Excerpted from a paper by Tom Speer to
the Chesapeake Sailing Yacht Symposium

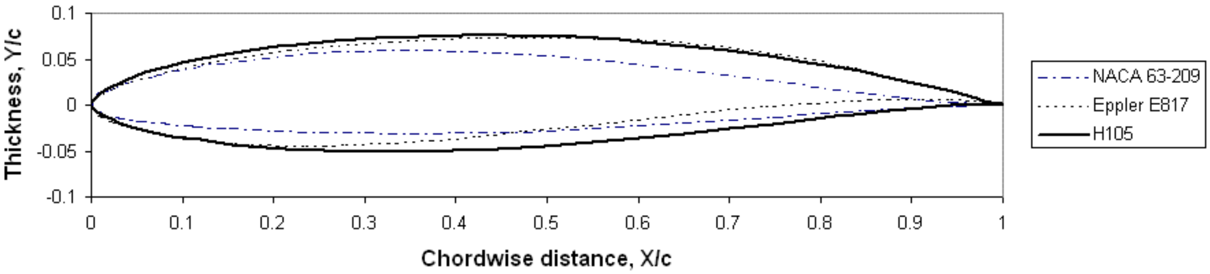

Fig. 15, Hydrofoil Section Shapes

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%.

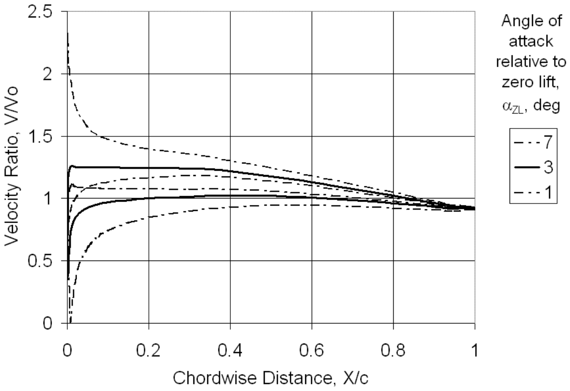

Fig. 16, NACA 63-209 Velocity Distribution

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.

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 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.

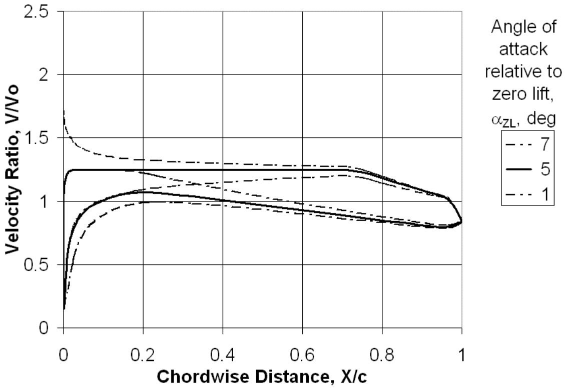

Fig. 17, Eppler E817 Velocity Distribution

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.

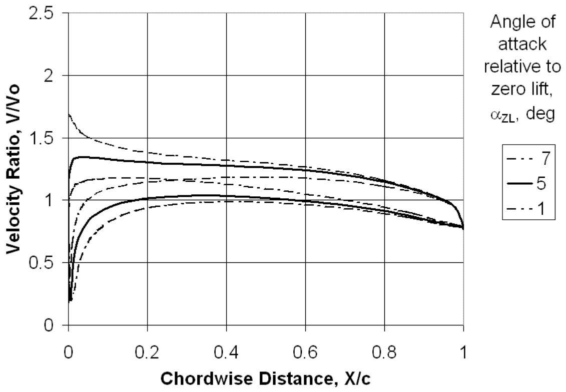

Fig. 18, H105 Velocity Distribution

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.

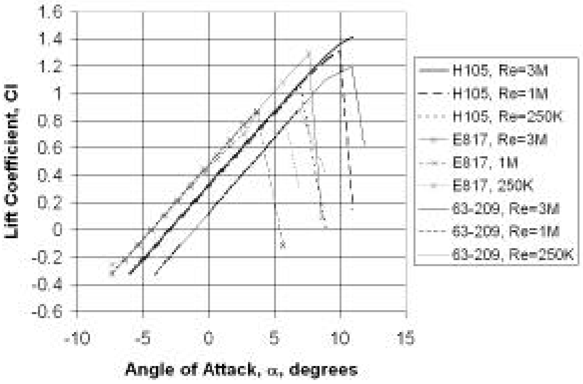

Fig. 19, Section Lift Curves

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.

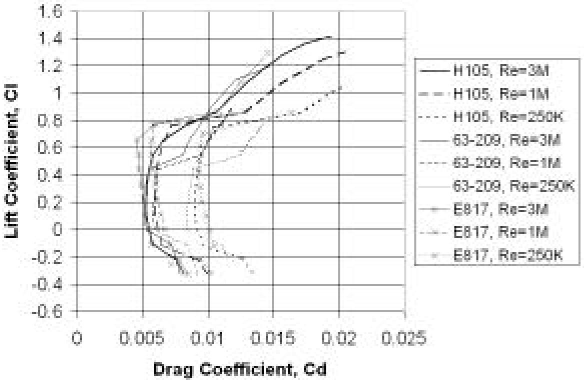

Fig. 20, Section Drag Polars

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.

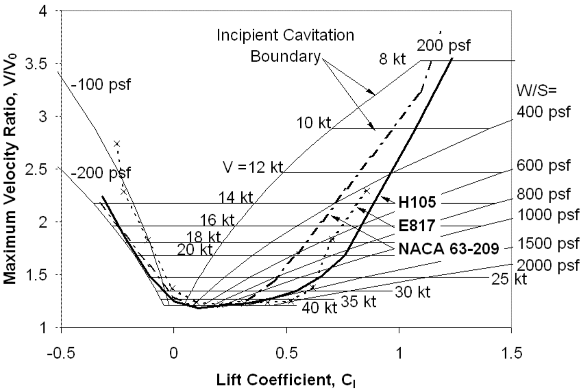

Fig. 21, Maximum Section Velocity

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.