers inherent dynamic stability over the widest range of conditions, and also has the ability to be "fail-safe." With bow and stern foils going deeper than the lateral foils, the craft takes on a modest heel under the influence of sail side forces.

FIGURE 2

RETRACTING THE STERN FOIL. THE FOIL PIVOTS ON A FRAME WHICH IS ATTACHED TO THE HULL THROUGH RUDDER GUDGEONS. RETRACTED FOIL INTERLOCKS WITH THE FRAME, AND TWIN STRUTS ENTER WATER AND ACT AS RUDDER BLADES. TO SET FOIL, IT IS KICKED OVERBOARD WITH TILLER AMIDSHIPS, AND SHEAR BOLTS ARE INSERTED BETWEEN TWIN STRUTS AND THE FRAME.

The windward lateral foil tends to come out of the water, and the leeward lateral foil digs deeper and supplies an antileeway force through its dihedral, even at zero leeway angle. With the trimaran form, one can obtain the desired near zero initial lateral stability, with a rapid stiffening up with modest heel, all with a minimum of hull wetted surface. Low speed hull drag is minimized this way, and foils give maximum roll damping. With foils retracted in light airs, the craft attains maximum boat speed relative to wind speed. With foils set in light airs, foil drag cuts speed to about that of an average conventional yacht. It was deemed impractical to be raising and lowering foils every time the wind drops or picks up. The overall light weight allows slender trimaran hulls, and a higher design take off speed. The higher design take off speed (12 knots on Williwaw) helps to minimize foil area, weight, expense, foil handling difficulties, hazards from pounding when stopped in heavy seas, and reduces the drag penalty of having foils set in light airs.

The only disadvantages of the higher take off speed are in the increased drag hump, and in the apparent wind drawing further ahead during take off, requiring more lateral stability and hence more pontoon buoyancy. Neither of these theoretical disadvantages have turned out to be practical ones. In marginal winds, one can use a sailing trick to break through a modest drag hump. When the drag hump blocks further speed increase while close reaching into the wind, one suddenly turns the craft 10 or 20 degrees away from the wind. This builds up a much greater sail force for a long enough period to break through the hump. Because of the speed increase, apparent wind draws forward again before the sails go into stall. The effect is similar to "sail pumping".

The trimaran hull form provides excellent fastening points for this four foil system. Hull and hydrofoil units complement one another beautifully in both structure and function. The monococque hull maximizes strength and rigidity and minimizes hull weight, while providing generous interior accommodations. Because the hull is lifted up whenever going fast, hull pounding is minimized and water clearance beneath the wing section joining the hulls can be reduced, allowing improved structural rigidity and generous space for wing bunks.

The foils are of the surface piercing variety, though at lower speeds they have deep submergence ratios and get a submerged foil type of stability through leading foils being set to higher angles of attack than trailing ones. High efficiency is obtained over a very broad speed range. For take off, the bow foil has excess lifting area, so that the bow rises higher than the stern, augmenting take off lift. The craft tends to level off at higher speeds, bringing lift coefficients closer to high speed optimums.

At lower speed, the system is a four foil symmetric system, but by take off speed it becomes a three foil asymmetric system. At high speed with no heeling forces, such as when running down steep waves, it actually becomes like a two foil power craft system, because both lateral foils can come clear of the water, and the result is maximum possible longitudinal stability. In normal hydrofoil sailing as a three foil asymmetric system, craft heel automatically puts the proper antileeway lateral foil into the water. Heel keeps the windward lateral foil out of the water most of the time, so that it doesn't produce lee forces. This system makes unnecessary any adjustments on tacking. Both longitudinal and lateral stability are maximized when needed, and yet the hulls are never subjected to any racking strains from foil lift. This unique combination of hull and hydrofoil appears to have many advantages over other hull and foil arrangements, and is especially suited to an offshore cruising boat. This foil configuration and its retraction means are the subject of U. S. Patent #3,561,388 and of British patent #1248890.

Using 6 inch chord elements, the foils have a fairly high aspect ratio. The bow foil is a deep "V", whereas the lateral and stern foils are ladder form. All the foils are trusses made up of lifting elements and struts, and are designed to withstand water forces of one ton per square foot. Shear bolts protect bow and stern foils from damage in striking debris. Hull framing is designed to carry the hydrofoil loads. The hull skin is mostly 1/4 inch marine plywood (covered with fiberglass), stressed by compound curvature to prevent flexing or "breathing" of panels. Although the hull longitudinal strength relies mostly on this 1/4 inch plywood skin, it would be able to take a ten times gravity load.

