Evaluating the Significance of Finite Wing Effects on Wing Lift Using XFoil and AVL

Thomas Greenhill, 1.15.2020

The purpose of this study is to evaluate the significance of the sum of downwash, tip effect and spanwise flow (finite wing effects) on wing performance. I am performing this study primarily to uncover sources of error to explain the discrepancy between AVL and XFoil-derived lift in the context of SparrowHawk load calculations. My curiosity is a secondary motivation, and coming up with an understanding of when, if ever, we can approximate finite wings as infinite is extremely valuable. This investigation will use a NACA 2412 airfoil and focus on the significance of total finite wing effects (tip effect, downwash & spanwise flow) for wings of different aspect ratio at different angles of attack. Finally, a comparison between the lift obtained with an actual wind tunnel, XFoil, and thin airfoil theory will be executed to validate XFoil's accuracy.

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Constants, Setup & Procedures:

Constants:

$$V_\infty = 45\frac{m}{s} = 0.1312\ Ma$$

$$C = 1\ m$$

Thin airfoil theory calculations are calculated with span efficiency ratio $e = 0.95$ and 2D lift coefficient slope $C_{l\alpha} = 0.11$.

Setup & Procedure:

A straight wing with NACA 2412 cross section & 1m chord will be used. Freestream velocity of 45 m/s will be used because it is close to the SparrowHawk's Va of 41.16 m/s and it produces Re = 3*10^6. Smooth surface condition will be assumed, with NCrit of 9. STP conditions are assumed.

Wings with aspect ratio 5, 10, 20, 30, 40, 50, 200 will be considered.

First, 2D analysis (infinite wing analysis) will be performed in XFoil with $\alpha = -2{:}\,2{:}\,16$. The C_L values for each angle of attack will be recorded and will be compared to the C_L values for finite wing determined in AVL.

In AVL, 3D analysis for finite wings with aspect ratios defined above will be performed with the same angle of attack range as defined for the 2D analysis.

C_L vs. Varying Aspect Ratio and Angle of Attack

Using AVL, wings of aspect ratio 5, 10, 20, 30, 40, 50 & 200 were analyzed with angle of attack -2:2:16. The results of the study can be seen in Figure 1 below.

