TECHNICAL NOTE ADS-TN-01

Verification and Validation of Aero Design Studio 2D CFD for Single-Element Airfoils

Aero Design Studio, aerodesignstudio.com | Version 1.0, October 2026

Abstract

Aero Design Studio (ADS) offers a two-dimensional CFD tool for airfoils. This note shows how far its results can be trusted for single-element airfoils in the mode the application calls "RANS, fully turbulent": the steady Reynolds-averaged Navier-Stokes equations with the k-omega SST turbulence model, and a boundary layer that is turbulent from the leading edge.

First, does the tool solve its equations correctly? For the NACA 0012 case of the NASA Turbulence Modeling Resource at a Reynolds number of 6×10^6, its lift and drag agree with three independently written codes within 0.1 and 1.4 percent. Second, how close do these equations come to a wind tunnel? The most direct test is the NASA GA(W)-1, measured with its boundary layer tripped near the leading edge at Reynolds numbers of 2.1×10^6 to 6.3×10^6. There the computed lift is within 4 percent of the measurement up to 8 degrees, and the computed drag is 9 percent lower on average. On five smooth wind-tunnel models with 1 to 10 percent camber, at Reynolds numbers of 2×10^5 to 3×10^6, the computed lift is within 8 percent of the measurement between 0 and 8 degrees, and 4 percent from it on average.

The computed drag is that of a turbulent boundary layer. Where a smooth model keeps a long run of laminar flow, the computation is up to 80 percent above the measured drag, and a smooth section that carries its load at the rear has up to 16 percent more lift than computed. The note also gives the numerical uncertainty of the results, the cases in which no steady solution exists and how they are reported, what to expect near maximum lift, and when the XFOIL tool of ADS is the better choice.

Accuracy at a glance

How close the fully turbulent mode comes to reference solutions and to wind-tunnel measurements, in one table. The first two rows compare like with like; the others show what the mode gives for wings in other states. The sections below give the details.

Table 1. Accuracy of the fully turbulent mode for single-element airfoils, 0 to 8 degrees unless stated. Against smooth models the differences in drag come from the laminar flow on the models, which the computation does not have.

Compared with	Lift	Drag
Reference solutions of the same equations (NACA 0012, Re 6×10^6, 0 to 15 degrees)	within 0.1% of three reference codes	within 1.4% of three reference codes
Model with transition fixed by a narrow strip (NASA GA(W)-1, Re 2.1×10^6 to 6.3×10^6)	within 4% of the measurement; within 7% up to 12 degrees	0 to 17% below the measurement, 9% on average
Models with heavier roughness, Re 2×10^6 to 6×10^6	0.03 to 0.10 in C_l above the S809 with fixed transition; 12 to 21% above the NACA 4412 with standard roughness	4 to 7% below the S809 with fixed transition; 12 to 27% below the NACA 4412 with standard roughness
Smooth models, Re 2×10^6 to 6×10^6	within 8% of the measurement (S809, NACA 4412); between 16% below and 1% above it on the GA(W)-1, whose smooth model has more lift than its tripped one	35 to 80% above the measurement in the low-drag range of the model; within 6% past it
Smooth models, Re 2×10^5	within 7% of the measurement where the run converges	from the measured value (S1223) to 37% above it (NACA 2414)
Numerical uncertainty of a converged result, Re 2×10^6 and above	1 to 2%	2 to 3%
Numerical uncertainty of a converged result, Re 2×10^5	1% at 2 and 4 degrees; up to 6% at 6 and 8 degrees (Section 5)	1% at 2 and 4 degrees; up to 5% at 6 and 8 degrees
Near and beyond maximum lift, any Reynolds number	indicative only, also where the run converges: on the NACA 4412 the computed maximum is 15% above the measured one and about 2 degrees late	indicative only
No steady solution (reported as such)	not to be used	not to be used

1. Introduction

ADS offers two tools for airfoils and wings. The XFOIL tool [1] is a panel method with a model of the boundary layer: it is fast, and it predicts where the boundary layer turns turbulent. The CFD tool solves the Reynolds-averaged Navier-Stokes (RANS) equations in the flow around the section. It is meant for users who need more than a polar: the pressure and velocity fields, the extent of separated flow, or shapes that a panel method handles poorly.

