Preliminary design of a high-altitude kite

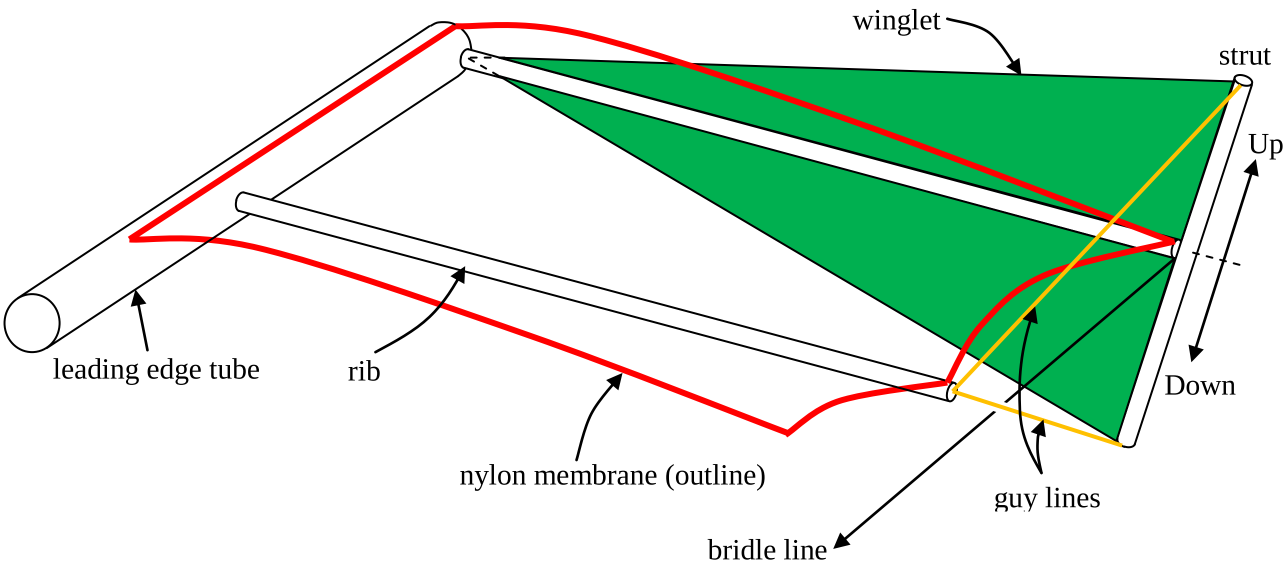
The question of winglets for a finite span kite

Over the past two decades, it has become fashionable for large jets to sport winglets. The benefits of winglets have been known since of the dawn of manned flight. Erecting a vertical fence along the wing tip prevents the lower pressure air on the top surface of the wing and the higher pressure air on the bottom surface of the wing from mingling.

It should not be taken for granted that winglets should be added to every wing. Winglets add weight. Perhaps it is no surprise that the proliferation of winglets has been concurrent with the widespread use of lighter, composite materials. A viable alternative to winglets is to add more wing span, except in the case of those large jets which are limited by the horizontal separation of ground facilities at the airports they service.

I would not consider adding winglets to the kite I have in mind except for one thing. In the next paper, I will examine yaw control. The usual mechanism for yaw control is a vertical fin and a hinged vertical rudder. It may be possible to use the winglets as vertical fins and as the physical support for rudders.

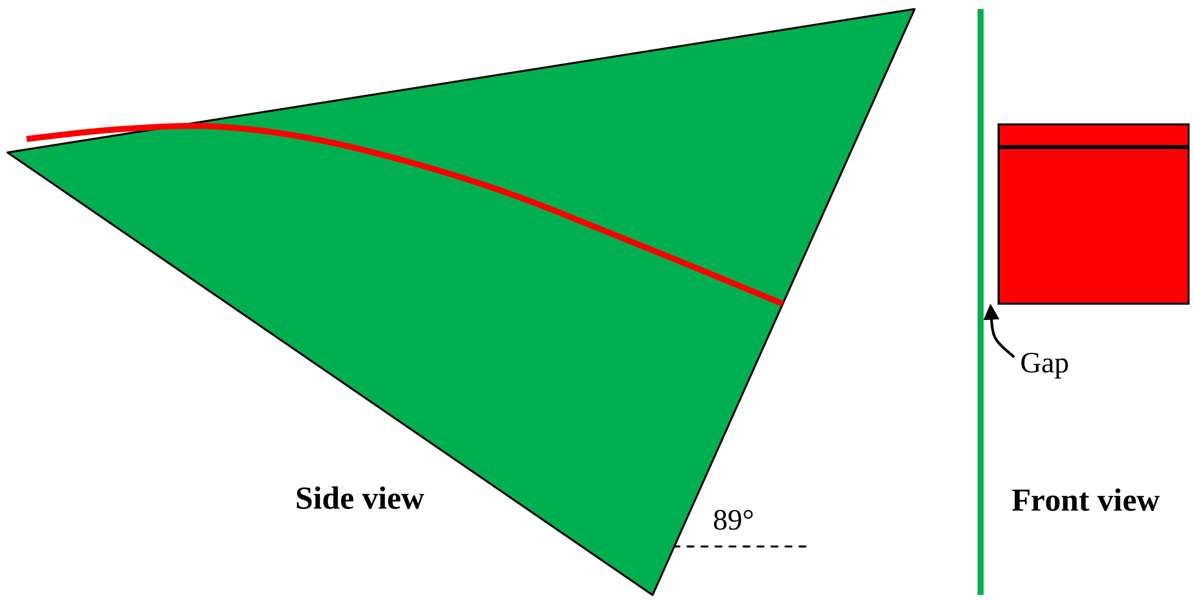
In this paper, I am going to look at winglets with the physical characteristics illustrated in the following figure. The figure shows the outboard meter or so of the right wing. As described in the earlier papers in this series, the leading edge tube will be a thin-walled aluminum tube one inch in diameter. The ribs will be thin carbon fiber tubes approximately one meter long. The flexible surface of the kite's wing is a sheet of (red) ripstop nylon. To avoid obscuring what lies below the membrane, I have only shown its outline in the figure. The winglet is a triangular piece of similar nylon sheet. I have rendered the winglet in green. Its front vertex will be secured to the front of the outer-most rib. The upper and lower vertices at the trailing edge of the winglet will be secured to the top and bottom of a vertical strut, which will be a carbon fiber tube similar to the ribs. I have labeled the directions "Up" and "Down" along the trailing edge of the winglet. In this study, I will look at winglets of various sizes and orientations, and will measure distances up and down from the aft end of the outer-most rib from the central point shown.



