Optimizing Blended Winglet Radii on Homebuilt Canard Aircraft

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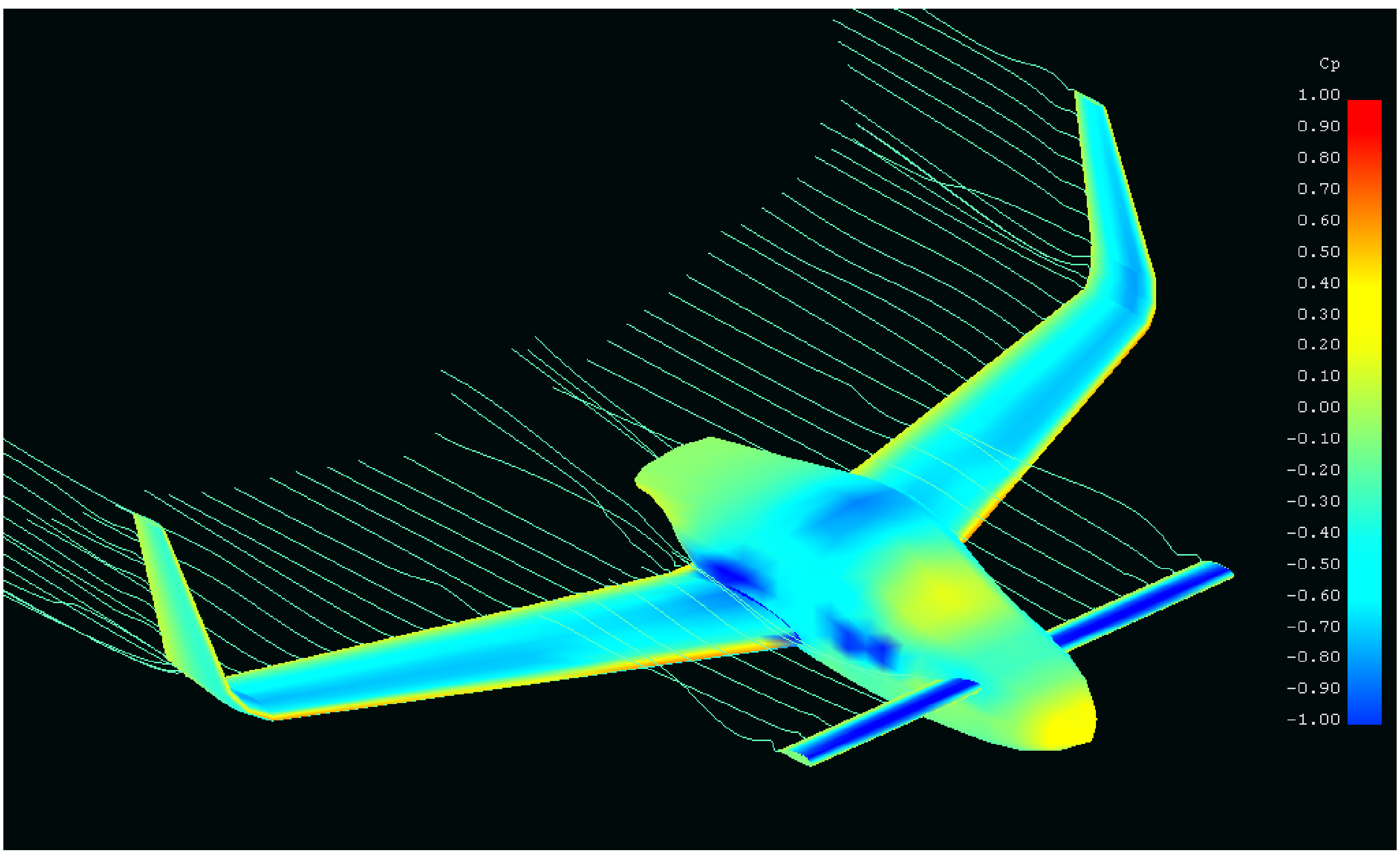
One of the most valuable tools for designing the wing of my airplane was XFLR5 software. I used this software to develop custom airfoils for the Apollo back in 2005. XFLR5 has been under continuous development since then and is now capable of 3D panel analysis of wings and entire aircraft. The developer strongly discourages the use of XFLR5 for "full-size" aircraft, but the software demonstrated impressive results during recent tests. While XFLR5 is no substitute for a professional CFD analysis, it can provide valuable insight into aerodynamic issues on small aircraft. It proved very useful for investigating different winglet configurations.