Before anyone relies on the results of the CFD tool, two questions need an answer, and they are not the same question. Verification: does the tool solve its equations correctly, so that it returns what other, independently written codes return for the same equations? Validation: how close is that solution to what a wind tunnel measures? This note answers both for single-element airfoils, the configuration most of our users work with: wings for motorsport, Formula Student and small unmanned aircraft.

The note covers the mode that the application lists as "RANS, fully turbulent". In this mode the boundary layer is turbulent from the leading edge. That is the state behind a boundary-layer trip, and it is close to the state of a wing in disturbed air: at the turbulence level of a few percent that a wing on a car meets, the transition correlation of Langtry and Menter [2] puts transition on a flat plate within the first few percent of its length at a Reynolds number of 3×10^6. The surface is smooth in the computation; roughness is not modelled. This is also the mode in which a steady computation gives results that hold when the grid is refined, as Section 6.3 explains.

2. What was computed

The CFD tool uses OpenFOAM® [3] to solve the steady, incompressible RANS equations with the k-omega SST turbulence model [4, 5]. No transition model is active in the mode covered here. The grid resolves the boundary layer down to the wall, so no wall functions are needed.

Every result is checked for convergence. A run counts as converged when its lift and drag have stopped changing. A run that does not get there is reported as not converged, together with the reason: still drifting, or oscillating. Its numbers should not be used.

Unless a section says otherwise, every result in this note was computed with the settings that the application uses from October 2026, the same for every case. The grid, the computational domain and the settings of the solver are the work of ADS and are not described here.

3. Verification against reference solutions

3.1 NACA 0012 at a Reynolds number of 6×10^6

The NASA Langley Turbulence Modeling Resource [6] publishes solutions for the NACA 0012 at a Reynolds number of 6×10^6 from several independently written codes that use the same turbulence model, computed on very fine grids. These solutions say what the equations give for this flow, without any experimental uncertainty, so a code that solves the same equations has to return them. Table 2 and Figure 1 compare ADS with three of those codes.

Table 2. NACA 0012 at Re = 6×10^6, fully turbulent, SST model: ADS CFD against the reference solutions of the NASA Turbulence Modeling Resource [6].

Alpha	C_l: CFL3D, FUN3D, NTS	C_l ADS	to their mean	C_d: CFL3D, FUN3D, NTS	C_d ADS	to their mean
0 deg	0	0		0.00809, 0.00808, 0.00809	0.00816	+0.85%
10 deg	1.0778, 1.0840, 1.0765	1.0804	+0.09%	0.01236, 0.01253, 0.01251	0.01252	+0.40%
15 deg	1.5068, 1.5109, 1.5100	1.5103 (a)	+0.07%	0.02219, 0.02275, 0.02187	0.02197 (a)	−1.33%

(a) At 15 degrees the run had not fully settled when it ended. Run twice as long, it gives $C_l = 1.5108$ and $C_d = 0.02196$.

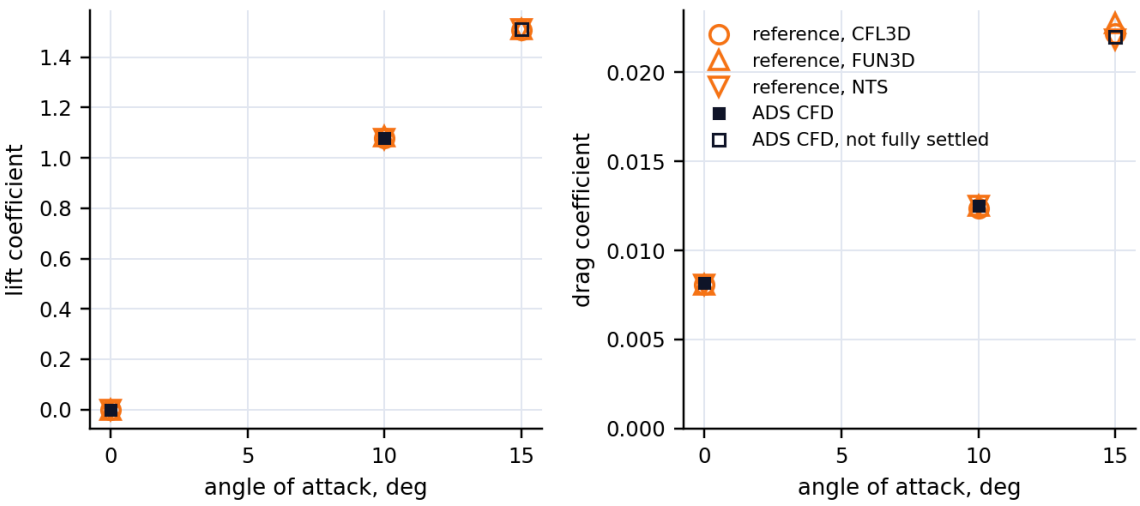


Figure 1. NACA 0012 at Re = 6 × 10^6: lift and drag coefficient of ADS CFD and of three reference codes [6].