Hull shape tries to minimize windage. It has a flush deck with reverse shear. Though the amount of reverse shear appears large when the craft is not moving, it is not at all noticeable when taking off, since the bow rises a foot higher than the stern. The decks slope off to the sides enough so that normal craft heel does not put the pontoon deck higher than mainhull deck. The wing sections between hulls are designed to have negative aerodynamic lift, since the windward side would tend to get more lift than the leeward, and it was desired to avoid any possible high speed windage hazards.

The masthead float weighs about 12 pounds and has a buoyancy of 300 pounds. Windage on it is minimal, because it is a shape with a low drag coeffcient. It is designed to prevent the craft from going upside down in the event of a knockdown. No water enters the craft when laid over on its float. The bow of the craft tends to be upraised in this condition, and the stern well immersed. Thus bow windage forms a couple with stern drag (at a 100 degree heel) tending to make the craft swing around to bring the wind onto the deck. Deck windage should right the craft. The experimental situation to verify this expected behavior has not yet occurred in spite of 7,000 miles of ocean cruising. It is believed that it offers a cure for the multihull capsize hazard. The weight of the Aluminum hydrofoils (400 lb.) will also assist with a righting moment. However, there is sufficient buoyancy in the wood in Williwaw to float all the metal and fiberglass in the craft, so that Williwaw is unsinkable. It appears to combine the good features of multihull unsinkability with monohull ability to recover from a knockdown.

Design displacement of Williwaw is 3200 pounds. Light weight is 2200 pounds. Two persons with long range cruising supplies bring the craft to design weight. Daysailing capacity is half a dozen persons. Hull length overall is 31'4", beam overall is 16'4", and draft is 16". Draft with foils set is 4 feet. Working sail area is 380 square feet. Calculated hydrofoil lift/drag begins to exceed hull lift/drag when the craft is 1/2 foilborne, that is at about 9 knots speed. The drag hump appears to be about 20%, but was expected to be surmounted through normal wind fluctuations, by wave boost if broad reaching, or by close reaching to build up the apparent wind velocity and reduce take off speed by putting more load on the leeward lateral foil.

3. PERFORMANCE

While increased speed potential has been the major impetus to development of hydrofoil sailing craft, the most remarkable benefit seen in Williwaw is in seakindliness, leading to far less tendency for crew to become seasick, and considerably less likelihood of crew falling overboard. The conventional approach to gaining comfort in heavy seas has been to go to a larger more massive yacht, whose inertia will lead to greater seakindliness. The approach to seakindliness in Williwaw represents a major break with tradition. Normally, a very light weight trimaran will have a quick, jumpy motion in rough seas. However, hydrofoils on such a trimaran will exert roll and pitch damping while going slowly, or exhibit the inherent lack of responsiveness of hydrofoil lift to an uneven sea surface at higher speeds. Also, hulls lifted out of the water do not pound.

Williwaw exhibits considerable versatility. Its lightweight and shallow draft (with foils retracted) allow it to go places where conventional yachts can't go, in spite of having no engine. On several occasions in Hawaiian waters, the hydrofoils or the mainhull have been bounced over coral reefs, sand bars, or river rocks, with insignificant damage. Caught on reefs, the crew jump off into water of wading depth and push the craft off. Yet, in heavy seas with the hydrofoils set, the craft exhibits tremendous stability and control, holding a course sometimes for hours or days with helm tied.