Software Evaluation

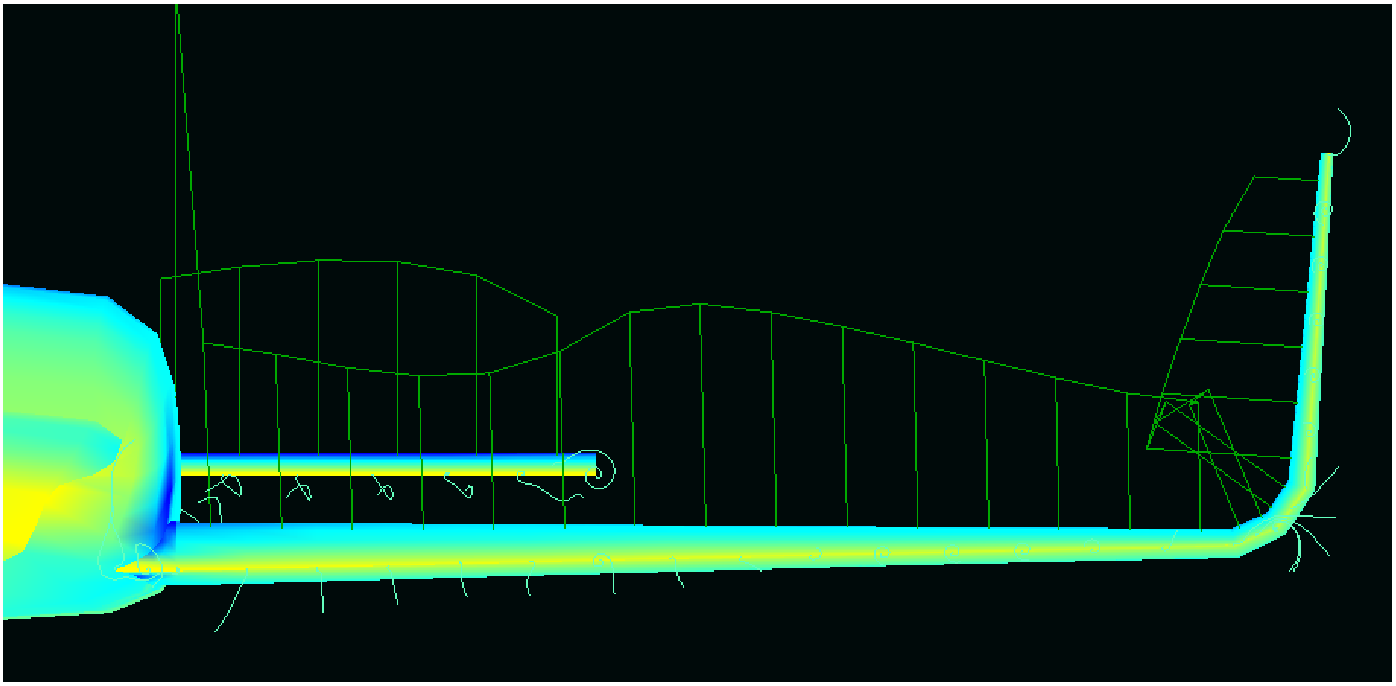
XFLR5 is open-source software available on the Internet. It's written for the layman and has a user-friendly interface. It does require knowledge of aerodynamics and experience with the program to determine which settings and displays can be trusted. Before focusing on winglets, I modeled my aircraft in XFLR5 and ran numerous analyses. The results from this free software were amazing! They correlated with known characteristics of canard aircraft and wings in general. A screenshot of the Apollo in XFLR5 is shown below. The flight condition is 190 mph and 1.0 degree pitch attitude. Pressure plots and streamlines are turned on. Other features like lift distribution, surface velocity, transition lines, etc. are available but turned off.



We can identify several aerodynamic phenomena in the screenshot on page one:

1) High and low pressure areas on the wing and fuselage are very evident, as well as low pressure on top of the hard-working canard.
2) Vortexes are forming at the tips of the canard and winglets (vortexes are more apparent in aft views). These are the price we pay for creating lift on a finite wing!
3) There is turbulent flow coming off the blended winglet intersection. What can be done to reduce or eliminate this turbulence?
4) Streamlines from the wing's inboard trailing edge are turbulent due to downwash from the wing mixing with upflow on the lower aft fuselage. A filleted fairing or trailing edge fence may help in this area.

The following screenshot is an aft view of the model looking forward under the same flight conditions. Lift distribution lines are tuned on. We can see the aforementioned vortexes and observe reduced lift on the wing area that is subject to downwash behind the canard.