At 0 and 10 degrees, ADS differs from the mean of the three codes by 0.1 percent or less in lift and by 0.9 percent or less in drag. For comparison, the three codes differ among themselves by 0.7 percent in lift and 1.4 percent in drag at 10 degrees. At 15 degrees, close to the maximum lift of this case, the ADS lift is 0.1 percent above their mean and the drag 1.3 percent below it.

One difference between the two sides is known. The reference codes solve the compressible equations at a Mach number of 0.15, and ADS the incompressible ones. Linear theory (Prandtl-Glauert) puts the effect of that Mach number at about 1.1 percent of the lift. Against reference values lowered by that amount, the ADS lift at 10 degrees is 1.2 percent high. Small differences in the shape of the trailing edge and in the grid account for this, and they are part of the numerical uncertainty given in Section 5. Table 2 is not corrected for the Mach number.

3.2 NACA 4412 close to maximum lift

The second case of [6] is harder: the NACA 4412 at 13.87 degrees and a Reynolds number of 1.52 × 10^6, with the flow separated over the rear of the upper surface. Table 3 compares ADS with two reference codes. The ADS lift is 3.4 percent above theirs, and the ADS drag 2.5 to 5.2 percent below. Separated flow is harder for every code than attached flow, and this is the larger of the two differences found in the verification.

Table 3. NACA 4412 at 13.87 degrees, Re = 1.52 × 10^6, fully turbulent, SST model: ADS CFD against the reference solutions of [6].

	CFL3D	FUN3D	ADS CFD	ADS to their mean
C_l	1.616	1.615	1.671	+3.4%
C_d	0.0311	0.0320	0.0303	−3.8%

4. Validation against wind-tunnel measurements

4.1 Measured data

Seven sections were chosen (Table 4). The S809, a thick section designed for long runs of laminar flow, was measured by Somers [7] in the low-turbulence tunnel of Delft University of Technology, both with free transition and with transition fixed by roughness near the leading edge. For the NACA 4412, NACA Report 824 [8] gives a smooth model and one with standard leading-edge roughness. Three sections come from the low-speed tests of the University of Illinois at Urbana-Champaign (UIUC) [9, 10] at a Reynolds number of 2 × 10^5: the high-lift sections S1223 and E423, of the kind used on racing-car wings, and the conventional NACA 2414. The NASA GA(W)-1 [11], 17 percent thick and designed for a maximum lift coefficient of 2, was measured in the Langley low-turbulence pressure tunnel at Reynolds numbers of 2.1 × 10^6, 4.3 × 10^6 and 6.3 × 10^6, smooth and with transition fixed at 8 percent of chord. The

UI-1720 [12], a section designed for maximum lift, was measured at the University of Illinois at a Reynolds number of 1.8×10^6.

Table 4. Sections and measurements. Thickness and camber are those of the coordinates used in the computations.

Section	Thickness	Camber	Reynolds number	Boundary layer of the model	Source
S809	21.0%	1.0%	2.0×10^6	free transition; fixed by roughness	Somers [7], read from figures
NACA 4412	12.0%	4.0%	3.0×10^6; 6.0×10^6	smooth; standard roughness	NACA Report 824 [8], read from figures
Selig S1223	12.1%	8.7%	2.0×10^5	free transition	UIUC, Vol. 1 [9], tabulated
Eppler E423	12.5%	10.0%	2.0×10^5	free transition	UIUC, Vol. 2 [10], tabulated
NACA 2414	14.0%	2.0%	2.0×10^5	free transition	UIUC, Vol. 2 [10], tabulated
NASA GA(W)-1	17.0%	2.1%	2.1×10^6; 4.3×10^6; 6.3×10^6	smooth; fixed at 0.08 c by a strip of grit	McGhee and Beasley [11], read from figures
UI-1720	13.8%	4.6%	1.8×10^6	free transition (a)	Sivier et al. [12], read from a figure

(a) Transition was seen at the start of the pressure recovery; the pressure taps on the centre line tripped the boundary layer locally [12].

