A New Airfoil Optimized For Light Aircraft Performance

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ABSTRACT

A new low Reynolds number, natural laminar flow airfoil design and its impact on performance of a generic light sailplane are presented. Several previously published airfoils, the Liebeck/Camacho LA203A and the Somers/Maughmer SM701, were used as a starting point. They are examined along with several new attempts to further the state of the art for natural laminar flow, single element airfoils. The computational tool XFOIL was used to analyze these airfoils, and the resulting data were adjusted and applied to a generic Sporting Class sailplane design. The results indicated that overall performance improvements are possible over the SM701, the LA203A, and a third reference airfoil.

NOMENCLATURE

α	alpha, angle of attack ~ degrees
ν	nu, kinematic viscosity = 0.00015723 ft^2/sec, sea level standard day
π	pi, 3.1415927
ρ	rho, density = 0.002377 lb sec^2 / ft^4, sea level standard day
AR	wing aspect ratio = b^2 / S_{ref}
b	wing span ~ ft.
cbar	mean aerodynamic chord ~ ft.
C_d	airfoil sectional lift coefficient
C_D	total aircraft drag coefficient
C_l	airfoil sectional lift coefficient
C_{lmax}	airfoil sectional maximum lift coefficient
C_L	total aircraft lift coefficient
C_{Lmax}	total aircraft maximum lift coefficient
C_m	airfoil sectional pitching moment coefficient about quarter chord
C_M	total aircraft pitching moment coefficient about moment reference center
C_p	pressure coefficient = (p-pinf)/qinf = $1-(v/vinf)^2$
D	drag ~ lb.
e	wing planform inviscid efficiency factor
L	lift ~ lb.
L/D	aircraft lift / drag ratio
q	dynamic pressure = $0.5*\rho*V^2$ ~ lb. / ft^2
Re	Reynolds number = V~mph * (528 / 360) * cbar / ν
S_{ref}	aircraft reference wing area ~ ft^2
V	aircraft true airspeed ~ mph
W	weight ~ lb.
X	airfoil longitudinal dimension
Z	airfoil vertical dimension

INTRODUCTION

Airfoil design continues to evolve as computational tools and aircraft build techniques both mature. The demand will continue for better airfoils that feature sustained runs of natural laminar flow coupled with a shape that is easily built. Laminar flow airfoils typically sustain a low drag laminar boundary layer over 50% of the upper surface and 70% of the lower surface. They require very accurate, smooth, and non-wavy surfaces that lend themselves well to composite construction materials.

There is limited published experimental data available for these airfoils that also includes airfoil ordinates because most development efforts are proprietary. Two such airfoils are the Liebeck LA203A and the Maughmer and Somers SM701. This paper describes the design of a new laminar flow airfoil derived from these two published baseline airfoils and designated the Okay230. The computational tool XFOIL was used to estimate the sectional aerodynamic characteristics and then these data were used as a basis to estimate full sailplane configuration performance. The Okay230 was compared to a reverse-engineered sailplane airfoil and found to have better estimated high speed performance.

XFOIL Test to Theory Comparisons

The theory and usage of the computational tool XFOIL are described in References 1 to 3. It has been shown

(Figures begin on page 29)

to model the effects of low Reynolds number laminar separation bubbles with reasonable accuracy. Two low Reynolds number airfoils that have published ordinates and experimental data include the LA203A designed by Bob Liebeck and Peter Camacho (Reference 4), and the SM701 designed by Dan Somers and Mark Maughmer (Reference 5). Both of these airfoils are shown in Figure 1 and were analyzed using XFOIL and compared with the experimental data of References 4 and 5 to verify the suitability of XFOIL for this study. Boundary layer transition was allowed to occur freely where the code predicted using an Ncrit value of 9.0, the recommended value for low turbulence wind tunnels per Reference 2.

The LA203A was designed for low drag between the C_l's of 0.5 and 1.5 at a Reynolds number of 400,000, and to have a C_{lmax} of 1.8 according to Reference 4. It achieved most of these goals by using a concave upper surface Stratford pressure recovery, and has relatively low drag at higher C_l's. Unfortunately there are several unpleasant features: High drag at low C_l's, a high pitching moment coefficient of –0.17, and a difficult to build cusp in the trailing edge. Lift, drag and pitching moment coefficient comparisons between XFOIL and the (former) Douglas Long Beach Low Speed Wind Tunnel at a Reynolds number of 650,000 are shown in Figure 2. Both the XFOIL estimate and the test data indicated a dramatic increase in drag below lift coefficients of 0.9 due to a premature laminar separation on the lower surface near the leading edge. XFOIL failed to converge at C_l's greater than 1.56, which was very close to the tested C_{lmax} of 1.60. Overall correlation between XFOIL and the test data was good.