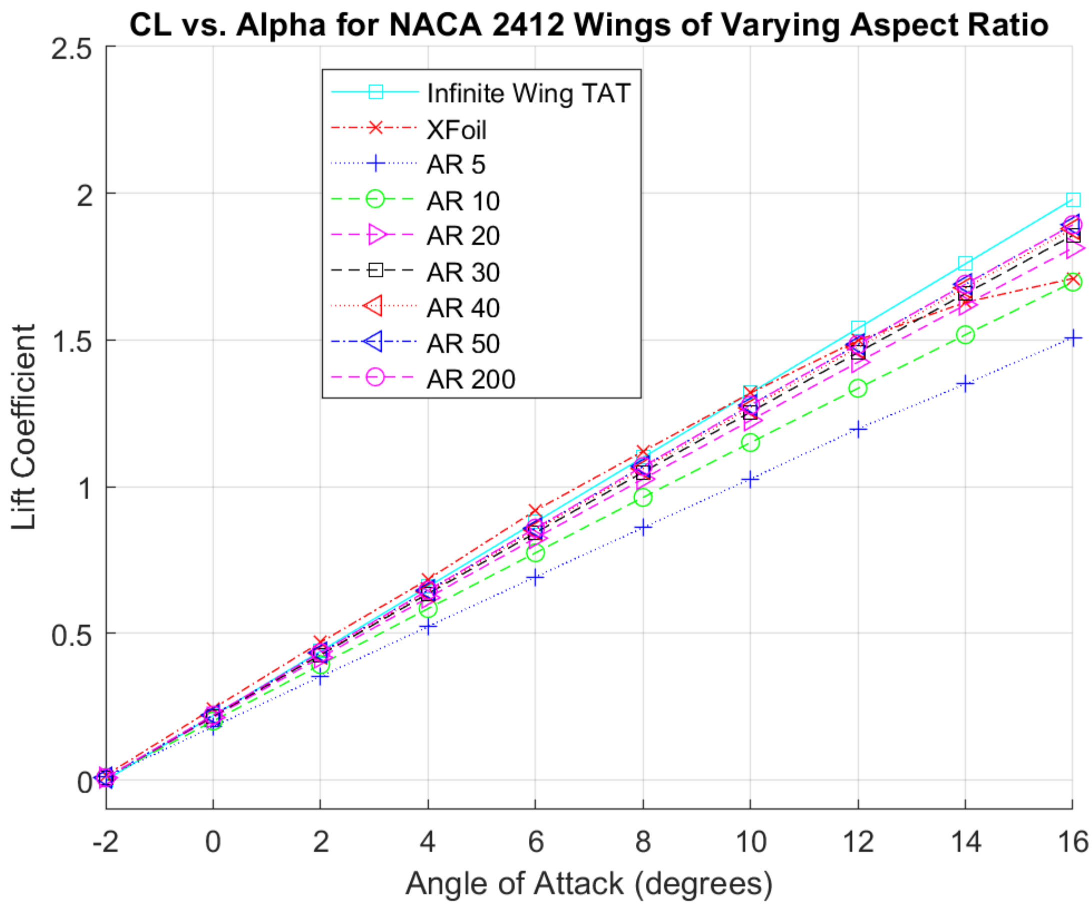

Figure 1: C_L vs. α for NACA 2412 Infinite Wings & Wings of Finite Aspect Ratio

As expected, the lift performance throughout the range of angles of attack of a wing with small aspect ratio is notably worse than that for a wing with infinite aspect ratio. For small angles of attack (-2:6), wings of aspect ratio of 30 or greater are within 4% of the XFoil and thin airfoil theory (TAT) infinite wing model. However, even with a practically infinite aspect ratio of 200 at high angles of attack, a >2% difference exists between thin airfoil theory for infinite wing and

AVL's finite wing model. This is probably the result of downwash effects, since with such a high aspect ratio wing, tip and spanwise flow effects should be negligible. Overall, when investigating wings with high aspect ratios (≥ 30) at small angles of attack (-2:6), the infinite wing models provide a close representation (within 4%) of the finite wings.

C_L vs. Angle of Attack for Aspect Ratio 30 Wing with Different Models

This section evaluates the difference in lift coefficient between infinite wing thin airfoil theory, 30 aspect ratio thin airfoil theory and 30 aspect ratio results from AVL. Figure 2 below provides a plot of the three with varying angle of attack.