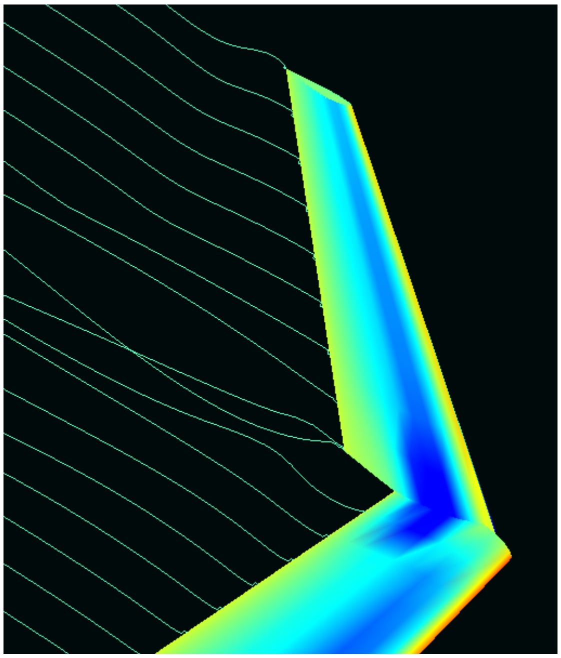


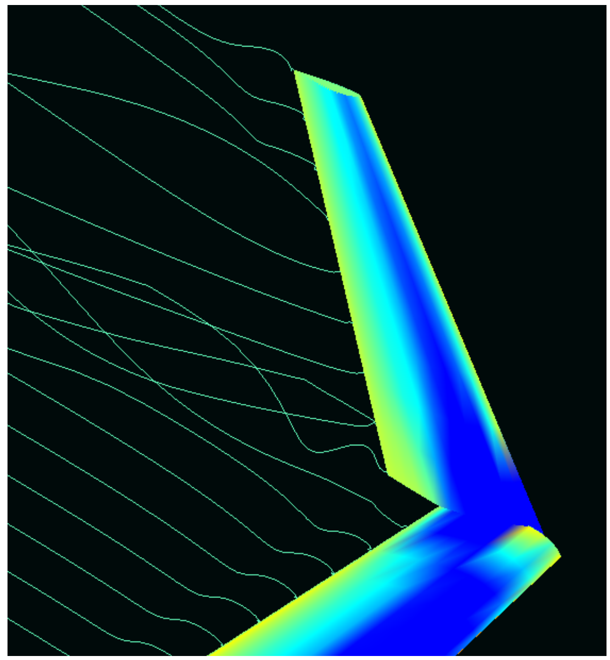
Note that some XFLR5 results are less reliable when the fuselage is modeled; the spike in the lift line at the fuselage is an artifact that illustrates this. Despite this anomaly, XFLR5 captured all the expected characteristics of a canard aircraft. There's no doubt the tool is less accurate and less capable than high end CFD software, and I wouldn't trust XFLR5 to determine the neutral point of my aircraft. But the ease of use cannot be beaten and I believe it's sufficiently accurate to optimize blended winglet configurations on homebuilt canard aircraft.

Winglet Investigation

A complete analysis of the Apollo's blended winglets can be found at www.apollocanard.com. Since the Apollo has different airfoils, chords and winglets than other canard aircraft, I decided to repeat the analysis series for the **Long-EZ and its derivatives.** A long-EZ wing was modeled as the baseline, but the E-Racer and Cozy aircraft use the same airfoils and chords.

The pictures below depict the standard EZ configuration with the winglet 4.5” behind the wing leading edge. This separation staggers the low pressure areas to reduce interference. The winglet has 0 degrees of cant and 0 degrees of incidence. **The lower winglet was omitted for these analyses.** The fuselage and canard are not modeled, so all data is for the wing and winglet only. The pressure distribution scale is the same as shown on page one.

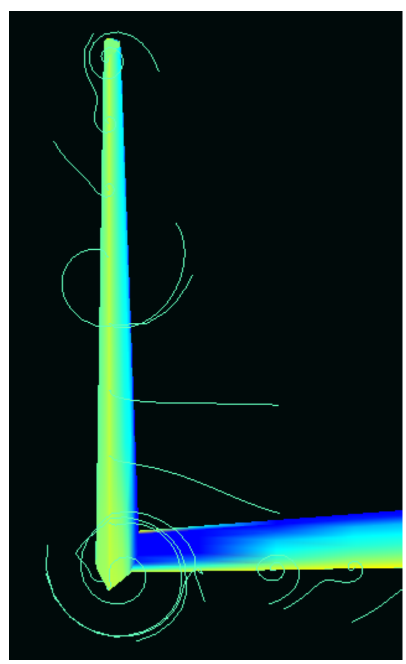




Airspeed: 190 mph
Pitch Attitude: 1.0 deg.
Lift Coeff: 0.2401
Drag Coeff: 0.0099
Cl/Cd: 24.2539

Airspeed: 90 mph
Pitch Attitude: 8.0 deg.
Lift Coeff: 0.7197
Drag Coeff: 0.0278
Cl/Cd: 25.8739