One of the helpful features of XFOIL is its ability to calculate composite airfoil drag polars where the Reynolds number corresponds to a flight condition at a given lift coefficient and is more easily adaptable to estimating full scale aerodynamic characteristics. In that case Reynolds number varies with the square root of the inverse of lift coefficient. Composite polars are described in more detail in Reference 6. The equation defining the Reynolds number, lift coefficient relationship for a sea level, standard day is:

$$\text{Reynolds number} = 184{,}500 \times \text{cbar} \times \text{sqrt}(W / (S_{ref} \times C_l))$$

For this paper the relationship will be simplified to:

$$\text{Reynolds number} = 1{,}000{,}000 / \text{sqrt} (C_l),$$

which corresponds to a Reynolds number of 1 million for a C_l of 1.0. This is close to a generic sailplane's wing chord and wing. This relationship will not be valid for an aircraft with a different wing loading or mean aerodynamic chord.

XFOIL drag estimates for the LA203A at Reynolds numbers of 0.5, 1, 2, and 3 million as well as its composite polar is shown in Figure 3. The composite polar crosses the constant Reynolds number polars at the appropriate lift coefficients.

Correlation for the SM701 was also good and is shown in Figure 4 for a Reynolds number of 1.5 million. Unlike for the LA203A, XFOIL tended to under predict drag by 15 to 30 drag counts. Correlations with other airfoils done by the author and not shown here tend to show XFOIL under predicted drag but usually captured the shape of the polar. Correlation with lift and pitching moment coefficient data was good with XFOIL slightly under predicting C_m as with the LA203A. Once again, XFOIL failed to converge at C_l's greater than 1.6, which was close to the tested C_{lmax} of 1.67. XFOIL drag estimates for the SM701at Reynolds numbers of 0.5, 1, 2, and 3 million as well as its composite polar is shown in Figure 5.

In summary, XFOIL generally predicted drag polar shape well for the two baseline laminar flow airfoils, although it underpredicted drag for the SM701. XFOIL came close to predicting C_{lmax} based on where it failed to converge relative to the test data. While XFOIL cannot predict post-stall characteristics, the C_l where it failed to converge indicated a rough maximum lift level. It is recommended that any airfoil intended for use on a full scale aircraft be wind tunnel tested in a well understood low turbulence facility to verify its aerodynamic characteristics, especially in the post-stall region.

Airfoil Design Requirements

A comparison of the composite drag data of both baseline airfoils is shown in Figure 6. The SM701 has low drag at C_l's less than 0.7 and the LA203A has low drag at C_l's greater than 0.9. It is desired to have an airfoil that envelops the low drag region of each airfoil. Some understanding to what is driving the drag characteristics of each airfoil may be gained by examining the estimated transition locations, which are also shown in Figure 6. They indicated longer runs of laminar flow over the lift coefficients having the lowest drag. The pressure distributions are shown in Figure 7 and are at a constant Reynolds number of 1 million with free boundary layer transition. At a C_l of 0.4, the LA203A has a notable C_p spike of nearly –2.0 on the lower surface near the leading edge, leading to what is believed to be premature laminar separation. The SM701 at a C_l of 0.4 in contrast has a pressure distribution that avoids laminar separation on its lower surface, and therefore, less drag. At a C_l of 1.2 the LA203A has a longer run of laminar flow on its top surface, and therefore, less drag. This is a logical outcome given that the LA203A has higher camber and is optimized for a higher C_l range than the SM701.

Other desirable characteristics for a new airfoil include maintaining the easy to build shape of the SM701 and its lower pitching moment coefficient. A summary of the design requirements and objectives is shown on the following table.

C_l below which drag increases at Re > 2,000,000	0.3
Drag at C_l up to 0.7, Re > 1,000,000	0.0050 to 0.0065
C_l for L/D max	0.8 to 0.9
Drag above C_l of 1.0, Re < 1,000,000	< 0.0100 as long as possible.
C_m	> -0.14 for less trim drag.
thickness	Generous for > spar depth, light structure
C_{lmax} at Re < 1,000,000	At least 1.6
Stall characteristics	gentle
Ease of manufacture	No TE cusp or sharp curvature changes.

Airfoil Design Methodology

The airfoil design process was different than what is typically done using state of the art CFD tools. Usual practice involves first specifying a pressure distribution that is believed to yield the desired characteristics and then mathematically deriving the airfoil shape that matches the design pressure distribution. The process used for this paper was similar to the process used in developing airfoils through wind tunnel testing prior to the availability of good CFD codes. The baseline airfoil's thickness, camber, or curvature was modified to yield a new smoothed shape. These changes were based on empirical knowledge and the engineering judgment of experienced aerodynamicists. XFOIL analysis was then used to obtain the force coefficients, boundary layer transition estimates, and pressure distributions. Drivers of the aero characteristics were discovered and altered by engineering judgment to iterate to the final airfoil.

Airfoil Improvements From the LA203A

Initial work centered on the LA203A as a baseline airfoil. The trailing edge cusp was eliminated with little deterioration of drag or C_{lmax} and an improvement in pitching moment coefficient. Next, the lower surface curvature was smoothed to try to eliminate the laminar separation. More "belly" was added like the SM701 and the resulting airfoil was designated the Okay206. Its shape is compared with the LA203A in Figure 8. There was minimal loss of C_{lmax} and the drag range was improved from C_l's of 0.6 to 0.9. Figure 8 also shows the composite drag and predicted boundary layer transition locations. Pitching moment coefficient was also improved, though is not shown. At C_l's below 0.4 the Okay206's drag is not that different from the LA203A and more improvement was desired to reach the design objectives. Further iterations did not provide any more drag improvements at low C_l due to the increased thickness, so it was decided to see what improvements were possible using the SM701 as a baseline airfoil.