A strut which extends both above and below the aft end of the outer-most rib has a practical advantage. It can be stabilized with two guy lines, rendered in orange in the figure, and tying the top and bottom of the strut to the end of the next rib inboard. These guy lines will not interfere with the outer-most aft bridle line, which I have also shown in the figure. This bridle line will run from the aft end of the outer-most rib both forwards and downwards, and will not intersect the two guy lines.

I will examine the aerodynamics of the winglet using the same three-dimensional OpenFoam virtual wind tunnel which I used in the previous paper, entitled *De-rating the 2D kite section for a finite span*. I will model only the wing with a six-meter span, and only the left half of that wing will be included in the wind tunnel. To the extent possible, the same dimensions and mesh sizes were used. As before, OpenFoam's `kOmegaSST` turbulence model was used.

The winglet used in the aerodynamic model for OpenFoam is a slight idealization of the physical layout shown in the figure above. The following figure shows the nature of the assumptions used to describe the winglet to GMesh, which constructs the mesh used by OpenFoam.



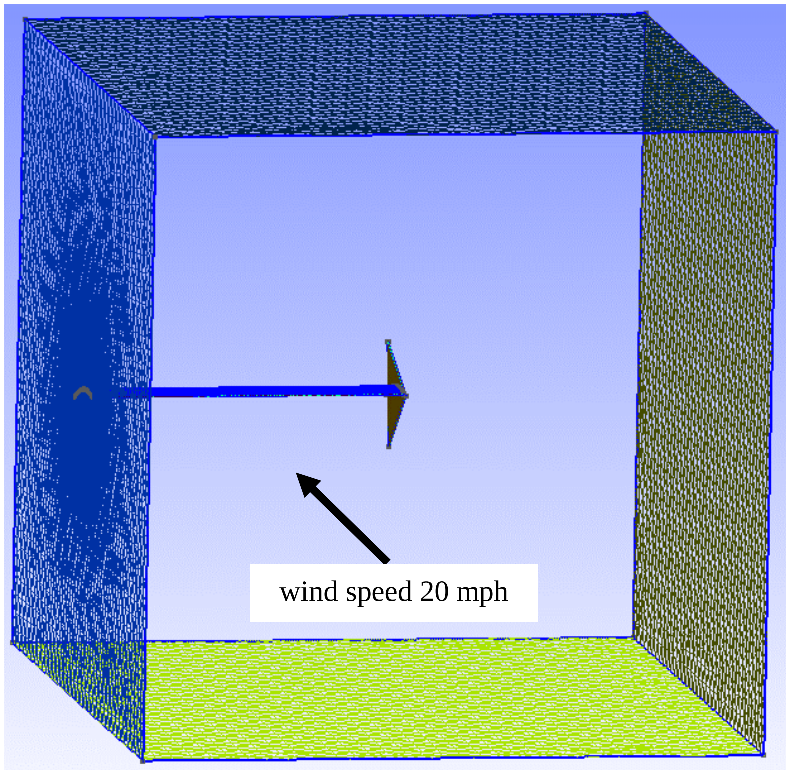
Recall that the three-dimensional aerodynamic model included only the free-flying segments of the nylon membrane. It did not include either the leading edge tube or the segments of the nylon membrane which lie tight on the surface of the leading edge tube. Nor did the three-dimensional model include the trailing edge strings which secured the aft edge of the nylon membrane to the aft ends of the ribs. The leading vertex of the winglet is assumed to coincident with the centrl axis of the leading edge tune. That is why the vertex is located slightly below and ahead of the first free-flying segment of the membrane, which begins at the "departure point" as defined in the earlier paper. The midpoint of the trailing edge of the winglet is assumed to be at the same location in the side view as the trailing edge of the membrane. In reality, the aft ends of the ribs are located downwind from the aft edge of the membrane by the length of the trailing edge strings.

One further assumption is shown in the front view. I have assumed that the horizontal membrane of the wing does not make contact with the vertical membrane of the winglet. I am reluctant to sew the outboard edge of the wing membrane to the winglet – doing so would restrict the horizontal membrane's ability to reshape itself in response to different flight conditions. In most of the OpenFoam simulations described below, the gap was set to two centimeters. But I did make a couple of runs with a one-half centimeter gap to estimate the effect. In all cases, the winglet was given a thickness of one millimeter and all three of its edges were left square.

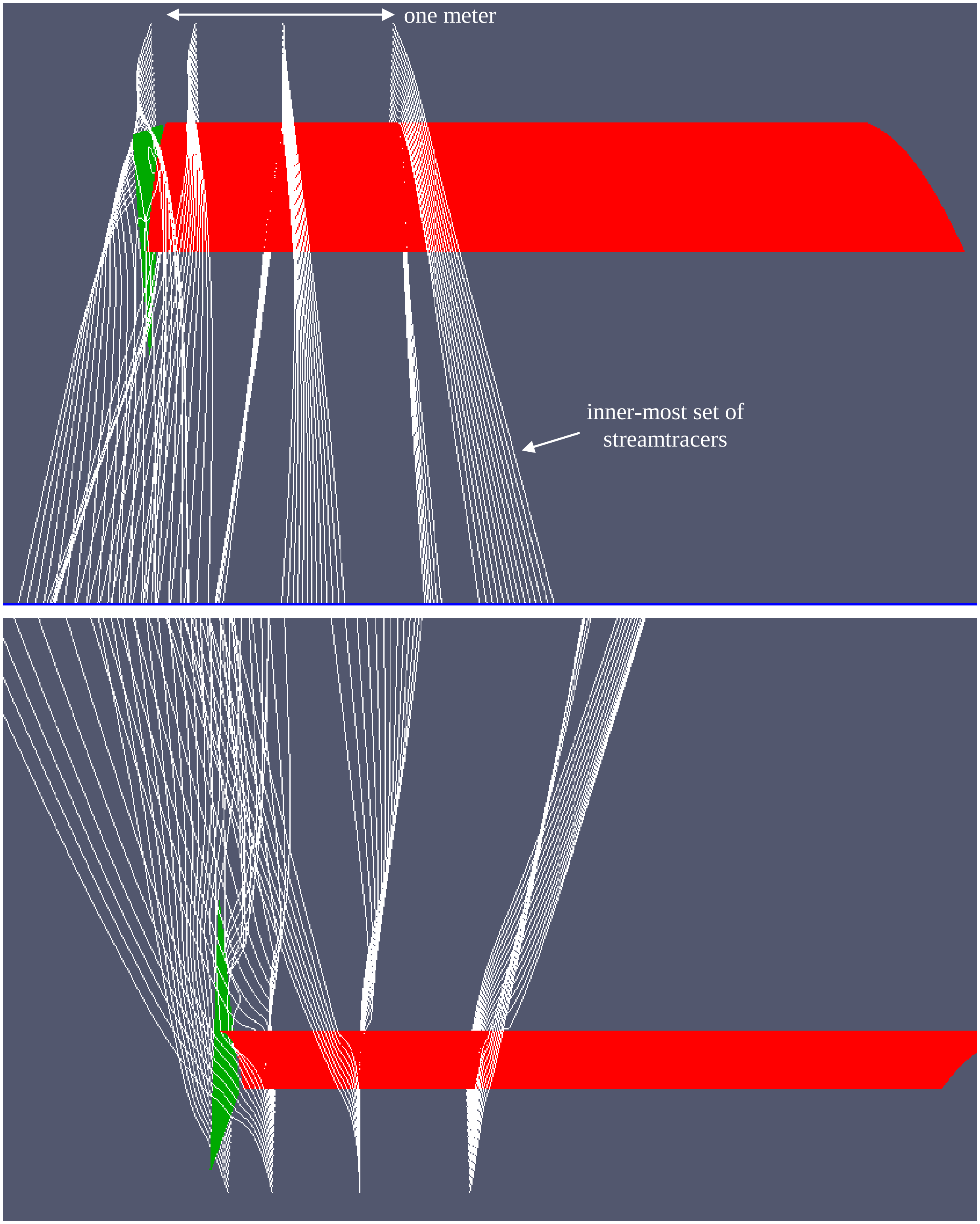
The trailing edge of the winglet is inclined at an angle of 89° to the horizontal. This is the complement of the 9° angle of attack used, and is the correct angle for the trailing edge if the strut is mounted perpendicularly to the outer-most rib at its aft end.

