FS Rudder and Centerboard Technology from AeroSouth

Engineering innovations often evolve in unexpected ways. Such is the case for our new company, AeroSouth, and our new "FS Technology" rudder blades and centerboards developed for small sailboats like the Sunfish and the Laser.

BACKGROUND

It all started a few years ago as I neared completion of a 13' runabout, the "Tuffy" design from the nice folks of GLEN-L in southern California. We were about to move from the Raleigh area to Seven Lakes, North Carolina, where I was building a manufacturing facility for a German industrial equipment company. I needed a trailer. I searched online and quickly found a nice elderly lady an hour away, offering to sell an old Sunfish, with trailer, for $250 - less than I had figured would be needed for the trailer alone.

When I made it out to her place in the sticks and saw the ancient Sunfish on the trailer, I planned to stop by the local landfill on the way home and bury that sad-looking old boat. Somehow during the drive I felt sorry for it, remembering the fun I had had on these boats many years prior, down in Ft. Walton Beach while taking a break from engineering studies at Auburn (War Eagle!). The trailer was perfect for transporting both the Tuffy and the Sunfish to our new home on beautiful Auman Lake (not Lake Auman - it's a Southern thang, y'all), a spring-fed, sandy-bottom, man-made lake about 10 minutes west of Pinehurst (from golfing fame), home to a few dozen Sunfish and various other sailboats.

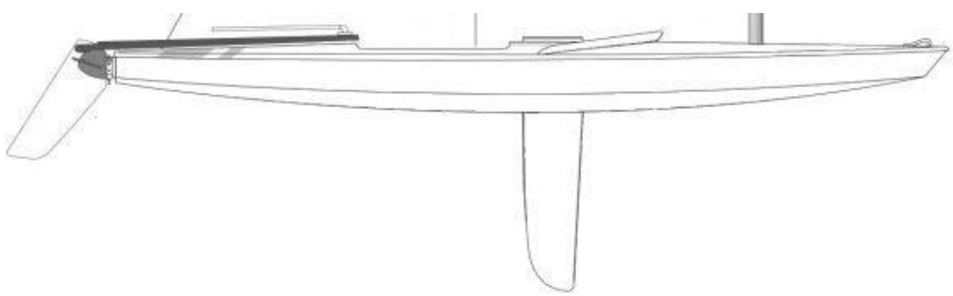
In 2018 the Sunfish was made seaworthy again (well, lake-worthy), which called for conversion to the "new style" (new in 1972!) rudder attachment, installation of an inspection port at the stern, acquisition of a new rudder and daggerboard, as well as the purchase and rigging of a new sail. I used the boat quite a bit that first summer to gain skills on a lake where the wind is strongly affected by wide coves and tall pines trees around its perimeter. As an engineer, I also noted many aspects of the boat where I thought improvements could be made. The first of these was a simple sheet guide clip to prevent the main sheet from fouling on my head when tacking. This became our company's first product in 2019.

Over the winter 2019-2020 I decided to have a closer look at the rudder and daggerboard. Having spent much of my 40+ year engineering career as an aerodynamicist, they sure looked a lot like wings to me, and I knew how to design them. My work had once included America's Cup boats when I was involved in the hydrodynamic design of Stars & Stripe '87. My contributions (which can be seen on the Nova episode 'Sail Wars' from 1987) were very minor but enough to whet my appetite for tackling the new design of a what to me is little more than wing that moves in water instead of air. That old designs found today on most dinghies can be improved can be seen on the underwater appendages of larger racing yachts, especially the latest America's Cup designs. Good design methods and strong materials exist for them, yet this technology has not trickled down to the masses – the people who own and sail the half million small sailboats, the combined production of Sunfish and Lasers. AeroSouth aims to change that, and at an affordable price.

Fortunately there is quite a bit of literature on the subject in technical papers found online, and I acquired some of the classic books, such as C.A. Marchaj's "Sailing Theory and Practice" as well as its modern equivalent, "The Science behind Sailing", from Dutch scientist Joop Slooff. I knew Joop from his years as a leading European aerodynamicist working at the Dutch aeronautical labs (NLR) and as the brains behind the reverse-taper, winged-keel of Australia II. Plus, he and I studied at the same school earlier in our lives, the Von Karman Institute for Fluid Dynamics, located just south of Brussels, Belgium.