Airfoil Improvements From the SM701

The first improvements were sought by keeping a similar lower surface shape as the SM701 and increasing the upper surface thickness to create a longer run of laminar flow on the top surface at C_l's between 0.8 and 1.2. This effective increase in camber was successful at reducing the drag at higher C_l's, but resulted in an increase in drag at lower C_l's due to the extra thickness. Further refinement of the curvature distribution near the leading edge was successful at mitigating this effect and even reducing the drag below that of the SM701 below C_l's of 0.27. There was some loss in potentially attainable C_{lmax} as XFOIL now failed to converge above a C_l of 1.5. On a given design application this would mean more wing area would be required to maintain the same stall speed as the SM701 with it's sectional C_{lmax} of 1.6. Further attempts to increase C_{lmax} either resulted in less buildable sections, or increases in drag near optimum cruise conditions. Conversely, attempts to reduce drag resulted in loss of C_{lmax}.

The new airfoil after 15 iterations was designated the Okay230 and is shown compared to the SM701 in Figure 9. The composite lift, drag and pitching moment characteristics of both airfoils are also shown. Relative to the SM701 it is a thicker section, which could potentially result thicker wing spars and therefore, lighter wing structure. The Okay230 drag at near minimum sink conditions was substantially reduced from the SM701. The transition data of Figure 9 indicated a longer laminar run on the top surface for the Okay230. The drag at a C_l above 1.2 was not quite as good as the LA203A. Fortunately this is not a problem since this would be at slower than sailplane minimum sink rate conditions where it is not advisable to fly anyway. The lift, drag, and pitching moment coefficients at various and composite Reynolds numbers are shown in Figure 10.

The pressure distributions of the Okay230 and SM701 are compared in Figure 11 and it may be seen that the Okay230 allows a longer laminar run along the top surface than the SM701, accounting for much of the improved drag at a C_l of 1.2.

Generic Sailplane Drag Buildup

A current generation Sporting class sailplane was chosen as a subject to better understand the impact of airfoil selection on a total performance. The Russia is a lightweight sailplane that offers a maximum L/D of 31 to the recreational pilot. More information can be found on the World Wide Web at Reference 7. Basic configuration particulars and a planform view are shown on Figure 12. Airfoil information about the Russia is not readily available but it was assumed to have an advanced airfoil. A drag polar was reverse-engineered from a plot of sink rate versus airspeed available from Reference 7. It was then possible to create an estimated drag buildup where total drag was as follows:

$$C_D = C_{Dsf} + C_{Di} + C_{Dp} + C_{Dtrim} \quad \text{where}$$

C_{Dsf} = skin friction drag of the fuselage and empennage (not adjusted for Reynolds number for simplicity),

C_{Di} = inviscid induced drag due to wing spanload = $C_L^2/(pi*AR*e)$, where e=0.94 was assumed,

C_{Dp} = airfoil profile drag adjusted from 2D XFOIL data to 3D,

and C_{Dtrim} = trim drag from horizontal tail deflection required to trim, expressed as a trim factor.

Wing profile drag was adjusted from the 2D values of XFOIL at the appropriate Reynolds number to get values for the 3D wing. Adjustments included a constant increment to account for the XFOIL to wind tunnel test to theory deltas plus typical additional drag due to excrescence items such as control surface steps and gaps. The total aircraft C_{Lmax} was reduced from the XFOIL 2D sectional C_{lmax} by 0.1 for each airfoil to account for the typical wing design that may not able to attain the full airfoil 2D C_{lmax}. The drag was then increased accordingly above the C_l for maximum L/D. Finally, some smoothing of the polars was needed to result in a smooth complete drag polar. This was typically no more than a few drag counts at a few C_L's. Figure 13 shows these corrections for the Okay230 and Figure 14 shows the "3D" airfoil profile drag of the Okay230, SM701, and LA203A.

The trim drag was accounted for by using an update of the theory of Reference 8 using the horizontal tail to trim with a center of gravity at 30% of the mean aerodynamic chord. The drag difference between an untrimmed and trimmed drag polar was converted to a trim drag factor as a percentage of total untrimmed drag versus lift coefficient. This approach rewarded wing airfoils with less negative values of airfoil pitching moment coefficient. Trim factor was allowed to vary with C_L.