Because of the close proximity of the winglet to the wing tip of the wing, I used the same characteristic length for mesh size on the winglet and on the wing tip. (Even though the membrane which forms the wing is only one millimeter thick, it still has a definable tip which must be closed in and meshed.) The winglet and the outer-most points on the wing membrane were meshed using a characteristic length of two millimeters. The points on the wing's root were meshed using a characteristic length of 7.75 millimeters. The eight vertices at the corners of the wind tunnel were meshed using a characteristic length of 20 centimeters. All of these mesh sizes are the same as used in the previous paper. As GMesh divides the interior of the wind tunnel into small tetrahedra, it varies the size of the tetrahedra as smoothly as it can while still meeting the target sizes at those locations where they are specified by the user. As I experienced in the previous paper, it was necessary to use the Frontal algorithm for 2D and 3D meshing, rather than the Delaunay algorithm, in order to get GMesh to complete the work. Even using the Frontal algorithm, GMesh needed more than three hours of computer time (using one processor only) at 4.8 GHz for some of the cases.

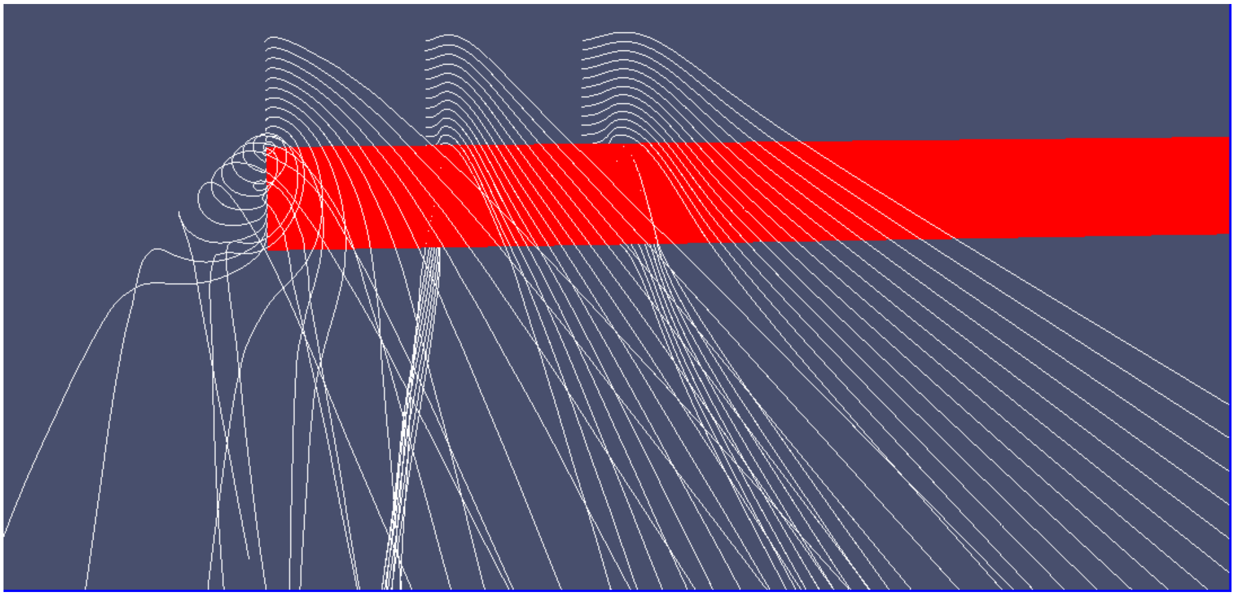
The following picture is a view through the virtual wind tunnel, from the upwind side, showing the grid on the surfaces of the left half of the wing and the left winglet.



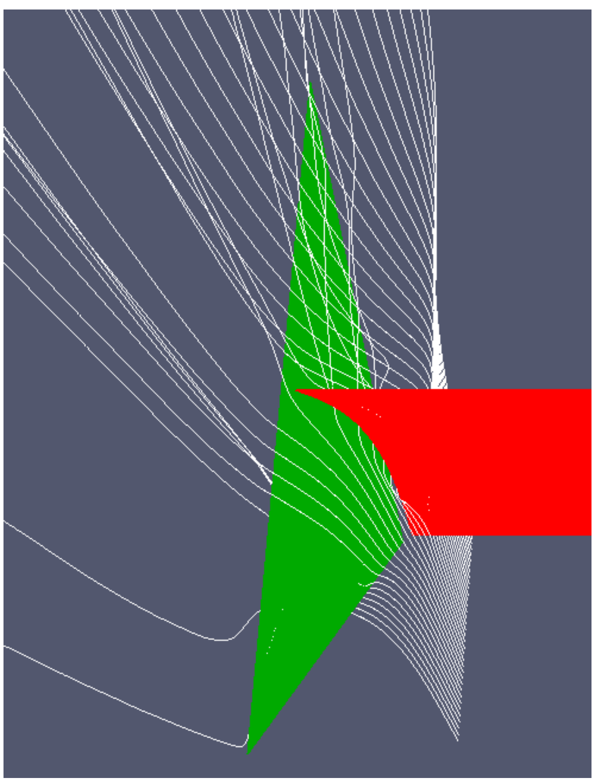
The length of the trailing edge of the winglet shown in the wind tunnel is one meter. Before getting into the quantitative results, I want to show the nature of the streamlines around this winglet. The following two pictures show the streamtracers emanating from four vertical generating lines located one-half meter upwind from the leading edge of the wing. The generating lines extend vertically from 30 centimeters below the leading edge to 30 centimeters above, and 20 streamtracers emanate from equally-spaced points along each line. The generating lines are concentrated towards the end of the wing. The inboard generating line is one meter in from the wing tip (or, two meters out from the midplane) and the "middle" generating line is located spanwise one-half meter in from the wing tip. The outer-most generating lines are located 10 centimeters inside and 10 centimeters outside of the wing tip, respectively. In both pictures, the camera is located five meters downwind from the leading edge and 2½ meters to the left of the midplane, due aft of the middle generating line. The first picture is looking down on the wing from above, with the camera placed two meters above the leading edge. The second picture is looking up at the wing from below, with the camera located two meters below the leading edge.