When I shared with him my ideas on improving the rudders and centerboards for small dinghies like the Sunfish and Laser, Joop patiently guided me in the correct direction, based on his decades of work on sailboats and vast knowledge of findings from the towing tanks of the Maritime and Transport Technology Department, TU Delft. The first result of this collaboration is our new "FS" rudder, named for the special consideration of Free Surface (thus FS) effects on surface-penetrating rudder blades such as found on the Sunfish.

The water's surface is called a Free Surface as its position and motion is determined not solely by a solid surface but by the physics of fluid mechanics, ie gravitation forces, the shape of the underwater portion of the boat, momentum of water as it must move out of the way of the passing boat, and even the forces on the water surface caused by wind, prevailing waves, etc. It is a complex scenario that can not be duplicated entirely and accurately in towing tanks, heuristic-based VPPs or detailed computer simulations. As sailors know, no two days (our hours!) on the water are alike, so the comparison between geometry modifications is a real challenge to sailboat designers. Frankly, designing similar shapes for airplanes, which spend most of their time in straight and level flight moving through a smooth, homogenous medium (air) is simpler.



Sunfish hull and current Class-Legal rudder blade and daggerboard.

DESIGN OBJECTIVES AND CONSTRAINTS

As with any wing, one of the key performance parameters is its overall lift-to-drag ratio as a function of speed and angle of attack. Or, in the terminology of sailing, the ratio of side force to resistance as a function of the speed and angle of leeway. An aircraft's wing is, with few exceptions, symmetric about its longitudinal axis (left and right wings are mirror images) and is immersed in a homogenous fluid, air. When designing a wing, engineers strive to maximize the ratio of lift to drag by varying the airfoil shape and size as well as its planform (shape when looking down on the wing), which is defined by a number of parameters including its taper (ratio of tip to root chord), aspect ratio (roughly the ratio of span over average chord), sweep and other factors. Many other aspects must be considered including the wing's ability to perform well at high and low speeds, when maneuvering, the internal volume, strength, cost to manufacture, etc. The task is a classical problem in design optimization with a multi-parameter objective, constrained by several factors.

Although a sailboat rudder is somewhat simpler, it too is defined by many parameters and constraints, even in the case of the small Sunfish. Following is what we felt were the key design parameters, objectives, constraints, and the relative importance of each, given by a weighting factor from 0 (not important) to 1.0 (very important).

Parameter	Objective or Constraint	Weight (1.0 max)
Ratio of side force to resistance	25% better than legacy rudder	1.0
Side force at a given angle of leeway	Approximately equal to legacy rudder	0.9
Fits existing rudder attachment H/W	Absolute requirement	1.0
Weight	90% of legacy rudder, or lower	0.5
Durability	Same or better than legacy FRP rudder	1.0
Cost	90% of legacy rudder, or lower	0.9
Appearance	Visual improvement over legacy rudder	1.0
Kick-up feature	Retain if possible	0.5
Draft	No greater than class legal daggerboard	1.0
Weather helm	Noticeable reduction	0.9
Sculling effectiveness	Retain from legacy rudder	0.5

DESIGN TOOLS

For CAD (Computer-Aided Design) we use the cloud-based system Onshape, recently acquired by the leading engineering software company PTC. For stress analysis we use SimScale, which is tightly linked to Onshape, making it easy to evaluate the results of design changes. We had hoped to test our designs using a VPP (Velocity Prediction Program) however were not able to find one that was appropriate for the Sunfish. Since our goal however was a significant reduction in rudder and daggerboard resistance, any improvement in this will naturally lead to better overall sailboat performance and thus does not really require validation through a VPP. But it would have been a good additional tool – something for the future perhaps.

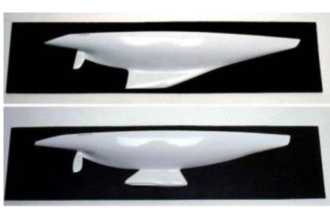
Being a startup company with limited facilities and a small budget, we chose from the outset to make extensive use of CFD (Computational Fluid Dynamics) for the hydrodynamic design. Fortunately, we have extensive experience with such tools, and understand very well their strengths, weaknesses, and limitations. Towing tanks were out of the question for cost and time reasons, and these too have their limitations in simulated real conditions at full scale. Fortunately, we could tap into the vast historical test findings from the TU Delft's towing tanks thanks to our advisor, Joop Slooff.