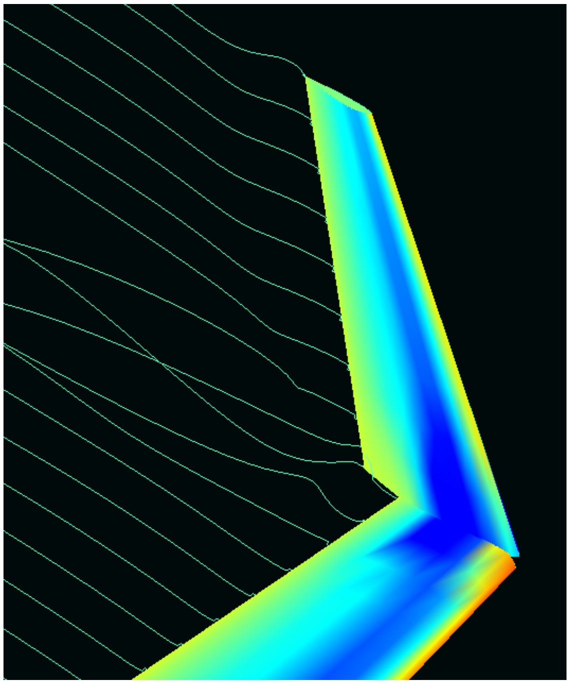
The streamlines indicate a weak vortex off the winglet root at 190 mph and a strong vortex at 90 mph. The vortex is more obvious in the aft view for the 90 mph condition, shown at right:

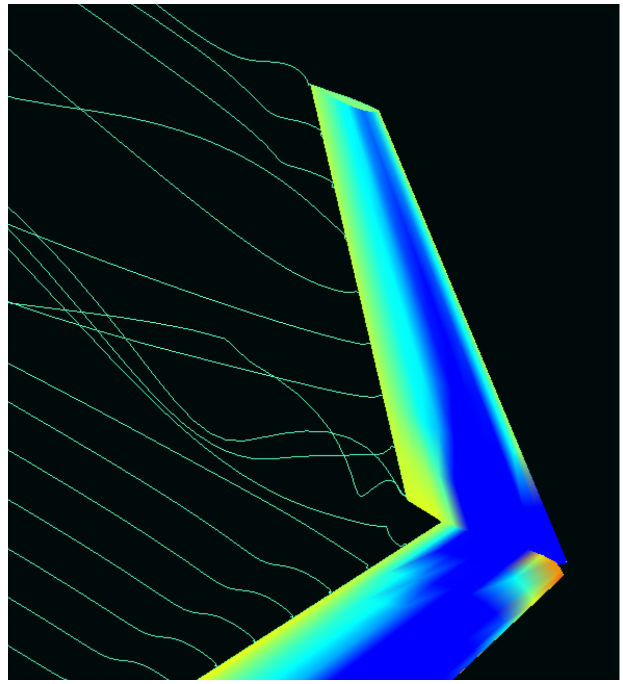


High lift coefficients at slow speed result in strong inflow to the winglet and this creates high angles of attack on the winglet that may strengthen the vortex. But even at 190 mph there is turbulent flow coming off the winglet intersection. The lower winglets that were omitted might reduce the vortex. There’s also a peculiar interaction between the low pressure area at the winglet root and the wing tip seen in the pictures above. Positioning the winglet aft of the wing’s leading edge is supposed to stagger the low pressure areas and reduce this effect, but it is still present.

Note the drag count for each flight condition. This will be the baseline for comparing other winglet solutions.

The next pair of pictures depict the same winglet with the leading edge aligned with the wing leading edge, similar to an **E-Racer** installation. Aerodynamicists claim this configuration has higher drag because the low pressure peaks on the wing and winglet coincide, leading to more mixing of the expanding air. Let's see what the analysis shows:





Airspeed: 190 mph
Pitch Attitude: 1.0 deg.
Lift Coeff: 0.2503
Drag Coeff: 0.0103
Cl/Cd: 24.3619

Airspeed: 90 mph
Pitch Attitude: 8.0 deg.
Lift Coeff: 0.7370
Drag Coeff: 0.0288
Cl/Cd: 25.6034

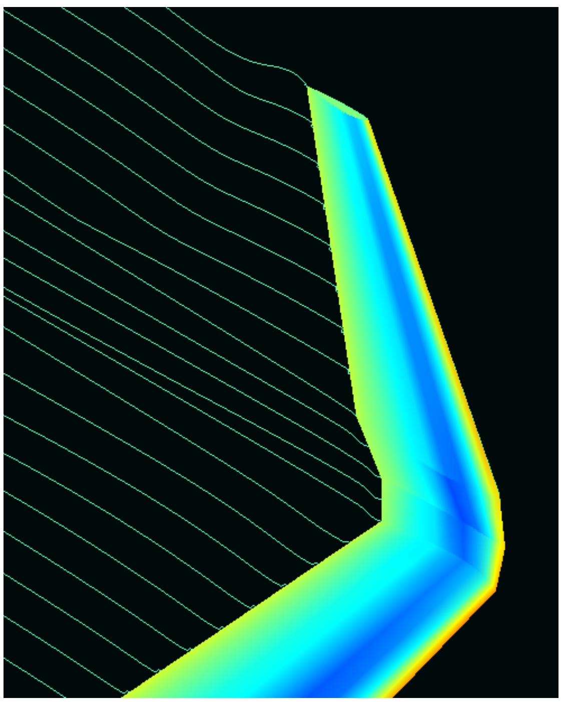
For the 190 mph condition, the larger blue area at the wing tip is evidence of increased interaction with the winglet root. Tuft testing on real aircraft indicate that separation is occurring in this area. A high pressure area has developed at the leading edge of the wing tip and drag has increased slightly. But lift increased in greater proportion and the lift/drag ratio is marginally better. It's just the opposite at 90 mph; the aligned winglet has a stronger vortex and lower l/d ratio than the offset winglet. While these results are interesting, no attempts were made to optimize these configurations since blended winglets seemed more promising.