The effectiveness of the winglet can be gauged by comparing these two pictures with the comparable one for the same wing without a winglet, which is shown below. The two outboard generating lines have been combined into one, whose spanwise location is the wing tip itself.

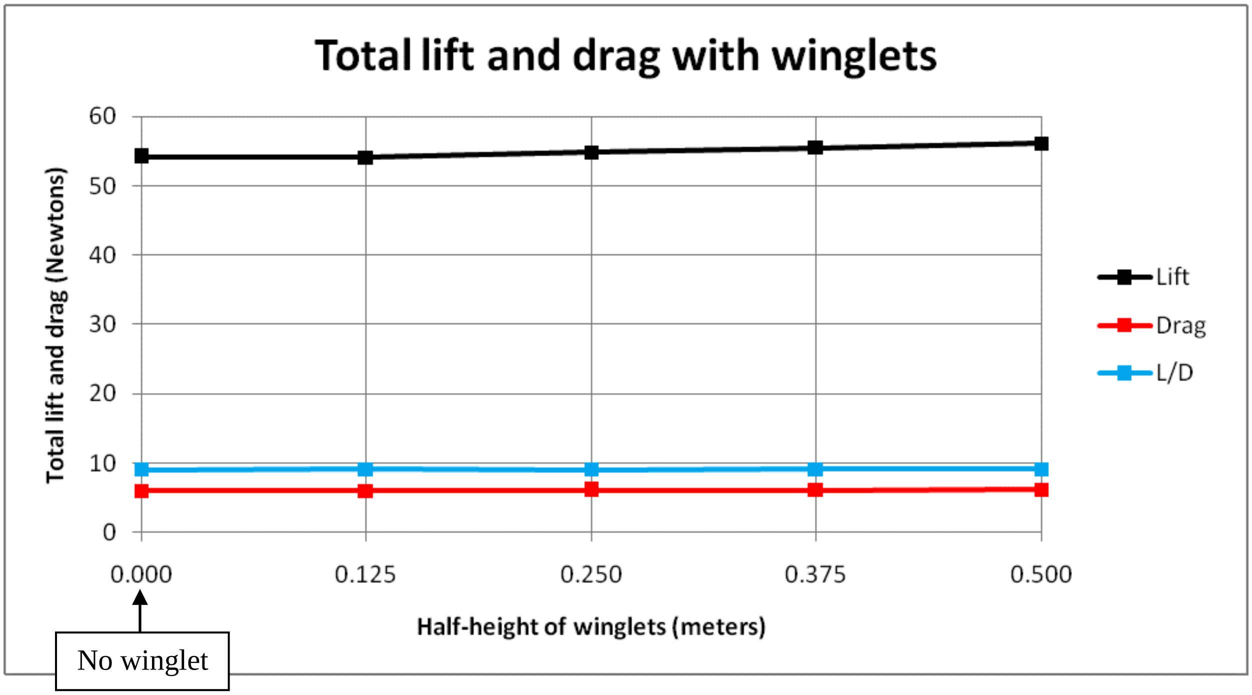


The winglet eliminates almost entirely the wing tip vortex. The winglet does a good job of keeping the vertical planes of streamtracers in their vertical planes. On the underside of the wing, none of the streamtracers cross the plane of the winglet. On the top side of the wing, only a few of the streamtracers from the region outboard of the winglet manage to cross over by flowing over the top of the winglet near its trailing edge.