CFD programs have made amazing progress since the author first started using them in the late 1970s. Some, so-called time-averaged RANS (Reynolds-averaged Navier-Stokes) solvers are capable of simulating the complex flows at the free-surface including wave-making and sprays, however the resources and time required for such calculations are a subject for Ph.D. candidates and not suited for rapid progression through a multi-parameter design space like the one we face with a sailboat rudder. Simplified tools that combine inviscid calculations with boundary layer corrections are well understood and fast, even on simple laptops. Based on recommendations from people who use such programs daily to design aircraft, we choose the French program XFLR5.

This program does not include effects of the free surface at the water-air interface or waves however. There have been some good attempts at including wave creation in simpler programs. For instance, Northrop-Grumman engineer Bruce Rosen developed the program SPLASH in the 1980s for his work on America's Cup boats. Unfortunately, he is no longer involved in such work and the program is not available. Since anyone using CFD programs must know where the physics they simulate end and where real-world knowledge must fill in the gaps, we needed some method to account for the losses caused at the surface pierced by the rudder.

Joop Slooff had been interested in this exact problem for many years. Towing tank tests performed at TU Delft investigated the effect of keel and rudder shapes to minimize losses created by the water's surface, and these are well documented in Joop's outstanding book, "Sailing Theory and Practice". Different mechanisms are involved with the free surface: 1) a "surface of reflection", doubling the span (which holds for solid and free surfaces) plus a so-called "pressure equalization effect" (free surface only). 2) wave-making resistances due to perturbation/deformation of the water surface. These help explain the presumed and observed "blanketing" effect of the hull. The first evidence of a design that followed guidelines evolving from this research was the inverse-taper, winged-keel of the Australia II, winner of the 1983 America's Cup. For details on this interesting chapter in sailboat design, read Joop's fascinating account found in "Australia II and the America's Cup: The untold, inside story of The Keel".

With Joop's help, we developed a mathematical method to modify the results from XFLR5 to include the effects of the free surface. While the details on this are our intellectual property, the background behind it can be found in "Sailing Theory and Practice" - the math is not for the faint of heart though.



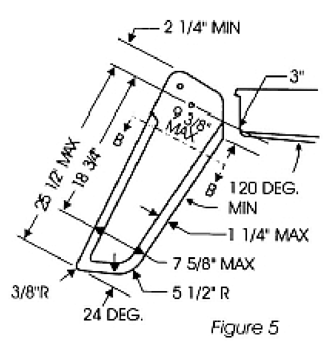
Influence of Dutch scientist Joop Slooff and the TU Delft towing tanks: Left: These two half models in the Australian National Maritime Museum's collection show a comparison of a conventional 12 meter Australia (1977 and 1980) above with Australia II below. (courtesy Australian National Maritime Museum). Middle: inverse-taper, winged-keel of the Australia II. Right: Hull of the Stars & Stripes '87, winner of the 1987 America's Cup. Note inverse taper on both the keels and on the rudder, chosen to reduce free-surface losses. (image courtesy www.americas-cup-history.at)

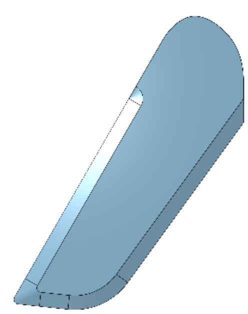
BASELINE RUDDER GEOMETRY, FLOW CONDITIONS AND PERFORMANCE

The baseline rudder geometry is the current approved design for Sunfish Class racing as set by the International Sunfish Class Association (ISCA) and World Sailing. Its key parameters and our CFD-based force results are shown in the table below. For sailing conditions, we assumed standard temperature of water (20 degrees Celsius) and a nominal speed of 10 mph = 4.5 meters/second. This appeared to be a good speed representing the higher loads that the rudder would need to withstand, an important input to its structural design. A nominal leeway angle of 5 degrees (called “angle of attack” AOA in aeronautical terminology) was found in the literature to be a good average for design purposes.

