Comparison of Kirsten Wind Tunnel Test and Aerodynamic Theory

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The test, sponsored by Microsoft under A. Kapoor, took place in September 2022. The RC-glider model was made by Seim, and the principal KWT contributors were M. Salguero and C. Winter.

Here, the theory and analysis are by Spalart, the airfoil calculations by Seim, and the figures by Dickson.

We first discuss the wing area. The true area includes the carry-over of the root region and body, and is around $S=0.365m^2$. The KWT report used a lower value for the Reference Area, namely $0.336m^2$, and results are plotted in these units. It's just a slightly different convention, by a ratio of 0.9.

The area of the horizontal tail is $S_{HT}=0.08S$. The Mean Aerodynamic Chord is about 0.16m, and we take a run with velocity 200mph, which gives a chord Reynolds number of 950,000.

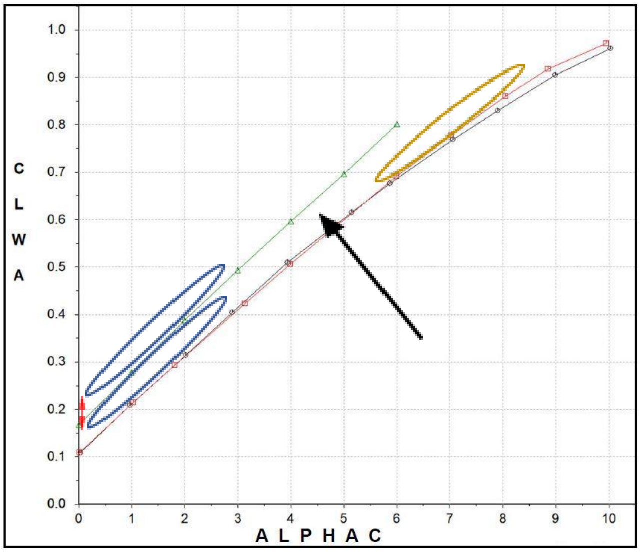
Seim ran the airfoil package XFLR5, which is based on Drela's XFOIL solver, first with free transition and n=5, and then with transition fixed at 10% of chord, as a crude way of reflecting the relatively high Free Stream Turbulence level of the tunnel. We also had early XFLR5 results from B. Gherardi, and they compared fairly well. Fully-turbulent skin-friction theory predicts $C_d \sim 0.01$ at low α; in XFLR5 free transition gives long laminar regions and 0.005, whereas tripped gives 0.011 which we used for the figures. We added 40% more parasite drag for the tail and body wetted area, and the interference drag.

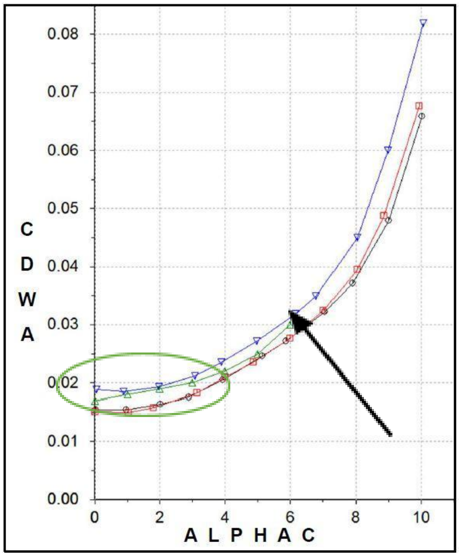
We combine Lifting-Line Theory with the XFLR5 results, and tail lift, with aspect-ratio corrections. The camber of 1.12% normally gives a C_l at 0 degrees near 0.11, and XFLR5 gives about 0.15. We also include the incidence of the wing with respect to the fuselage reference axis, which averages 0.25^o. Lifting Line is used to give the induced drag with an Oswald Efficiency factor e=0.95, which is reasonable for such a clean wing in free air. We then calculate the induced drag in the tunnel, with four walls, and then e~1.3, in other words the induced is much lower. We have a span of 8ft and a tunnel height of 8ft. The aspect ratio is 15 and 3D effects reduce the lift relative to 2D by a factor (1+2/eAR).