On its longer passages, Williwaw did not meet consistent enough winds to set any new sailing records. However, it appears to have set one new interisland sailing record. It made a 95 mile passage from Pokai Bay, Oahu, to Hanalei Bay, Kauai, in ten hours. As is typical, light wind and calm was met while in the wind shadow of Oahu. Hydrofoils were set as the craft approached the wind line at Kaena Point. At first, badly confused seas held speed down, but as Williwaw approached open sea conditions, she began staying foilborne for long stretches, broad reaching in Force 4 and 5 Northeast trade winds with seas averaging a six foot height. In mid channel, a heavy rain squall began bearing down on Williwaw. With a bit extra wind on the fringe, Williwaw began averaging 15 knots, with bursts of speed to 22 knots, and outran the squall. No rain was felt, but sheets of salt spray swept the deck every time we sliced into freak waves. Seeing that Williwaw held a pretty good course with helm tied, I ducked inside the cabin. Approximately every five minutes, a freak wave would push Williwaw off to quartering the wind, but I only had to reach an arm out and give a brief helm correction to get Williwaw back to broad reaching. My two neophyte crew members were sleeping in the wing bunks all the while. We averaged better than 12 knots crossing the Kauai channel, but the lighter evening winds slowed us down as we approached Kilauea Light and Hanalei.

While curves of allowable wave height have been published for power hydrofoil craft, they don't appear applicable to Williwaw. Heavy seas slow Williwaw down, but no matter what, the craft is always better behaved with its hydrofoils set, as compared to trimaran hulls. By this time, Williwaw has encountered nearly 2000 miles of heavy seas (up to 20 feet) and strong winds. Sudden dropping of the craft from foils back to hulls is a rare event, and can probably be eliminated with a small modification of the bow foil. Heavy seas appear to slow Williwaw primarily because of inadequate hull clearance, which can be remedied easily in later craft. No hazardous decelerations have ever been felt, nor has any pitch-pole tendency been noted. Normal transition from hull to foil and back again always tends to be smooth.

The apparent ability of Williwaw to operate in unlimited sea states with hydrofoils set can be explained. The sailing hydrofoil attains its highest speeds on winds from around the beam, the very heading on which hydrofoils are least troubled by wave orbital motions. Furthermore, the considerable sailing craft width prevents the dangerous rolling that a power hydrofoil craft might experience in heavy beam seas. Sail pressure also represents a steadying force. Lower speeds close reaching or wind aft put the foils deeper, and less influenced by wave orbital motions. Wind aft would tend to be the most hazardous heading, but sail inefficiencies with wind aft usually keep boat speed down to approximately wave speed. However, when Williwaw goes over the top of a wave and surfs down at 25 knots or so, wind speed is exceeded, causing the sails to go aback. The loss of the normal sail pitching moment brings higher angles of attack onto the foils, augmenting lift. Approaching the trough at 25 knots, Williwaw's bow deck might be 6 feet off the water, and the foils have sufficiently large reserve area to allow several G's pull out. Climbing the back of the next wave, speed is lost through conversion to potential energy, and wave orbital motion reduces lift coefficients. Here the hulls reenter the water, and the bow deck might go a few inches beneath the water's surface. On succeeding craft, the height of the bow deck may be raised slightly, since it is only 30 inches above the zero speed waterline on Williwaw.

In flat water, Williwaw tends to exceed true wind speed while foilborne. Lightly loaded, it can take off in a 10 knot wind by close reaching. In such marginal winds, the take off run may be rather lengthy, for the difference between propulsive force and drag near the drag hump may be small. The craft not only has to overcome inertial forces to accelerate, but has to gain considerable potential energy. Here, the "one-stroke sail pump" technique, mentioned previously, can be used. In a strong wind, Williwaw may take off in about two boat lengths. The high sail forward pitching moment is presumed to increase the required boat speed for take off, but it has never caused the craft bow to "dig in". In a wave chop, there is a very noticeable disappearance of the sensation of feeling the chop at the moment the hulls leave the water's surface. One gets a floating or gliding sensation.

In several years of testing, Williwaw has met and raced informally with a number of craft. It would appear worthwhile to mention some of the results: Hobie Cat 14'. Williwaw was evenly matched with a Hobie Cat, both craft doing 18 knots, exceeding wind speed, in moderate sea conditions coming into Hanalei Bay, Kauai. The Hobie Cat had two men aboard, with an expert helmsman, both men leaning out to weather and the craft flying a hull. In lighter winds, when Williwaw wasn't fully foilborne, the Hobie Cat was faster. It should be noted that the Hobie Cat had a sail area to displacement ratio twice that of Williwaw, and the further advantage of a rotating mast. Perhaps we can say that at 18 knots Williwaw's foils are twice as efficient as a Hobie Cat hull.