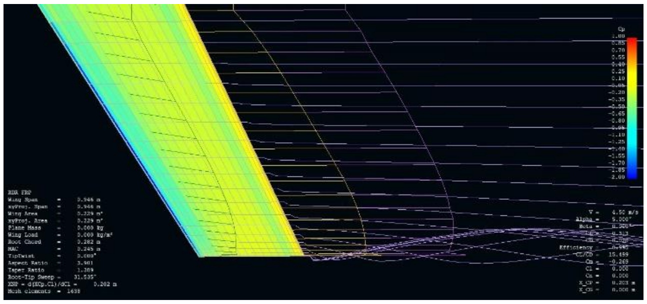
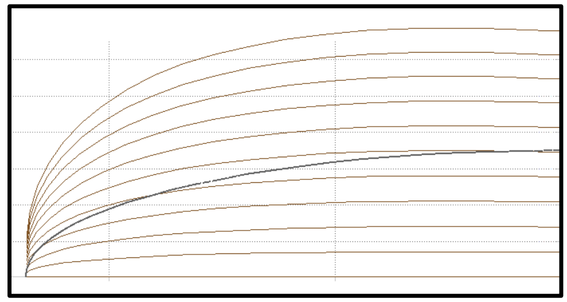
Area (half-span)	0.114 m^2
Aspect ratio (half-span)	1.94
Half-span (draft)	470 mm
Taper ratio	0.72
Sweep angle	31.5^o
Speed	4.5 m/s (10 mph)
Water density at 20^o C	998 kg/m^3
Water kinematic viscosity at 20^o C	1.0e-06 m^2/s
Side force at 5^o AOA	724N
Drag at 5^o AOA	46.7N
CL/CD (side force / drag) at 5^o AOA	15.4

Table of baseline rudder parameters and performance at nominal conditions of 10 mph and 5 degrees angle of leeway (Half-span = distance from water surface to lowest point on rudder = draft of rudder; Aspect ratio = (half-span)^2 / Area (half-span); Taper ratio = ratio of tip chord to root chord at water surface; Sweep angle = angle that the quarter-chord line from root to tip makes with vertical axis; CL/CD = ratio of side force to drag force = hydrodynamic efficiency; AOA = Angle of Attack [leeway]; N = Newton, metric system unit of force)





Left: Design of 2020 ISCA Class Legal Sunfish rudder. Center: The rudder attaches to the hull through a gudgeon bracket and spring-loaded pintle pin. Note the convenient pop-up feature which should be retained in a new design. Right: legacy rudder blade as modeled in Onshape CAD.

Left: CFD results for baseline/legacy rudder, showing pressure on the suction surface and flow streamlines. Right: Side force distribution for 0-10 degrees leeway, shown from the blade's lower tip (left) to the waterline (right), shows poor correlation with the optimal distribution, depicted by the gray curve for 5 degrees leeway.

To get an impression of the forces generated by this rudder, note that a side force of 724 N is equivalent to a mass of approximately 74 kg or 162 pounds applied to the center of force, which is about halfway down the baseline rudder. This has a critical implication on the strength that will be required for a new rudder, an important topic that is described below. The 46.7N drag generated by the baseline rudder is equivalent to a 5 kg (11 lb) load pulling the rudder backwards. Considerable research has been done on the drag of a swimmer's hand, seeking to improve athletes' speed. These results show a drag of 20-40 N at a speed of 2-3 m/sec. Drag varies approximately with the square of speed; double the speed and the drag increases by a factor of four. Therefore, the drag of the baseline rudder moving at 4.5 m/s (10 mph) is roughly equivalent to dragging two hands immersed completely in water and oriented perpendicular to the direction of sailing – a significant force and cause to seek improvements! Try it the next time you are sailing fast to get a good impression of the drag force on the rudder caused by water, whose high density creates significant loads even on small, thin surfaces like a dinghy's rudder.