A spreadsheet was then used to build up the total sailplane drag and performance of the sailplanes using the LA203A, SM701, and Okay230 airfoils. Stall speed and wingspan were held constant when building up the total sailplane performance. This meant an airfoil with more C_{lmax} required less wing area and also had a slightly higher wing aspect ratio. The sink rate performance of sailplanes with all three airfoils is shown in Figure 15 and the only differences are due to airfoil choice. The LA203A has the best minimum sink rate of the three, but has poor high speed performance because of the lower surface separation. The SM701 has the best high speed performance but has relatively high minimum sink rate. It can be seen that the Okay230 offers the best overall balanced performance across the range of airspeeds. It has better low speed performance than the SM701 with almost as good of high speed inter-thermal cruising ability. One bonus is the Okay230 achieves this with a slight increase in thickness, which could help reduce structural weight by allowing thicker spars. Lift over drag ratio versus airspeed for all three airfoils is also shown in Figure 15. The value of L/D_{max} was nearly constant for all three airfoils, though at different airspeeds.

As a final comparison, this analysis was done for a reverse engineered airfoil for the Glaser-Dirks DG300 sailplane, obtained from Reference 9. This airfoil was considered state of the art ten years ago, and was considered a good candidate reference section. It should be noted that operationally this airfoil uses pneumatic turbulators to obtain better high speed performance, so XFOIL analysis may be conservative. A comparison of the DG300 airfoil and the Okay230 airfoils is shown with composite lift, drag, pitching moment and transition shown in Figure 16. The Okay230 achieves lower drag overall than the DG300 except at higher C_l. Because it has a lower C_{lmax}, much of this benefit goes away when applied to a sailplane with constant stall speed and span. The sink rate performance comparison is shown in Figure 17 and it may be seen that their performance is almost equal, with the Okay230 having a slight edge at high speed.

Conclusions

1. XFOIL is an excellent tool for comparing airfoils under similar theoretical conditions and has good test to theory correlation.
2. A new airfoil designated the Okay230 was developed that offers overall performance improvements over the LA203A and SM701 with potentially increased structural thickness. Most of the design goals were met.
3. These improvements must be verified by wind tunnel testing and the stall characteristics need to be experimentally verified as benign.
4. It is possible to improve over existing airfoils by using a simplified design process and XFOIL analysis.
5. Overall aircraft performance will improve even if airfoil profile drag is allowed to increase at high C_l's where flight occurs behind the power curve, as long as there is reduced drag at lower C_l's.
6. Apparent airfoil drag improvements indicated by comparing sectional data at constant Reynolds number must be verified by comparing at flight Reynolds number, which varies across the C_L range. This may be done with XFOIL by creating a composite polar.

7. An airfoil that offers reduced high speed drag at the expense of C_{lmax} will have less real performance improvement when stall speed is kept constant.

Acknowledgements

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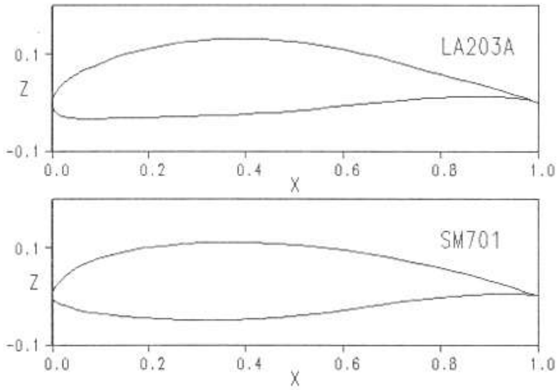