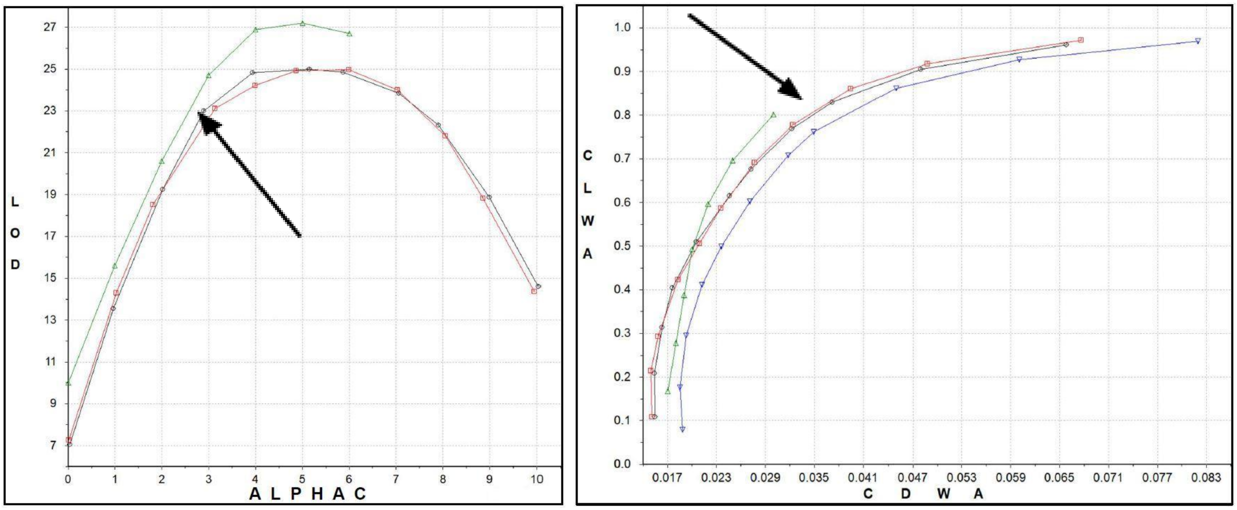
This leads to the following table.

α	C_{l2D}	C_{lwing}	C_{lHT}	C_l	$C_l/0.9$	$C_{d2Dfree}$	$C_{d2Dtrip}$	C_{diFA}	C_{diWT}	C_d	C_l/C_d	$C_d/0.9$
0	0.146	0.150	0	0.150	0.167	0.005	0.011	0.000	0.000	0.015	10.0	0.017
1	0.246	0.236	0.014	0.250	0.278	0.005	0.011	0.001	0.001	0.016	15.6	0.018
2	0.346	0.321	0.028	0.349	0.388	0.005	0.011	0.003	0.002	0.017	20.6	0.019
3	0.440	0.402	0.042	0.444	0.493	0.007	0.011	0.005	0.003	0.018	24.7	0.020
4	0.532	0.481	0.056	0.537	0.597	0.008	0.011	0.007	0.005	0.020	26.9	0.022
5	0.622	0.556	0.070	0.626	0.696	0.009	0.012	0.009	0.007	0.023	27.2	0.025
6	0.715	0.638	0.084	0.722	0.802	0.011	0.013	0.012	0.009	0.027	26.7	0.030

The figures show lift, drag and L/D versus α, and then drag versus lift. The columns $C_l/0.9$ and $C_d/0.9$ were input.







Results of wind tunnel (black and red, at two speeds) and theory (green). Four graphs: lift coefficient versus α; drag versus α; L/D versus α; lift versus drag coefficients

We begin with the lift coefficient. The slope is the most fundamental quantity. At low α, the test gives 0.106 per degree, and the theory 0.111, which is 5% higher (blue ellipses). We tentatively explain this with elastic deformation as seen below, but cannot explain the fact that the theoretical lift is higher by about 0.07 (red arrow). The incidence and camber of the wing would justify a $C_l/0.9$ near 0.18 at α = 0, which is very close to the theory.

At even higher angles of attack, the KWT lift bends downwards (gold ellipse). We attribute this to elastic deformation of the wing. There is both flexing and twisting in the direction of washout. Stills from the movie suggest about 1.4° washout at the tip. The weighted average local angle-of-attack reduction would then be about 0.4°, worth 0.044 in $C_l/0.9$. This is close to the amount the curve ends up below a straight line extrapolated from low α. The theory has no such bending, but it was based on a rigid model.

The theoretical drag is consistently lower than in the test, especially if compared with the wind-tunnel test that had trips at 50% chord; trips at 10% as they were in the XFLR5 run would raise the drag even more. However, in the useful region of the polar, the *L/D* predictions differ by only 8%: 27 versus 25.

Lessons Learned for Airsim

1. The combination of XFLR5 airfoil predictions (1980's technology) and Lifting Line Theory (1910's) comes very close to reproducing the wind-tunnel results, at very low cost compared with 3D CFD. This is shown here only without sideslip β, for which 3D CFD would be needed, but such effects are minor in flight. The strongest disagreement is a 0.7-degree shift in the lift curve (red arrow).

   The only step taken to improve the agreement was to trip the boundary layers at 5% chord in XFLR5, which brought the drag up and was consistent with the idea that the wind tunnel has high freestream turbulence. The agreement is still not great (green). Drag is hard!

2. The drag is significantly lower in the tunnel than in flight due to wall effects, so that test results would need to be heavily corrected either by theory or CFD.
3. The extrapolation to speeds outside the tunnel's range must be done with aerodynamic theory based on the Dynamic Pressure q, and definitely not with the AI tool applied to the raw lift and drag! The black arrows show how well the dynamic pressure makes different-speed runs collapse, so that q scaling will work very well until the Mach number exceeds maybe 0.65.
4. A fair amount of the disagreement between test and theory is plausibly due to the elastic deformation of the wing under high loads (i.e. washout, which is visible in the video). This is not known numerically as of today, either from Theory or 3D CFD with a rigid model. Confirming the washout on the existing model would take days of work with sandbags.