Based on our review of sailboat design articles from the past few decades, we found that the contribution of the rudder to the total hydrodynamic side force and drag is often overlooked. Perhaps this explains the relatively simple designs of boards and blades on small sailboats. Unlike an airplane, where the tail surfaces have small areas and forces compared to its wing, the rudder on the Sunfish contributes 40% of the combined drag of the daggerboard and rudder. When running downwind, with the daggerboard partially or fully retracted, the drag from the rudder becomes dominant. Under the same conditions, with the mainsail approximately perpendicular to the boat, the rudder must create a significant side force to balance the moment caused by the displaced center of force of the mainsail. Rudder drag and weather helm on the tiller become more pronounced as a result.

HYDRODYNAMIC DESIGN

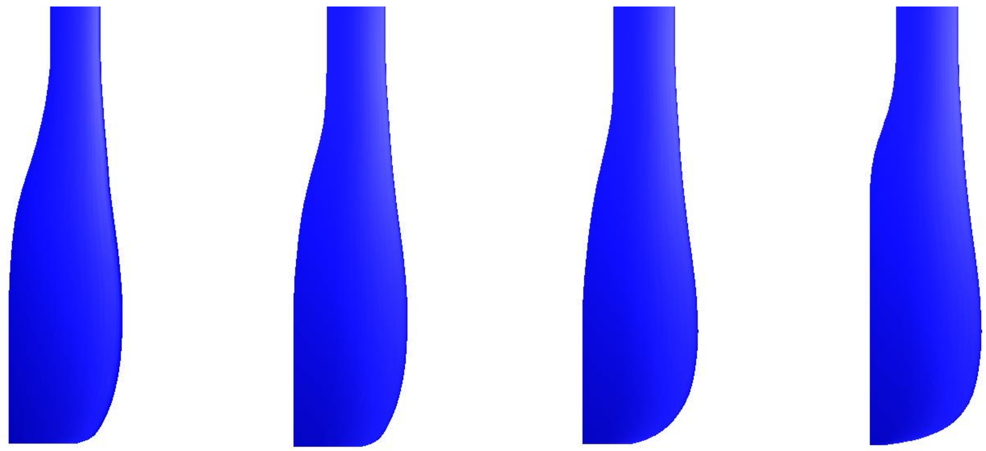
We began the hydrodynamic design with a study of appropriate rudder cross-sections, called airfoils in aircraft design. Standard, so-called NACA shapes were evaluated and then modified according to their thickness, location of maximum thickness, trailing edge thickness, and nose radius. These were run at different speeds (Reynolds numbers, essentially the ratio of momentum forces to viscous forces acting on the rudder) over a range of angles of attack (leeway, the angle the oncoming flow makes with the rudder) from 0 to 10 degrees. This provided a good array of choices. The resulting sections - also our unique design - were a good compromise between low drag, length of laminar "run" (distance from the leading edge downstream where the flow remains laminar and skin friction is lower), and behavior (stall) at higher angles of leeway and rudder deflection, for instance while maneuvering.

With the desired cross sections chosen, the 3D design iterations started with a rectangular planform of aspect ratio 5 (based on half-span) and area sufficient to generate side force equivalent to the baseline rudder at the same angle of attack. Each design iteration sought to lower drag while maintaining the side force generated by the legacy rudder at the same leeway angle. Our "FS" methodology was used to account for free-surface effects by estimating the loss in side force and increase in drag force on cross-sections of the rudder as one moves from the lowest point on the rudder towards the surface. This had the tendency to move the center of side force away from the free surface and reduce the chord and thickness of the rudder where it pierced the surface. What this means is that the widest section of the rudder, where most of the side force and drag are created, occurs further away from the water surface. Most rudders of small sailboats with surface-piercing rudders have their largest chord (cross-section) at the free surface, the worst imaginable design from an hydrodynamic efficiency standpoint. This is the case for both the Sunfish and the Laser.

Since an additional design objective was to reduce weather helm, blade sweep should be kept to a minimum. Indeed, TU Delft towing tank results show an advantage for negative sweep for keels and presumably also for surface-piercing rudders as on the Sunfish. This is thought to be due to the "blanketing" effect of the hull. In the case of hull-mounted rudders as are more typical for keel boats, free surface losses are much lower and the hydrodynamic force distributions are more similar to that of an aircraft, effectively doubling the aspect ratio, which greatly lowers the drag component resulting from side force. References for sailboat hull design indicate that the keel of most sailboats exhibits this same "doubling" effect of the effective aspect ratio. Since however, on the Sunfish, the rudder is mounted a few inches behind the stern, it is not possible to sweep far forwards to take advantage of the hull blanketing effect.