The UIUC values are tabulated in the source. The values for S809 and NACA 4412 were read from the published figures, to within about 0.005 in lift coefficient, 0.1 degrees in angle and 0.0001 in drag coefficient. Measured values at the computed angles were obtained by linear interpolation between neighbouring measured points.

A fully turbulent computation and a smooth model in a quiet wind tunnel are not the same flow. On the smooth model the boundary layer stays laminar over part of the chord, over more of it the lower the Reynolds number and the gentler the pressure rise, and a laminar boundary layer has less friction. The fairest comparison is therefore with models whose boundary layer was tripped, and it comes first (Section 4.2). The comparison with smooth models follows (Sections 4.3 to 4.5). It shows what you get when you use the fully turbulent mode for a smooth wing in clean air.

4.2 Against models with a tripped boundary layer

Table 5. ADS CFD, fully turbulent, against measurements with fixed transition (S809, Re = 2.0 × 10^6 [7]) and with standard roughness (NACA 4412, Re = 6.0 × 10^6 [8]).

Section	Alpha	C_l measured	C_l ADS CFD	Difference	C_d measured	C_d ADS CFD	Difference
S809, transition fixed	0 deg	0.108	0.136	+25.6%	0.0122	0.0117	−4.0%
	1 deg	0.218	0.253	+16.4%	0.0123	0.0117	−4.7%
	2 deg	0.327	0.370	+13.3%	0.0124	0.0119	−4.3%
	4 deg	0.537	0.598	+11.5%	0.0131	0.0126	−4.5%
	6 deg	0.738	0.818	+10.8%	0.0145	0.0138	−4.7%
	8 deg	0.921	1.023	+11.1%	0.0171	0.0158	−7.4%
	9 deg	0.975	1.118	+14.6%	0.0226	0.0173	−23.5%
NACA 4412, roughness	0 deg	0.370	0.448	+21.2%	0.0098	0.0086	−12.4%
	2 deg	0.578	0.668	+15.6%	0.0103	0.0091	−11.7%
	4 deg	0.781	0.883	+13.1%	0.0116	0.0098	−14.9%
	6 deg	0.971	1.091	+12.3%	0.0135	0.0109	−19.1%
	8 deg	1.143	1.290	+12.8%	0.0170	0.0124	−27.0%
	10 deg	1.280	1.469	+14.8%	0.0230	0.0147	−35.9%

For the S809 the computed drag is 4 to 5 percent below the measurement from 0 to 6 degrees and 7 percent below it at 8 degrees. The computed lift is higher than the measured one, by 0.03 to 0.10 in lift coefficient. Somers notes that his roughness was too large at this Reynolds number, so that the measured drag is probably too high and the measured lift too low [7]. The differences have that sign, and Section 4.3 shows the computed lift close to that of the smooth model up to 6 degrees.

For the NACA 4412, the standard roughness of Report 824 is a band of grit over the first 8 percent of chord on both surfaces. Grit of that size thickens the boundary layer more than a turbulent boundary layer on a smooth wall does, so a fully turbulent computation should come out above this lift and below this drag. The computed lift is 12 to 21 percent above the measurement from 0 to 10 degrees, and the computed drag 12 to 19 percent below it from 0 to 6 degrees. At 8 and 10 degrees the roughened model is on its way to its maximum lift coefficient of 1.38, which it reaches at 13 degrees, and its drag is 37 and 56 percent above the computed one.

Neither of the two models is the smooth wall with a turbulent boundary layer that the computation describes, so this comparison brackets the computation rather than testing it. The computed drag lies below that of both roughened models, as it should: by 4 to 7 percent for the S809, whose roughness is a strip near the leading edge, and by 12 to 19 percent up to 6 degrees for the NACA 4412, whose standard roughness covers the whole nose and is the heavier of the two. The computed lift lies above both.

4.3 Against smooth models at Reynolds numbers of 2×10^6 and 3×10^6

> These differences are not numerical errors: the model in the tunnel has laminar flow, the computation does not.

Table 6. ADS CFD, fully turbulent, against smooth models with free transition: S809 at Re = 2.0×10^6 [7] and NACA 4412 at Re = 3.0×10^6 [8].