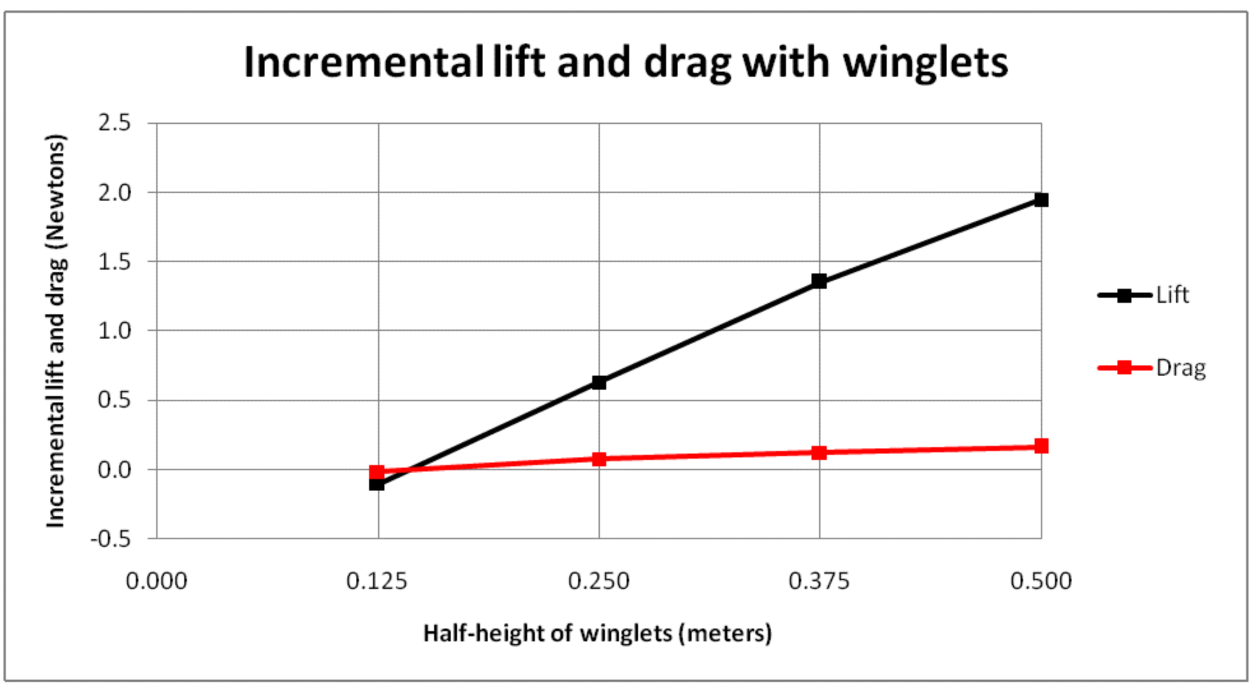


A few of the streamtracers on the underside of the wing do flow through the gap between the wing tip and the winglet. Their escape is shown in a close-up of the gap shown to the left. The vertical line which generates these streamtracers is 2.95 meters from the midplane, only five centimeters inboard from the wing tip. In the appropriate section below, I will show a similar picture of the leakage through the narrower, one-half centimeter, gap.

The following graph shows the total lift and drag on the wing. Since the virtual wind tunnel only includes half the wing and one winglet, the magnitude of the forces in the graph is twice the values calculated by OpenFoam. Four sizes of winglets were tested. They varied in the length of the vertical strut. The total lengths range in equal steps from one-quarter meter to one meter. (The streamtracers shown above are for the one-meter total length.) In each case, one-half of the length was "Up" and the other half "Down".

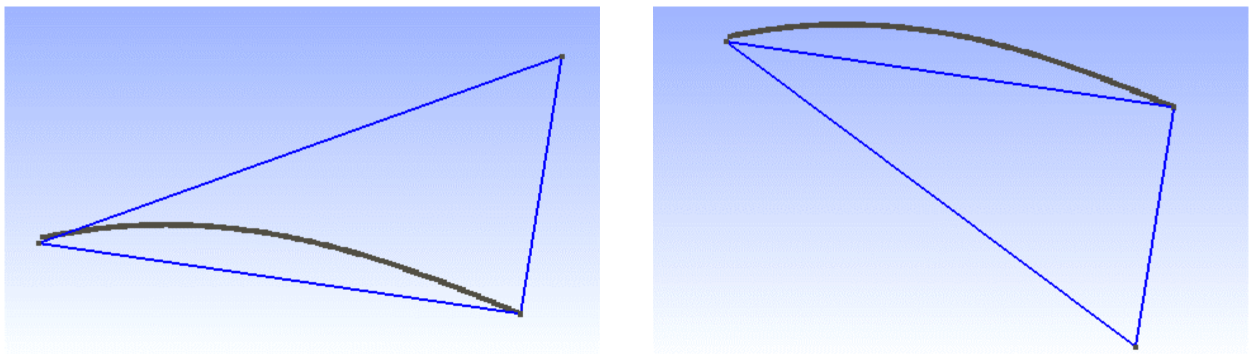


Winglets cause a small increase in total lift (the black line). The increase increases with the length of the strut. The effect of winglets on the total drag, and on the lift-to-drag ratio, is not discernable to the eye in this graph. In order to isolate the effect, I re-plotted the data. I subtracted the lift and drag of the no-winglet case from the lift and drag of each of the four cases with winglets. The difference, called the incremental lift and incremental drag due to the winglets, is plotted in the following graph.



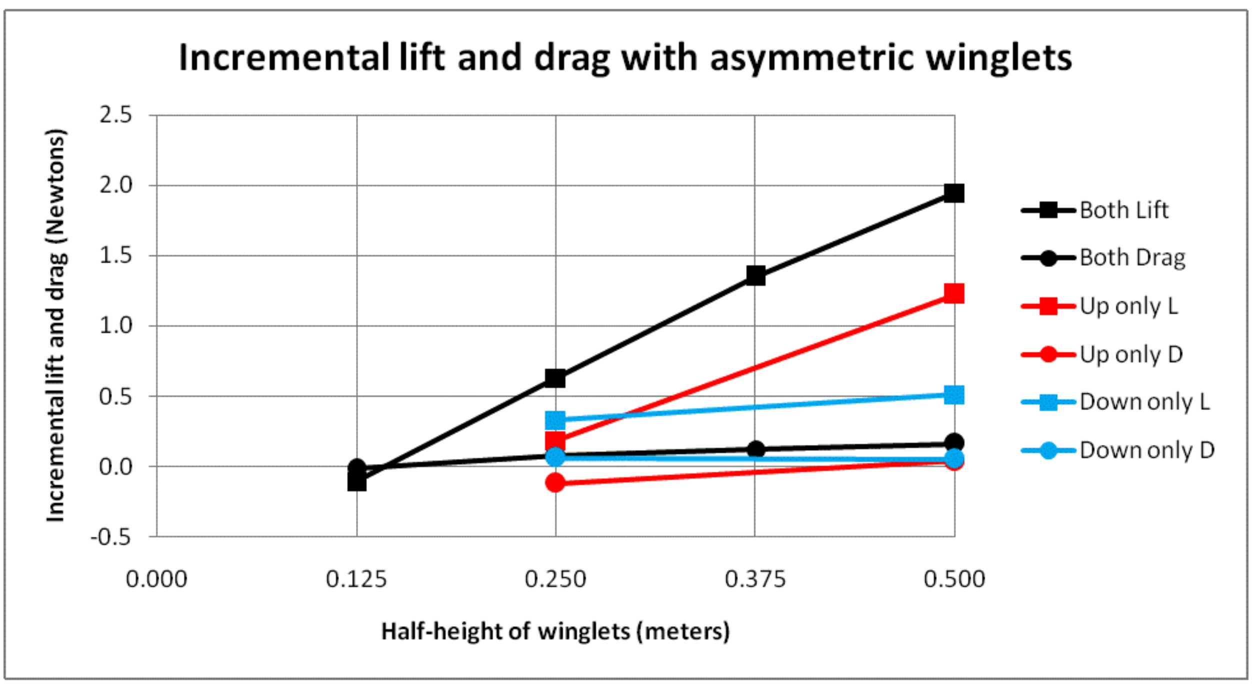
The largest winglet tested – with a one-meter vertical trailing edge – increases the total lift by about two Newtons, which is approximately one-half pound. It looks like the lift increases almost linearly with the length of the strut, but starting with zero increase in lift when the strut is one-quarter meter long. The incremental drag (the red line) increases very slightly, and approximately linearly, as the size of the winglet increases. The incremental drag, too, starts at zero when the strut is one-quarter meter long.