We did however distribute some of the rudder area in front of the axis of rotation, primarily to reduce weather helm. This in turn reduces sweep and might have had a small positive effect on free surface losses. The greater consequence however of moving area forwards was to reduce weather helm beyond the improvement achieved through the overall reduction in sweep. When blade area is shifted increasingly further forward, control stability becomes an issue. When using the older, highly-swept rudder blade, any deflection resulted in a strong moment on the tiller in the opposite direction, so-called positive stability. As sweep is decreased and the blade area in front of the axis of rotation is increased, forces on the tiller reduce to eventually zero, which is called "neutral stability". Take your hand off the tiller in such conditions and there is no force to return it to its undeflected position. Shift even more area forward of the center of rotation and negative stability will occur: deflect the tiller by a small amount, and the rudder will want to increase the angle further, an undesirable condition. Thus, had we wished to use negative sweep, it would have been necessary to change the entire rudder attachment hardware, something we did not wish to do. As in all engineering designs, the final chosen configuration was a compromise between competing factors.

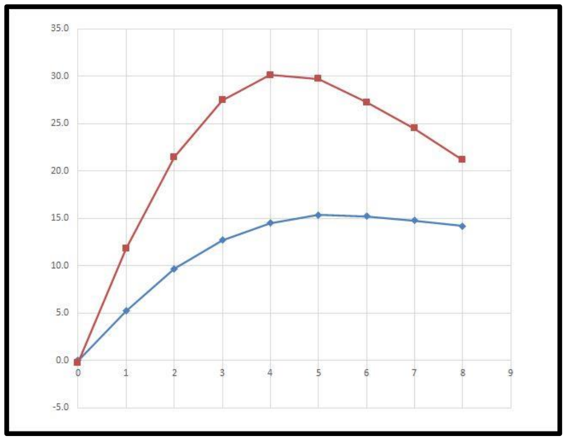
Images from a few design iterations can be seen below. The entire design optimization process required several hundred iterations and a few weeks of work. Below are our results.



Progression of rudder shapes during design iterations. Small, subtle changes resulted in an increase of the CL/CD ratio by 8% from the shape on the far left to the final design shown on the far right.

Rudder Blade Design	**Baseline/legacy**	**New "FS" Blade**
Area (half-span)	0.114 m^2	0.0845 m^2
Aspect ratio (half-span)	1.94	5.00
Half-span (draft)	470 mm	650 mm
Taper ratio	0.72	0.21
Sweep angle	31.5^o	8.08^o
Speed	4.5 m/s (10 mph)	4.5 m/s (10 mph)
Water density at 20^o C	998 kg/m^3	998 kg/m^3
Water kinematic viscosity at 20^o C	1.0e-06 m^2/s	1.0e-06 m^2/s
Side force at 5^o AOA	724N	706N
Drag at 5^o AOA	46.7N	23.4N
CL/CD (side force / drag) at 5^o AOA	15.4	29.7

Comparison of baseline legacy rudder blade with the final design. Note the doubling of CL/CD, while the side force achieved in the new design is 98% of the force from the legacy blade, at the same angle of leeway (AOA), despite the new design's area being approximate 25% less.