Figure 1. LA203A and SM701 airfoils

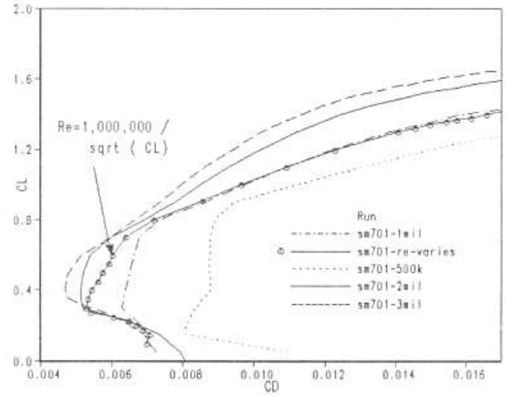

Figure 5. SM701 XFOIL drag estimates

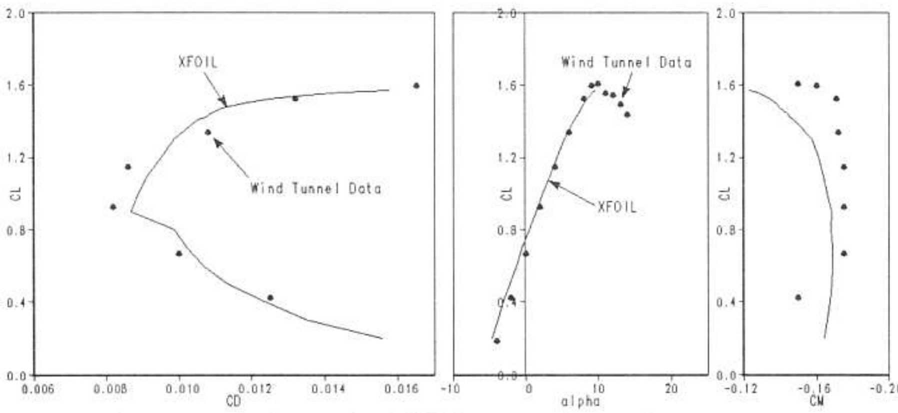

Figure 2. LA203A wind tunnel to XFOIL comparison, Re=650,000

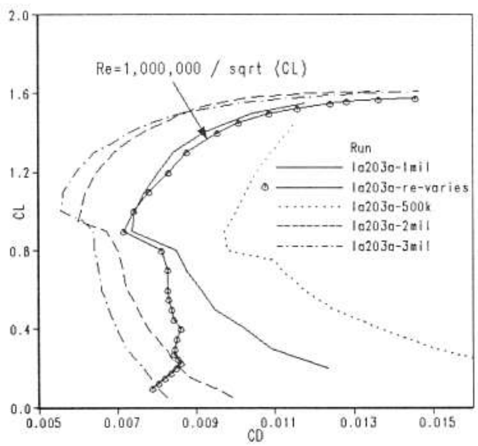

Figure 3. LA203A XFOIL drag estimates

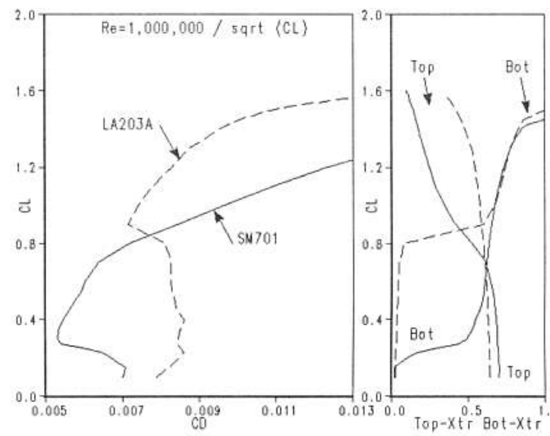

Figure 6. Comparison of LA203A and SM701 XFOIL composite drag and boundary layer transition location

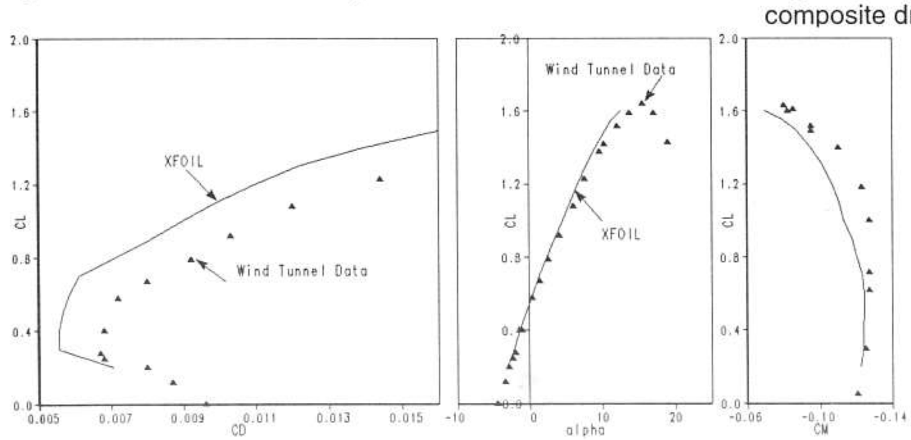

Figure 4. SM701 wind tunnel to XFOIL comparison, Re=1,500,000

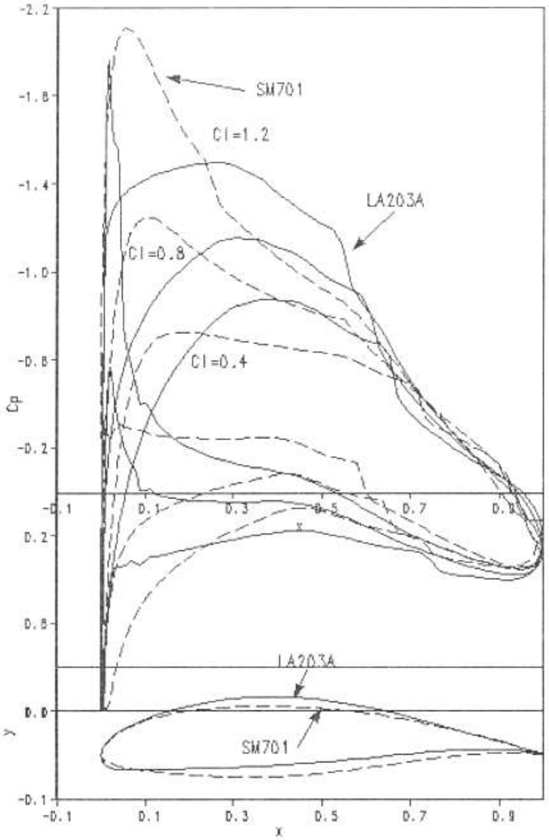

Figure 7. LA203A and SM701 XFOIL pressure distributions at Re=1,000,000, free transition