I next looked at the effect of asymmetrical winglets. I modeled winglets which consisted of only the top half, or only the bottom half, of the basic triangular shape. The following two figures are end-on views of the wing with a top half-only winglet with a trailing edge length of one-half meter (on the left) and of the wing with a bottom-half only winglet with the same one-half meter trailing edge (on the right).



The Up-only winglet gains a bit of an advantage from the camber in the wing – its straight bottom edge runs alongside the reference chord (and the ribs) and provides a partial fence to air flow along the bottom side of the wing.

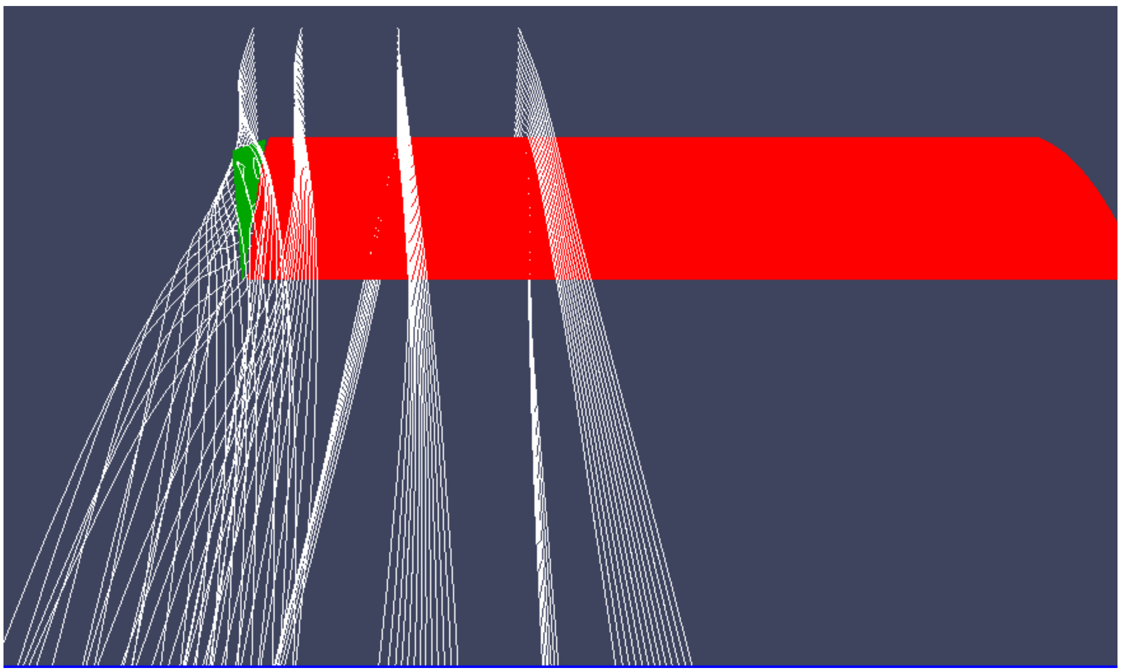
The following graph shows the incremental lift and drag from these two winglets and from a similar Up-only and Down-only pair of winglets whose trailing edge length is one-quarter meter. For the purpose of comparison, the lines in the graph above, for the symmetrical winglets, are also shown.

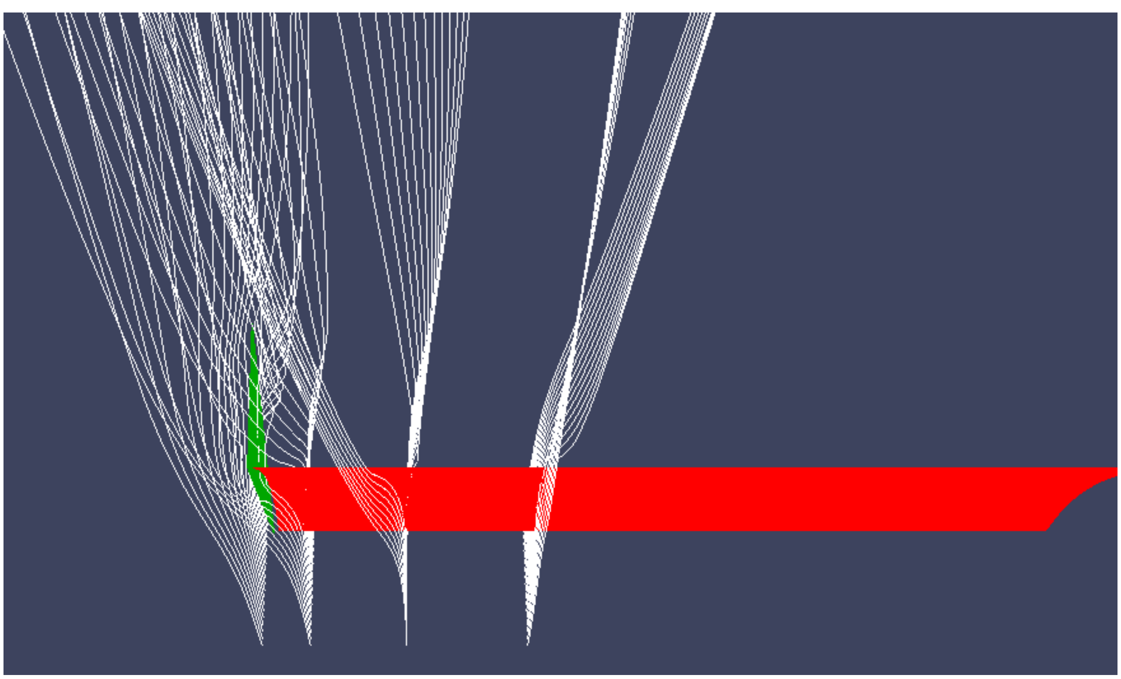


In the larger size, with the one-half meter trailing edge, the Up-only winglet is clearly more effective than the Down-only winglet. They have the same incremental drag, but the Up-only incremental lift is more than twice as large.

In the smaller size, the conclusion is not so clear. The Down-only winglet has the greater lift but the Up-only winglet has the lesser drag. Both winglets have the same difference between incremental lift and drag. If the lift-to-drag ratio is used as the figure of merit for a comparison, the Up-only winglet would be ruled the better one in the smaller size, too.