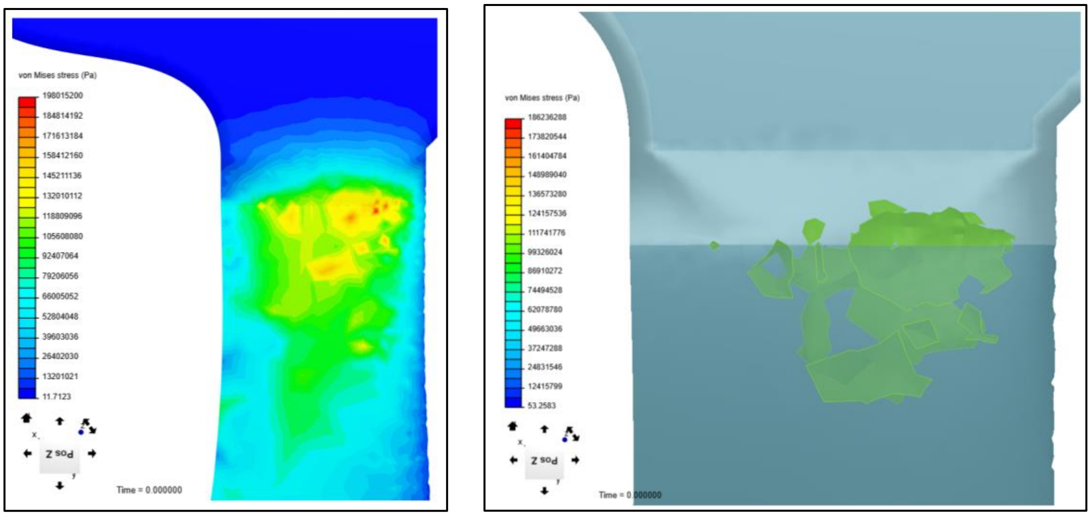
CL/CD versus angle of leeway for the baseline legacy rudder blade (blue) compared to the new "FS" rudder blade (red).

One sees that the new design peaks at 4-5 degrees leeway, which was one of the design objectives. CL/CD for the new design remains significantly greater than for the legacy blade over a wide range of angles. The overall increase in CL/CD of about 100% greatly exceeds our design goal of 25% improvement and represents a 50% drop in rudder blade drag for nearly the same side force. The smaller area also results in lower weight, another design goal. Smaller area leads to lower material and labor costs and thus to lower prices to users, another important goal.

STRENGTH, MATERIALS and FABRICATION

We knew from the outset that the unique design of the FS rudder blade, with its small, thin chord at the waterline, would pose some real challenges during the choice of materials and design of its internal structure. To lower costs, we favored wood as the primary material and fabrication methods requiring a minimum of labor. The ideal wood would be generally available at a reasonable cost, have high structural strength, natural properties that resist rot, and that could be machined to a tight tolerance. We reviewed traditional wood types used for boats, and selected sapele, a variety that is commonly used in the boat-building and furniture industry, the latter of which is large in our state of North Carolina. Also called sapele mahogany, this variety has properties similar to African mahogany but is available at significantly lower cost. It machines very well to sub-millimeter precision on the advanced CNC equipment used for our rudder blades and daggerboards. To increase strength beyond sapele's already high values, planks of the wood are first laminated from strips of this wood.

In order to determine the load distribution during design point conditions of 4.5 m/s speed and a leeway angle of 5 degrees, we performed a stress analysis on the final hydrodynamic design. As expected, the highest stresses occurred at the thinnest section of the blade. By specifying the properties of various varieties of wood, these analyses showed that it would not be possible to achieve the needed strength with wood alone; some means of reinforcing it would be necessary.



Left: stress distribution (von Mises stress) on the surface of the FS rudder blade just below the waterline. As expected, the highest stresses occur at the thinnest parts of the blade. Right: isosurface (green) defining the region within the rudder blade where the predicted loads exceed the strength of sapele wood.

Reinforcement – a number of different approaches were tested, starting with an encapsulation of the laminated wood blade within a single layer of fiberglass. This increased the blade's strength somewhat, but during actual, aggressive tests on our lake, this rudder failed at the exact location as predicted in our analyses. After much trial and error, we achieved and exceeded the needed strength by adding long, uni-directional carbon fiber rovings into the lamination process.

Surface protection – Although sapele's high density results in a smooth hydrodynamic surface following precision milling of the hybrid sapele / carbon fiber lamination, we felt it prudent to further protect the surface from impact, moisture and ultraviolet radiation with several coats of a two-part clearcoat urethane finish. This has the additional advantage of further improving the already smooth surface, important to achieving laminar flow and thus lower drag. The finished blade is also quite attractive, another one of our design goals.

Above: first production FS rudder blades, provided with holes for quick replacement in the standard attachment hardware.