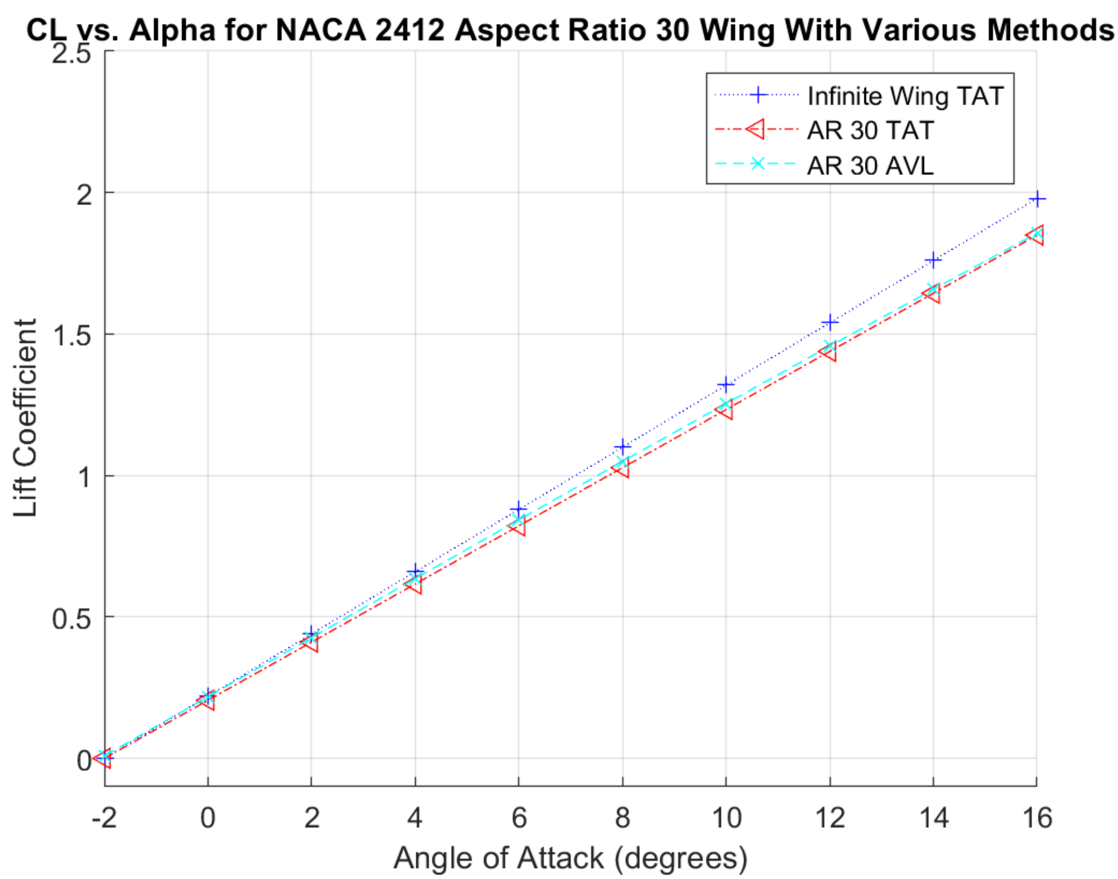

Figure 2: C_L vs. Angle of Attack for 30 Aspect Ratio Wing and Infinite Aspect Ratio Wing

Throughout the angle of attack range, the two methods used to analyze the lift coefficient of the 30 aspect ratio wing are nearly identical. As mentioned in the first part, the discrepancy between the infinite wing analysis and finite wing analysis is reasonable at small angles of attack, but with a linearly increasing error propagation, the infinite wing approximation is not acceptable for larger angles of attack.

C_L vs. Angle of Attack for Infinite Wing with Different Models

In this part, the relative accuracy of each infinite wing model is evaluated. I am most interested in evaluating the accuracy of the XFoil results compared to the wind tunnel results, as this sheds some light on how accurately the software represents reality. See the plot in Figure 3.