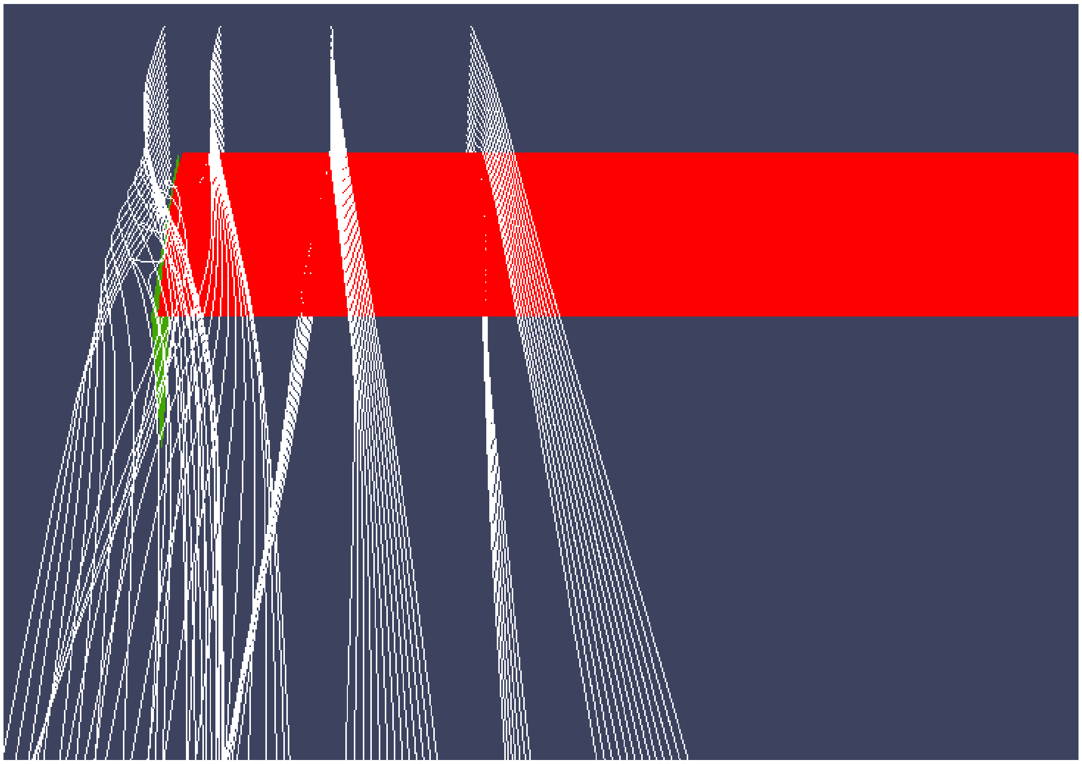
The following two pictures show the streamtracers around the Up-only half-meter winglet, from vantage points above and below the wing. The generating lines for the streamtracers, and the camera position, are exactly the same as those used in the pictures above for the symmetrical winglet.

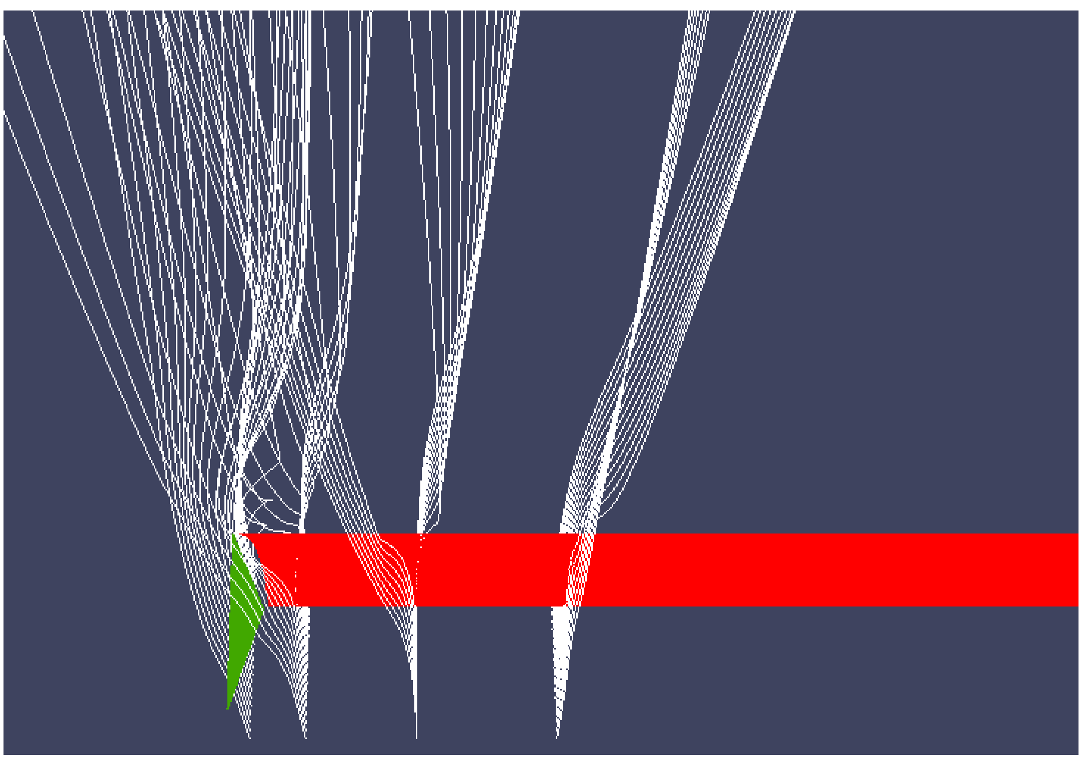




The streamtracers above the wing are very similar to those in its corresponding symmetrical case. With very little "fence" below the wing, there is less to prevent the streamtracers near the wing tip from flowing outwards, which they clearly do. And, once they are outboard of the wing tip, they begin to curl upwards in an incipient vortex.