30-Foot Trimaran. Williwaw was challenged to a race from Sausalito to San Francisco and back by a relatively fast 30-footer. Williwaw had its foils set the entire race. In a light air at the beginning, the trimaran took the lead. By the time the wind had picked up to 8 knots, Williwaw was half-foilborne and passing the trimaran. When the wind picked up to Force 4, Williwaw lifted off and streaked ahead of the trimaran. When Williwaw was halfway back from San Francisco, it met the trimaran again, which was only halfway to San Francisco.

39-Foot trimaran "Nomad". During efforts to get photographs of Williwaw flying off of Kaanapali, Maui (see FIGURES 3, 4, and 5), it was found that the two boats were evenly matched when Williwaw was 60 to 90% foilborne, but Williwaw moved ahead rapidly whenever it obtained wind enough to get fully foilborne. Nomad was flying a genoa jib, whereas Williwaw had only working sails.

FIGURES 3, 4 & 5

THE PHOTOGRAPHS ARE A SERIES TAKEN FROM THE 39-FOOT TRIMARAN "NOMAD" OFF OF KAANAPALI, MAUI. THEY SHOW WILLIWAW CATCHING UP TO AND PASSING THE LARGER BOAT. WILLIWAW IS DOING 18 to 20 KNOTS, EXCEEDING TRUE WIND SPEED.

65-Foot racing trimaran "Pen Duick IV". The two craft met on San Francisco Bay. Pen Duick IV's hulls had just been cleaned, prior to its 8 day 13 hour run from San Pedro to Honolulu alongside the (monohull) Transpac Race of 1969. Williwaw had foul hull bottoms, 7 persons aboard, and lower than normal foil setting angles were being tried that day. Williwaw was unable to get fully foilborne, or exceed 16 knots. The Pen Duick IV was faster in practically all conditions, except that during a Force 5 wind gust Williwaw managed to hold even, doing 16 knots.

50-Foot monohull Transpac racer "Warrior". Not really a match, but the two craft sailed from Hawaii to San Francisco at the same time. Williwaw set out two days earlier and came in two days later, for a 22 day passage. Very light winds prevailed

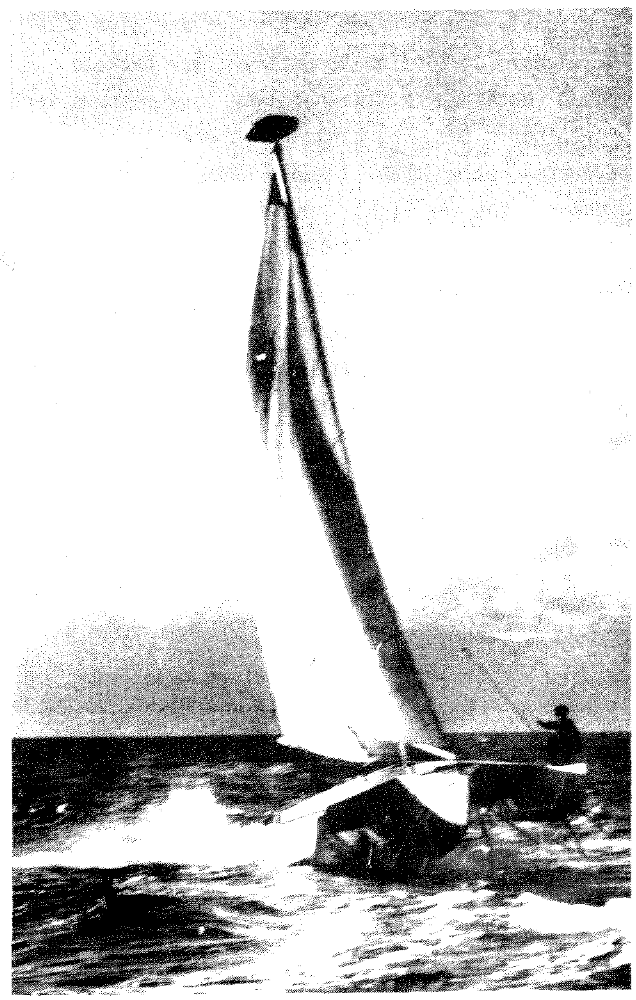

FIGURE 3

LEEWARD PONTOON IS TOUCHING WATER. SAILS WERE NOT PROPERLY DOWNHAULED, AND HAVE TWISTED AND GONE ABACK UP TOP IN THE LARGE APPARENT WIND.