Blended Winglet Analysis

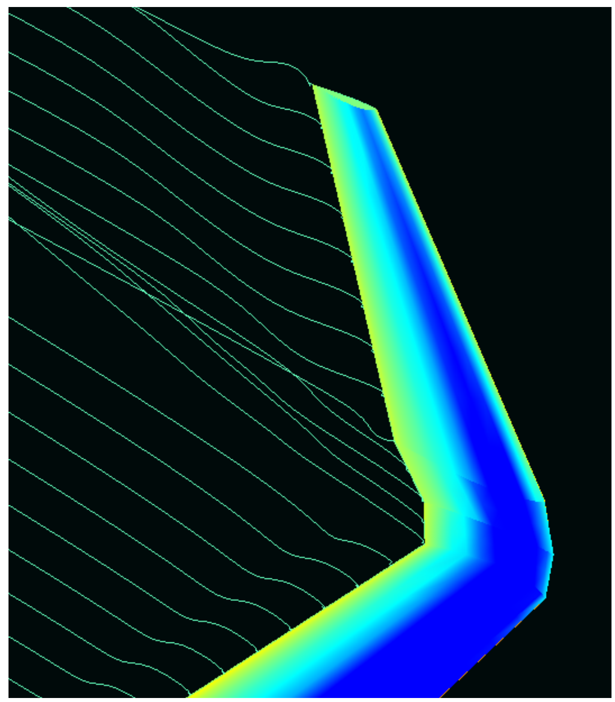
XFLR5 can't model blended winglets directly, but it does allow an unlimited number of wing segments with independent dihedral values. For a 3D panel analysis, the blend radius can be approximated with short straight sections. This works only if the approximation has enough discretion to support accurate analysis. After some experimenting, I determined that limiting the bends between straight sections to 30 degrees or less was adequate. The user must be sure to **set analysis parameters for XY projected areas** when modeling this way, otherwise the winglet areas will be added to the wing reference area and produce incorrect lift coefficients.

Bend radius parameters must be properly defined before comparing blended winglets to each other and to the previous analyses. I started with a 6” radius to emulate the winglets used on Jack Morrison’s E-Racer. The radius is measured from the top of the wing to the inboard winglet surface at the spar location, which is close to max airfoil thickness. The radius <u>increases</u> as we move toward the leading or trailing edge to account for reduced airfoil thickness at those sections. Therefore, the 6” radius is the minimum radius the airflow will see.

Adding a 6” radius onto the wing tip increases the wingspan, which improves wing efficiency all by itself. I decided to shorten the wing by 6” per side before starting the bend radius, leaving the total wingspan unchanged. The same radius also pushes the winglet up by 6” and increases the vertical tail area. Since the straight portion of the winglet includes the rudder, I shortened it by just 4” as a compromise. The winglet leading edge lines up with a smooth extension of the wing leading edge. Like previous models, the winglet cant and incidence were set to 0 degrees. Here are screenshots for the 6” blended winglet:



6.0 inch radius



Airspeed: 190 mph
Pitch Attitude: 1.0 deg.
Lift Coeff: 0.2386
Drag Coeff: 0.0096
Cl/Cd: 24.7719

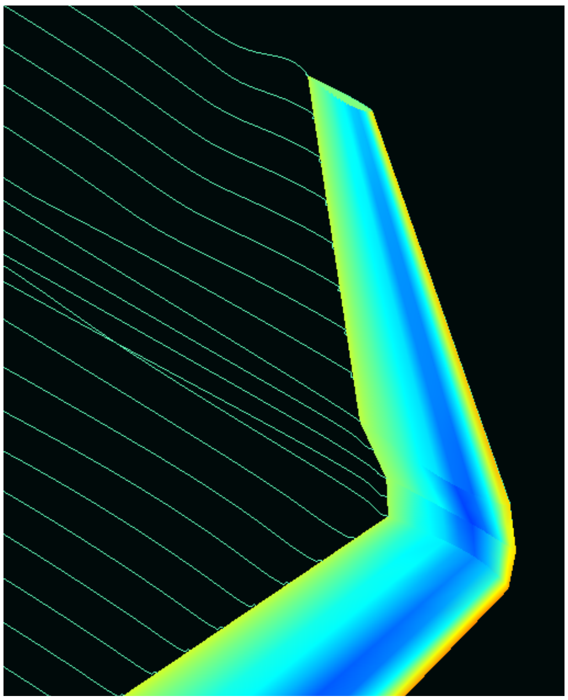
Airspeed: 90 mph
Pitch Attitude: 8.0 deg.
Lift Coeff: 0.7251
Drag Coeff: 0.0261
Cl/Cd: 27.7972