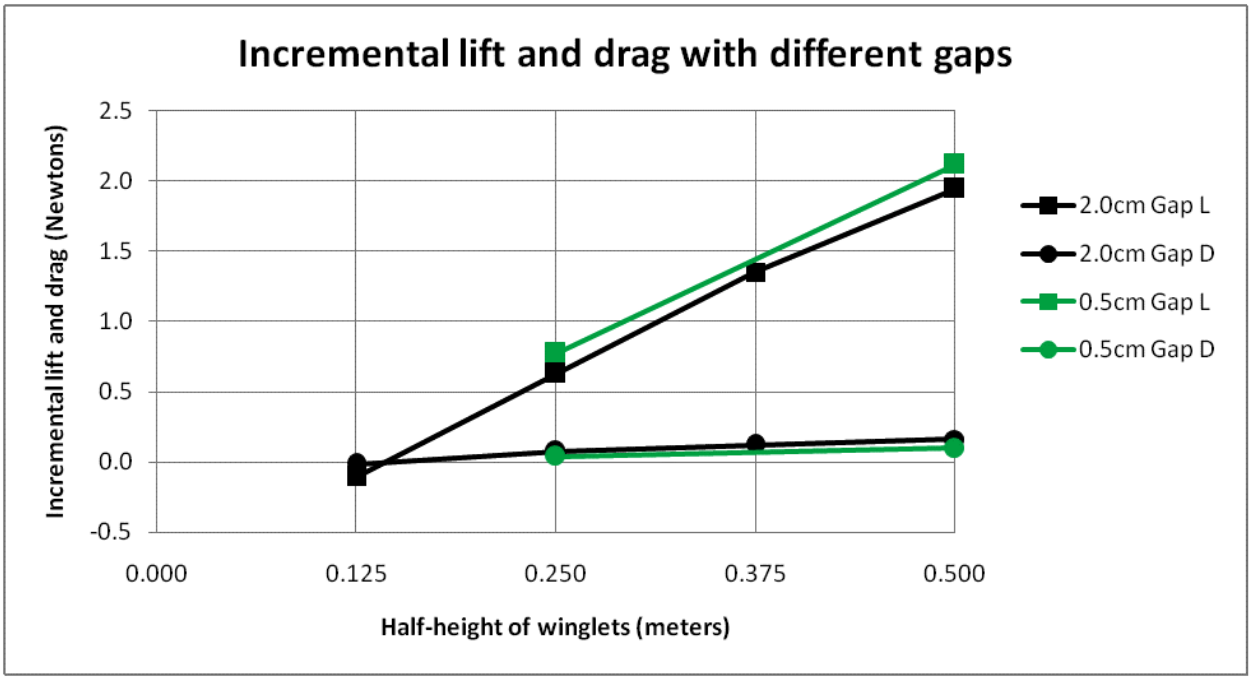
The following two pictures show the streamtracers around the Down-only half-meter winglet, from vantage points above and below the wing. The generating lines for the streamtracers, and the camera position, are the same as used above.



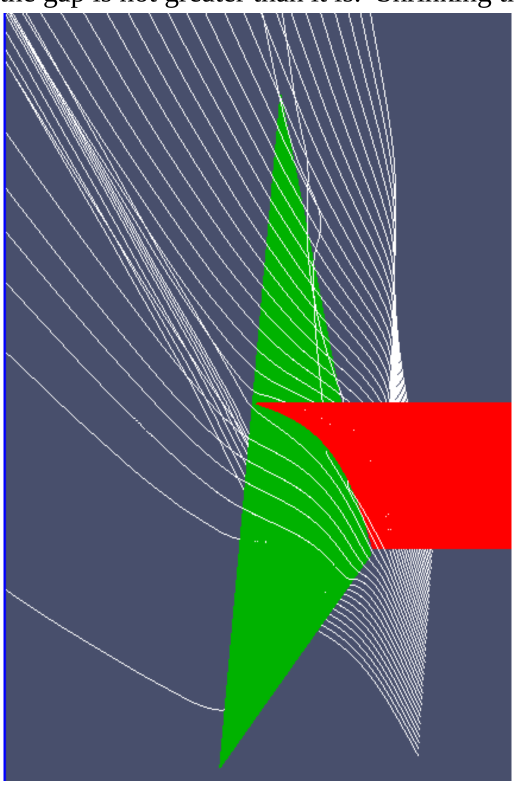


The Down-only winglet keeps the streamtracers below the surface in their vertical planes. But, it does nothing above the wing, and the vortex becomes much fuller than it does for the Up-only winglet.

The size of the gap may also be an important factor. To explore this, I re-ran two of the cases with symmetrical winglets, but using a smaller gap. In all of the cases described above, there was a two centimeter gap between the wing tip and the inner side of the winglet. In the new cases run now, the gap was reduced to one-half centimeter. The following graph shows how the incremental lift and drag vary with different gaps.



The black lines are for the two centimeter gap; the green lines are for the smaller gap. Narrowing the gap increases the lift and reduces the drag, as one might expect. What is surprising is that the effect of closing the gap is not greater than it is. Shrinking the gap by 75%, from 2 cm to 0.5 cm, increases the incremental lift by less than 10%. I conclude from this that it would not be necessary to sew the outer edge of the surface membrane to the winglet. However, attempts should be made to keep the two as close together as possible, but it is not necessary that the gap be sewn shut.



The picture at the left shows the leakage through the one-half centimeter gap. The leakage is much less than appears on the corresponding picture above for the two-centimeter gap.

Before concluding this paper, I want to circle back and assess the benefits and costs of adding winglets. Let me compare the total lift and drag of three configurations: (i) the basic six-meter wing without winglets, (ii) the same wing with one-meter winglets, deployed with the smaller 0.5 centimeter gap, and (iii) a seven-meter wing without winglets. The data for the seven-meter wing is taken from the earlier paper titled *De-rating the 2D kite section for a finite span*. The comparable figures are set out in the following table:

Configuration	**Total lift**	**Total drag**	**L/D ratio**
6m span	54.15 N	5.98	9.06
6m span + 1m winglets	56.27 N	6.08	9.26
7m span	64.51 N	6.83	9.45

Adding winglets to the six-meter wing increases lift by 2.12 Newtons, or 3.9%. Adding another meter of span increases the total lift by 10.36 Newtons, or 19.1%. This increase is five times greater. Remember that increasing the span has a two-fold benefit: (i) it increases the lifting area and (ii) it also increases the lift on the inner six-meters of the span. Increasing the span by one meter increases the lift-to-drag ratio by twice the increase provided by winglets.

What are the costs? Two one-meter winglets add the following structural components: (i) two one-meter lengths of thin carbon fiber tube, (ii) about one square meter of nylon membrane (each winglet is a triangle with a one-meter "base" and a one-meter "height"), (iii) four guy lines with supporting hardware and (iv) two elbow connectors to hold the struts at right angle to the ends of the outer ribs.

Adding an extra meter of span adds the following structural components: (i) another meter of the aluminum leading edge tube, (ii) one more rib, which is a one-meter length of the carbon fiber tube, (iii) about one square meter of nylon membrane and (iv) four more bridle lines.

It is true than the extra meter of leading edge tube (needed for the wider span) weighs more than the extra meter of carbon fiber tube (needed for the winglets). The four extra bridle lines (needed for the wider span) will likely weigh more than the four guy lines (needed for the winglets). Whether the difference in the weight between the two alternatives is greater than a factor of five requires further study.

There is also a cost in terms of convenience. Rigging the kite with an extra meter of span will be faster than setting up and trimming two winglets.

It is not at all clear that winglets are the better choice. As I mentioned at the outset of this paper, my interest in winglets is driven by the possible use of their trailing edge struts as mounting hinges for rudders, which might be the best way to control yaw.

Jim Hawley
October 2014

An e-mail setting out errors or omissions would be appreciated.