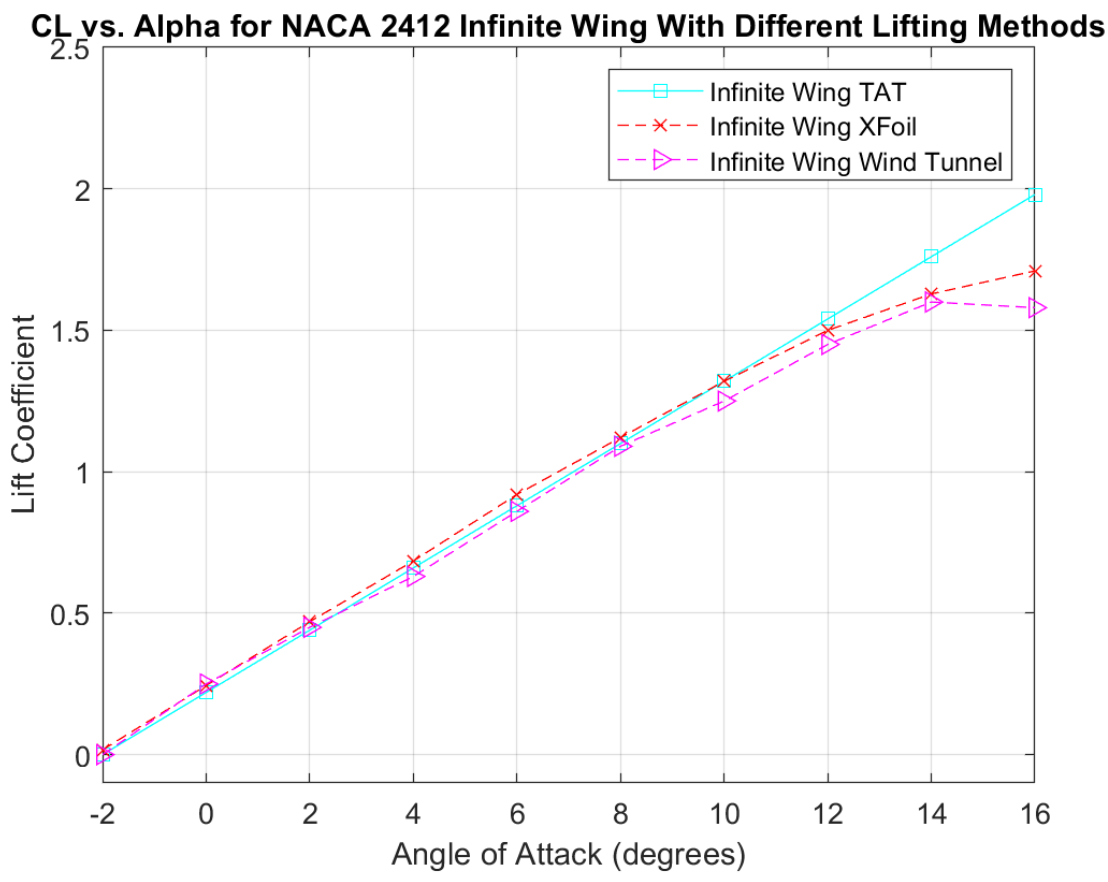

Figure 3: C_L vs. Angle of Attack for Infinite Wing with Different Models

Clearly, the XFoil results closely match the wind tunnel results for the given angle of attack range, but the two curves are not identical. The wind tunnel data was taken from a chart in Appendix C of *Introduction to Aircraft Flight Mechanics, 2nd Ed,* so a small error may be present due to the fact that I had to read the points off of the plot by hand with fairly coarse axis scales. The general trend, though, indicates that the XFoil results are more conservative than the wind tunnel results. This difference is likely the result of greater surface roughness of the wing in the wind tunnel than the ideal computer model. This conservative trend does not pose any issues in the context of structural analysis but must be taken into consideration when projecting performance figures as to not overpredict performance.

In the Context of SparrowHawk

The load calculations performed for SparrowHawk were completed using AVL and XFoil for validation. In general, the results derived from XFoil were 10-15% greater than the results from AVL. With an aspect ratio of 7, the horizontal stabilizer falls within the range where the XFoil model was shown to not very accurately represent finite wings. A compensation factor based on linear interpolation of the relative error between the finite and infinite wing models calculated above at appropriate angle of attack has been imposed on the SparrowHawk loads and can be seen in the table below.

Load Case	Using	LHstab (N)	%Error
6	AVL	930.85	
6	XFoil (compensated)	931.05794	0.022334
7	AVL	-1010.46	
7	XFoil (compensated)	-1044.3756	3.247448

Table 1: SparrowHawk Horizontal Stabilizer Max Loads in AVL and XFoil, Compensated for Finite Wing Effects

Whereas the relative error between AVL and XFoil had previously been around 10-15%, with the compensation factor, the results collected with XFoil are within 3.25% of the results collected using AVL. Because I had to use linear interpolation to come up with the compensation factor and the fact that the airfoil used to create the compensation factor is not the same as the SparrowHawk horizontal stabilizer airfoil, I am tempted to conclude that the results from AVL are almost certainly more representative of reality.

I propose that we use the results from AVL to conduct the load tests, and that we use the results from XFoil as a secondary data point "sanity check" only.