Wow, look at those nice streamlines at 190 mph! Note the smooth pressure gradient across the wing-to-winglet blend area. These results confirm that separation is no longer present at 190 mph. The blended winglet has lower drag and higher l/d ratios for both flight conditions. There is some turbulence and upflow coming off the blend area at 90 mph, but it looks much better than the non-blended winglets at that speed.

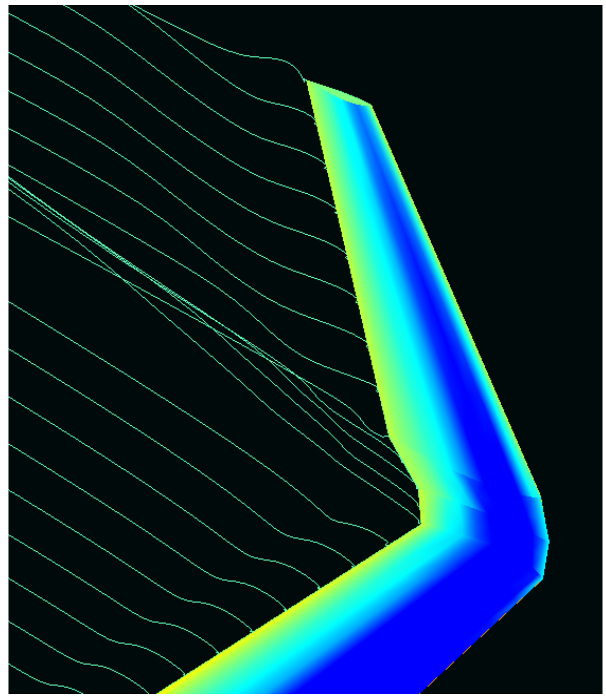
After evaluating these results, two questions come to mind:

1) How much smaller can the bend radius be and still maintain smooth flow at 190 mph?
2) How much larger does the radius need to be to obtain smooth flow at 90 mph?

For all subsequent analyses, the basic wingspan was left the same as the previous version (which was shortened 6" per side) and changes to the radius were allowed to grow or reduce the total wingspan. I modeled the 5" radius to see what effect it had. See the results below:



5.0 inch radius



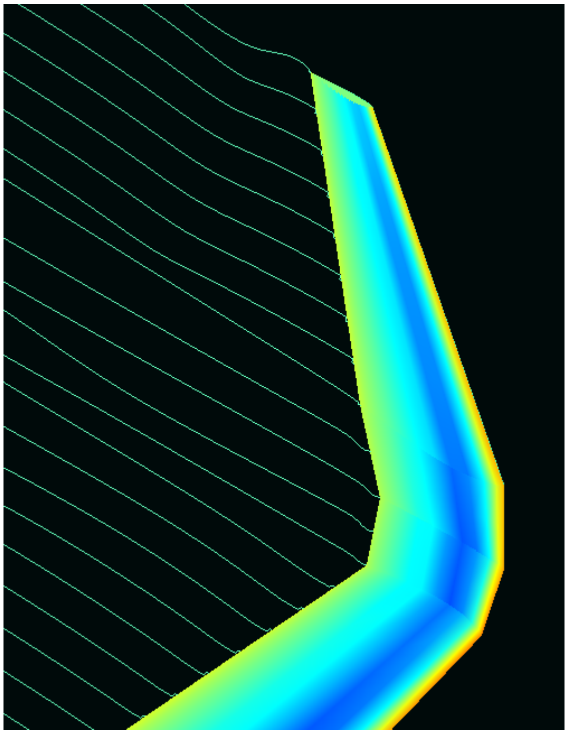
Airspeed: 190 mph
Pitch Attitude: 1.0 deg.
Lift Coeff: 0.2384
Drag Coeff: 0.0096
Cl/Cd: 24.7311

Airspeed: 90 mph
Pitch Attitude: 8.0 deg.
Lift Coeff: 0.7241
Drag Coeff: 0.0262
Cl/Cd: 27.6212