TESTING, PERFORMANCE AND TESTIMONIALS

As described in the first paragraphs above, we were not able to find a Velocity Prediction Program (VPP) adapted to the design of the Sunfish sailboat. A VPP, in theory, would have provided one means to validate our designs. Since the drag generated by the rudder blade is one of the largest components of overall underwater drag, we ultimately realized that a VPP was not an essential requirement for success. All prototypes are first “bench tested” for strength in our workshop, and then tested on the lake adjacent to our property. Once satisfied with the basic functionality, we asked experienced Sunfish competitors in our region to try our blades under conditions typical for regattas. Following are several comments they sent us:

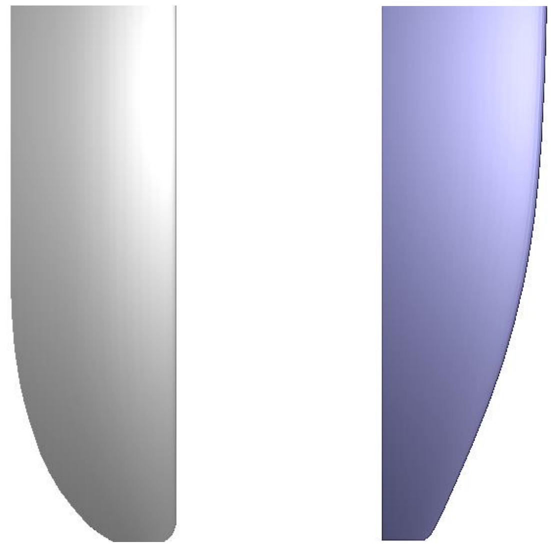
"The boat feels fast and smooth with the new rudder. The helm is very light, and you don't have to fight with any weather helm. It was a real joy to sail!" Alex Dean

"I had the pleasure of trying out the rudder blade a few weeks ago. I was surprised by the ease of steering through the waves going upwind. There was very little stress in the wrist or forearm." John Butine

“I tested it this past Saturday. It was blowing between 20 and gusting to 27mph. I reefed my sail 3 inches, had the Jens rig, gooseneck at 17 and no weather helm!!! It was fabulous, I had speed sailing upwind for the first time in that much wind. It's not class legal but is truly a lot of fun to sail with this rudder! I sailed for 2.5 hours.” Sonya Dean

THE FUTURE

With our first rudder blade using the FS design methodology now in production and available through aerosouth.net, we are nearing the first tests of a new daggerboard for the Sunfish following the same process. As a consequence of the fixed dimension of the boat’s trunk, we had less flexibility in geometry changes. Nevertheless, our resulting board is showing a theoretical reduction in drag of 25% at the same side force produced by the legacy daggerboard. Given the blocking effect of the boat’s flat hull, our calculations showed no appreciable benefit from a reduction of chord as with the rudder. With the widest chord at the point where the board emerges from the trunk being also the thickest section, stresses are relatively low, and the addition of carbon fiber reinforcements was not required. The shapes of the legacy daggerboard and our new design appear below. When combined with the FS rudder blade, the overall drag due to the two underwater appendages is reduced by 35%. Retracting the daggerboard shifts the efficiency improvements to the rudder blade, with its 50% drag reduction, meaning the boat should see even greater gains when sailing downwind. We believe that our methods for design and fabricating such blades and boards for the Sunfish can be applied to many other types of sailboats and are happy to work with others to achieve the gains we are seeing now.



Left: Legacy daggerboard for the Sunfish. Right: New daggerboard using the design and fabrication procedures developed for the FS rudder blade. Water flow is from right to left in both cases. (only geometry below hull shown)

Special thanks go to the esteemed aeronautical and maritime scientist Dr. Joop Slooff of The Netherlands, without whose guidance this work could not have been possible.

The author wishes to also express his thanks to Sunfish experts Alex and Sonya Dean, John Butine and Lee Montes for evaluating the early FS rudders, their important comments on needed improvements and for their proofreading of this text.

AeroSouth makes no claims concerning the approval of its products for use in competition sanctioned by the International Sunfish Class Association or World Sailing.

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Kent Misegades
Founder and President
AeroSouth
Seven Lakes, North Carolina, USA
kent@aerosouth.net
www.aerosouth.net
+1.910.568.2580