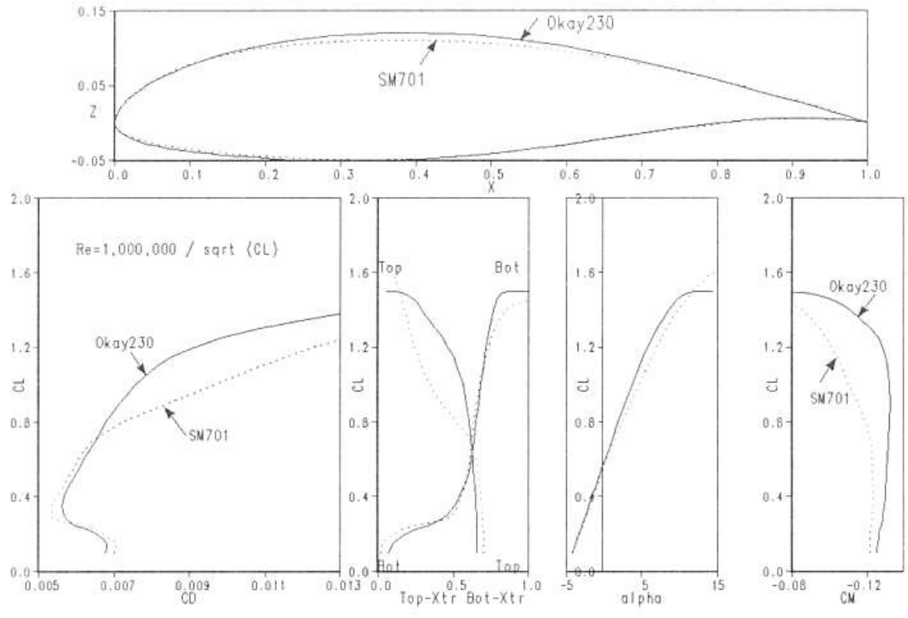

Figure 9. SM701 and Okay230 XFOIL results at composite Reynolds number

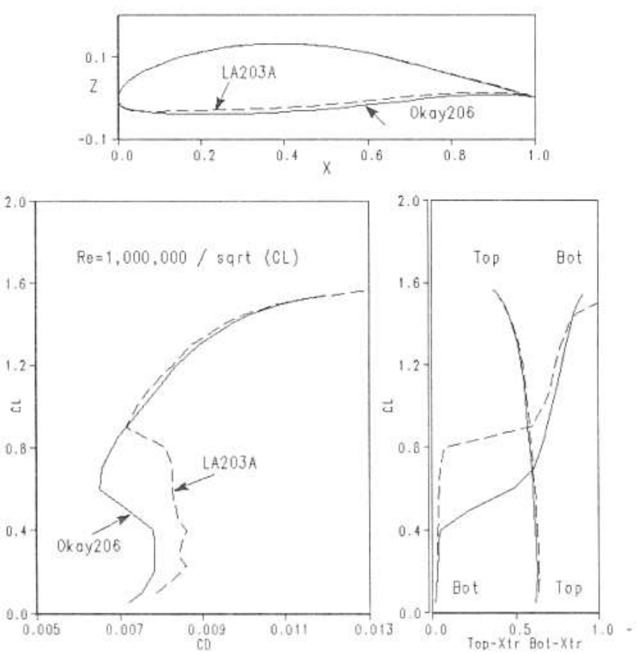

Figure 8. Okay206 compared with the LA203A

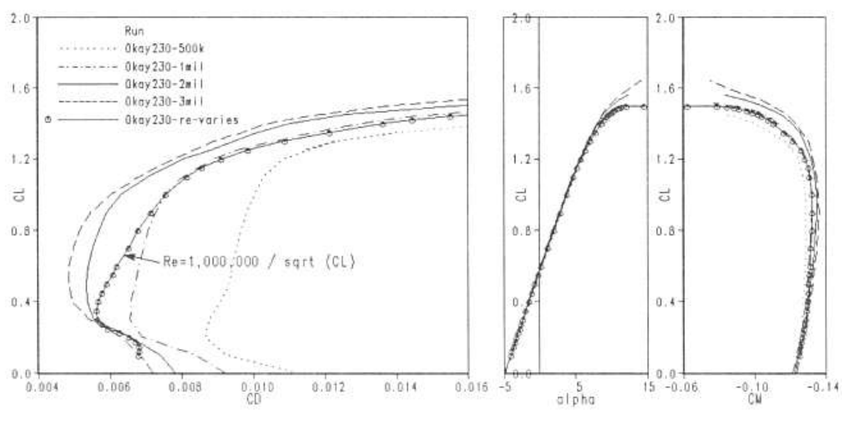

Figure 10. Okay230 XFOIL results

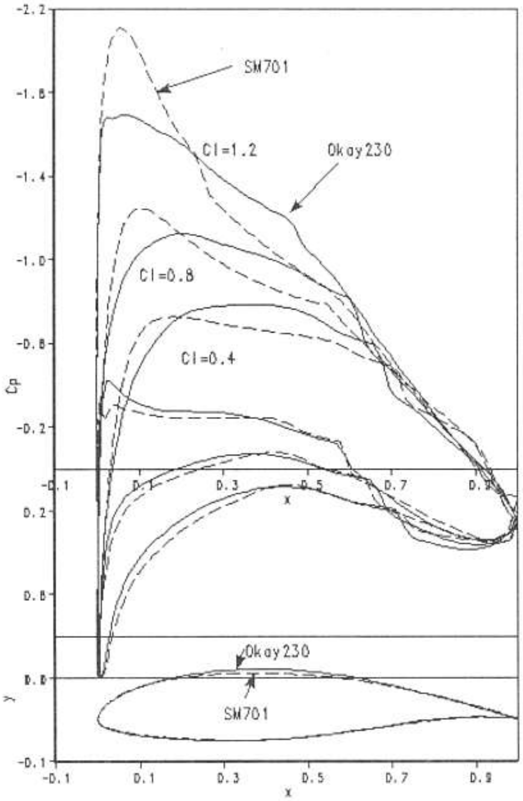

Figure 11. Okay230 and SM701 XFOIL pressure distributions at Re=1,000,000, free transition

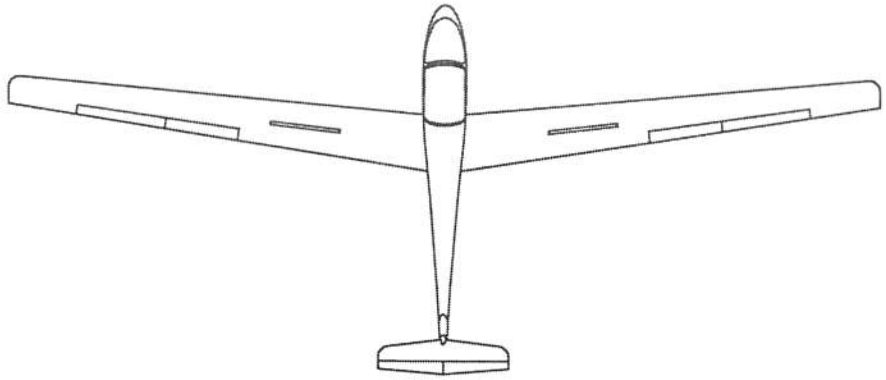

Figure 12. Russia AC-4A planform (span = 41.3 ft., S_{ref} = 82.9 ft^2, AR = 20.6, W/S = 6.0 lb/ft^2)