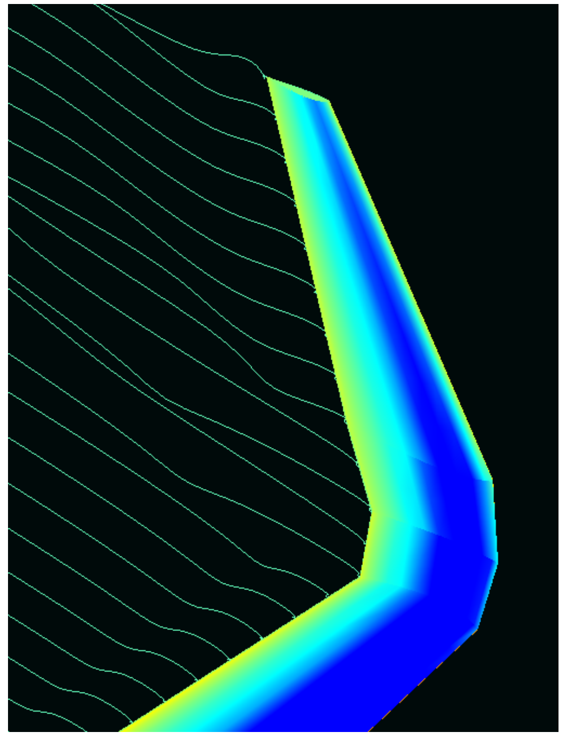
The crossing streamlines at 190 mph indicate we are on the verge of creating a vortex off the winglet root. This is confirmed by checking other pitch attitudes and by observing spiral flow in the aft view (not shown). The streamlines at 90 mph appear to be more divergent and there is increased upflow. The analysis data is somewhat inconsistent since the l/d ratios decreased more significantly than changes to the lift and drag coefficients would indicate. This could be because the wing was shortened 1" per side compared to the 6" blended winglet.

In any case, the streamlines confirm the 5" radius has more turbulent flow than the 6" radius. Since the 5" value appears to be on the cusp of deteriorating performance, I did not pursue modeling anything smaller than that. Note that even the 5" radius has better performance than either of the conventional (non-blended) configurations.

Having found the lower limit, I decided to **double the radius** to determine if we could establish an upper boundary for achieving the desired flow. The screenshots below are for a 10" radius from the top of the wing to the inboard winglet surface.



10.0 inch radius



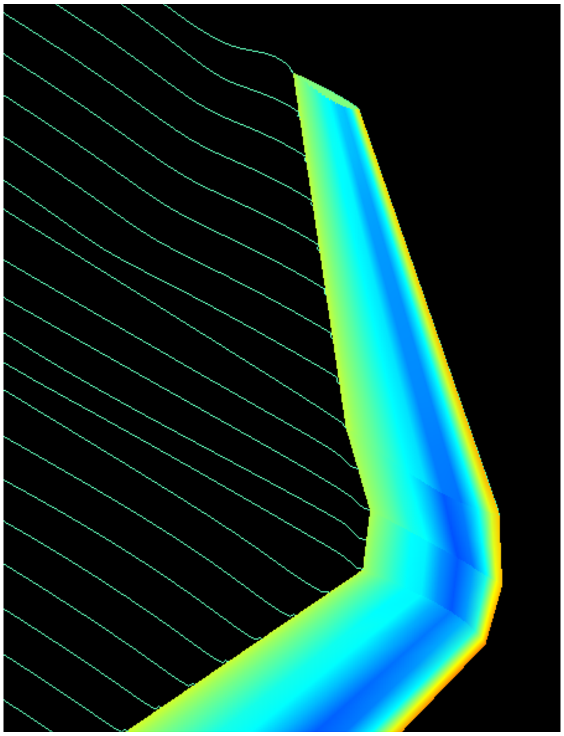
Airspeed: 190 mph
Pitch Attitude: 1.0 deg.
Lift Coeff: 0.2402
Drag Coeff: 0.0096
Cl/Cd: 25.0350

Airspeed: 90 mph
Pitch Attitude: 8.0 deg.
Lift Coeff: 0.7305
Drag Coeff: 0.0256
Cl/Cd: 28.5481