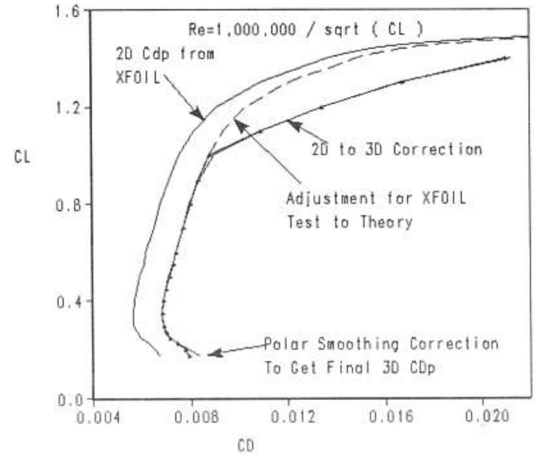

Figure 13. Example of airfoil 2D to 3D drag correction

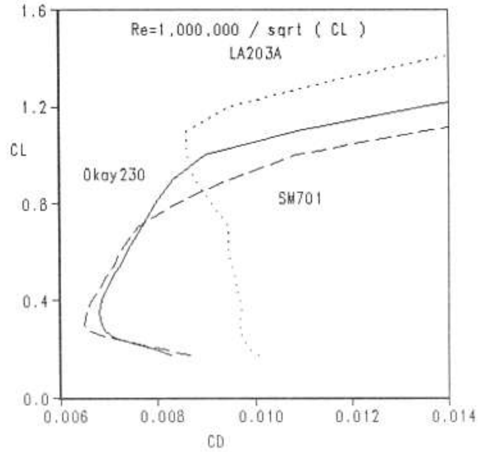

Figure 14. Sailplane profile drag with various airfoils

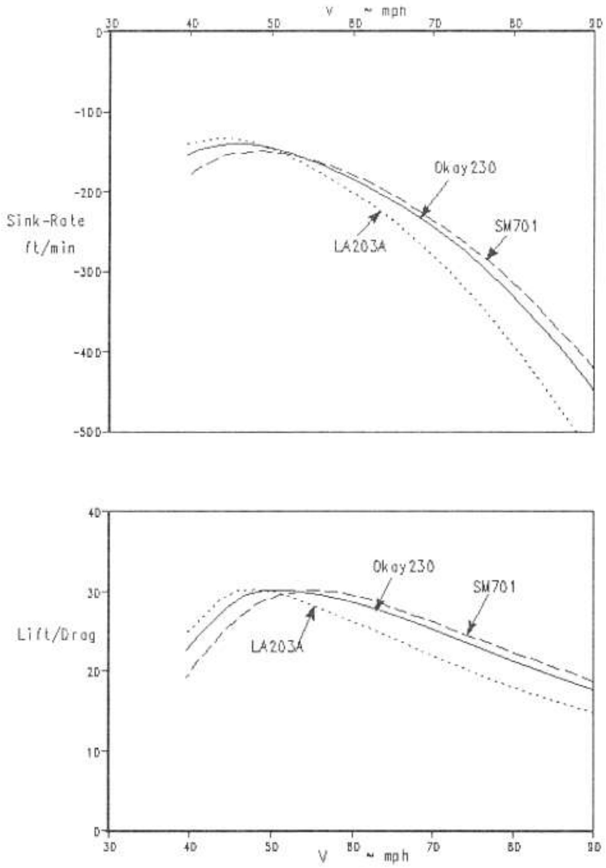