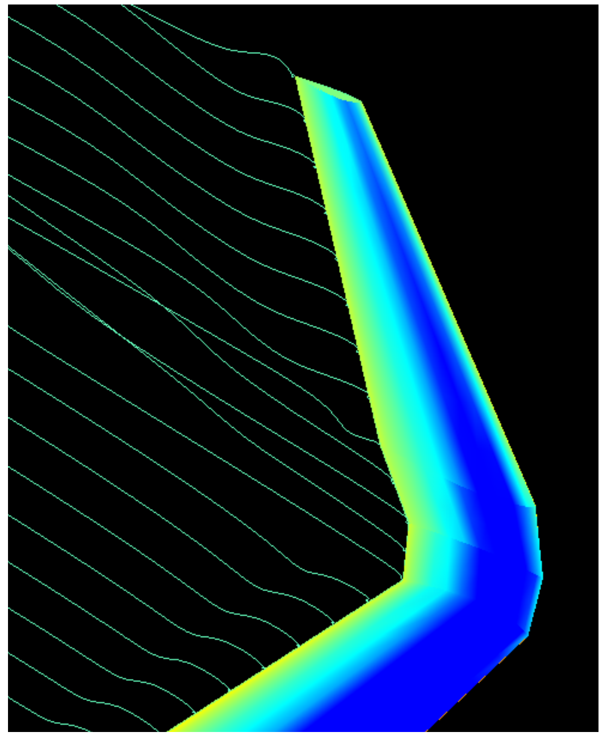
The larger radius results in pretty good streamlines at 90 mph. The l/d ratios increased for both flight conditions, but the 190 mph streamlines are only marginally better (if at all) with the 10" radius compared to a 6" radius. Aircraft designers must balance the aerodynamic benefits of a larger radius with practical limitations. To keep things in perspective, here are some reasons for minimizing the radius:

- The larger radius elevates the winglet and creates excess vertical tail area, but the winglet cannot be shortened to compensate (very much) since it contains the rudder and we want to preserve rudder length.
- To minimize the weight and wetted area associated with the blend transition area.
- To avoid moving the neutral point or CG on existing canard aircraft.
- To minimize the bending moments created by the winglet during rudder use.
- To avoid increasing wingspan that elevates the risk of scraping a winglet at high pitch angles with small roll maneuvers during the landing flare (for EZ-type aircraft).
- A smaller radius looks better to most people, except for aerodynamicists.

The final analysis was for an 8” blend radius, halfway between the 6” and 10” radii. Screenshots are provided below:



8.0 inch radius



Airspeed: 190 mph
Pitch Attitude: 1.0 deg.
Lift Coeff: 0.2395
Drag Coeff: 0.0096
Cl/Cd: 24.9210

Airspeed: 90 mph
Pitch Attitude: 8.0 deg.
Lift Coeff: 0.7280
Drag Coeff: 0.0258
Cl/Cd: 28.1802

The results show smooth streamlines at 190 mph with no change in drag compared to the 10” radius. The streamlines at 90 mph indicate some minor upflow and they are less smooth than with the 10” radius, but not as divergent as with the 6” radius. The drag count and l/d ratio for the 8” radius are about halfway between the 6” and 10” values at 90 mph.

Conclusions

XFLR5 analysis results confirm that blended winglets have less drag than conventional Long-EZ winglets. The drag data was less useful when comparing different radii on blended winglets; the drag count changed very little across the 5” to 10” range, especially at 190 mph. But there were significant differences in streamline quality at 90 mph. I think the streamlines, pressure plots and l/d ratios are better indicators for comparing winglets within XFLR5.

It appears that a 6” radius is an acceptable minimum for blended winglets using the Long-EZ airfoils and chord lengths. This approximates the radius that was successfully tested on Jack Morrison’s E-Racer. Larger radii are beneficial at lower speeds and should improve performance over a wider range of pitch attitudes. Other parameters such as winglet airfoil, cant angle, offset and incidence also affect winglet performance and there was no attempt to optimize those variables.

It should be noted that larger wingtip chords require larger blend radii to achieve optimum results. For example, the Long-EZ has a relatively small 20” wingtip chord with offset trailing edges between the wing and winglet. This permits a 6” blend radius to work quite well, whereas the Apollo has a 28” wingtip chord with aligned trailing edges (between the wing and winglet) and requires an 11” radius to match the streamline quality of the 6” radius on the Long-EZ.

XFLR5 includes additional displays that could yield greater insight on winglet behavior. Used properly and with caution, XFLR5 can provide valuable data for optimizing aircraft configurations. This is a wonderful tool for amateur designers and I look forward to future releases.

Caveats

All conclusions presented herein are my opinions only. While I believe the analyses presented in this document are useful, the results may be inaccurate or misleading. They should not be relied upon for designing or modifying any aircraft. None of the XFLR5 data and displays should be trusted without confirming those results with other sound analytical methods. Consult a qualified engineer before making unapproved or untested winglet modifications to any aircraft.

Disclaimers and Warnings

1. Blended winglets are unapproved deviations from the Vari-EZ, Long-EZ, Cozy and E-Racer plans. <u>They involve significant structural and aerodynamic modifications that could adversely affect the safety of these aircraft</u>. Consult a qualified structural engineer before building untested or unproven winglet structures.
2. Removing the lower winglet on the Cozy Mk IV reduces the CG range and the deep stall margin at aft CGs. <u>The Cozy plans mandate the use of lower winglets to preserve safety margins</u>. Consult a qualified aerodynamicist before modifying winglets on any aircraft.
3. XFLR5 is written exclusively for the design of model sailplanes. <u>The code’s use for all other purposes especially for the design of real aircraft is strongly disapproved</u>. This program is distributed WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the GNU General Public License for more details.