Figure 15. Sailplane L/D and sink rate with various airfoils

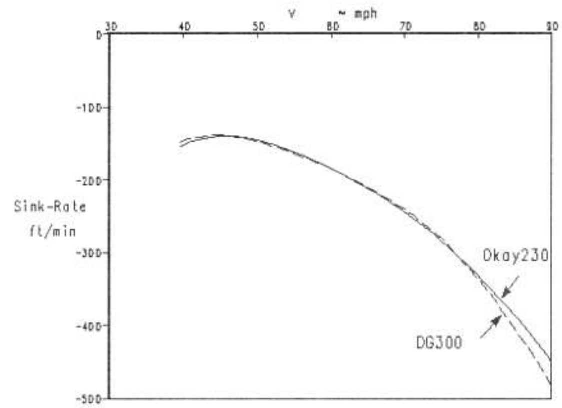

Figure 17. Sink rate of sailplanes with Okay230 and DG300

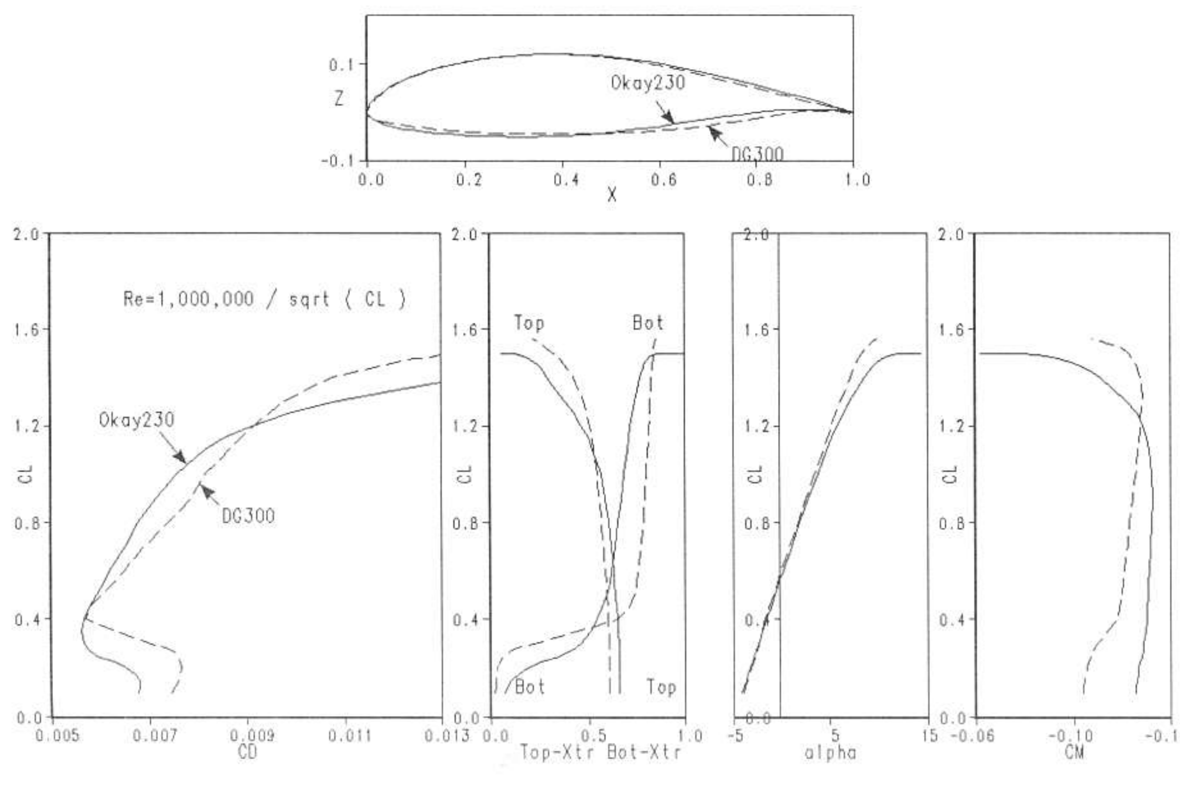

Figure 16. Okay230 XFOIL results compared to the DG300