Section	Alpha	C_l measured	C_l ADS CFD	Difference	C_d measured	C_d ADS CFD	Difference
S809, free transition	0 deg	0.146	0.136	−7.1%	0.0070	0.0117	+66.4%
	1 deg	0.264	0.253	−3.9%	0.0072	0.0117	+63.4%
	2 deg	0.379	0.370	−2.4%	0.0072	0.0119	+65.7%
	4 deg	0.617	0.598	−3.0%	0.0070	0.0126	+80.5%
	6 deg	0.812	0.818	+0.8%	0.0091	0.0138	+52.8%
	8 deg	0.951	1.023	+7.5%	0.0153	0.0158	+3.4%
	9 deg	1.002	1.118	+11.5%	0.0201	0.0173	−14.0%
	mean, absolute			**5.2%**			
NACA 4412, smooth	0 deg	0.433	0.440	+1.7%	0.0068	0.0096	+41.5%
	2 deg	0.625	0.658	+5.3%	0.0069	0.0102	+47.5%
	4 deg	0.855	0.870	+1.7%	0.0071	0.0110	+55.3%
	6 deg	1.045	1.073	+2.7%	0.0090	0.0122	+34.9%
	8 deg	1.197	1.266	+5.8%	0.0132	0.0140	+5.8%
	10 deg	1.337	1.445	+8.0%	0.0170	0.0166	−2.5%
	mean, absolute			**4.2%**			

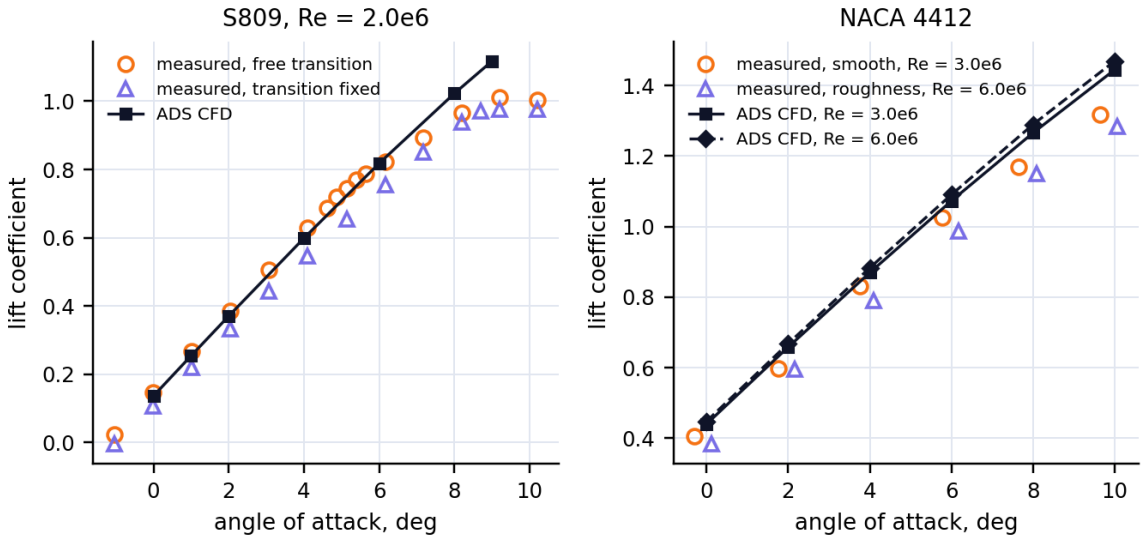


Figure 2. Lift coefficient of S809 and NACA 4412: measured with free transition and with a tripped boundary layer [7, 8], and ADS CFD.

The computed lift of the S809 is between 7 percent below and 8 percent above that of the smooth model from 0 to 8 degrees, and within 0.02 in lift coefficient up to 6 degrees. From 8 degrees the measured curve bends over while the

computed one carries on, and at 9 degrees the computation is 12 percent high. The computed lift of the NACA 4412 is 2 to 8 percent above the smooth model. Part of that scatter is the figure itself: for the same point, the lift coefficient read from the lift curve and from the polar of the report differs by up to 0.013, which is 2 percent of the lift at 2 degrees.

The drag shows the difference between the two flows. In the low-drag range of the smooth models, where much of the surface is laminar, the fully turbulent computation is 53 to 80 percent above the measurement for the S809 (0 to 6 degrees) and 35 to 55 percent above it for the NACA 4412. At 8 degrees, where the low-drag range of both models has ended, the computation is within 6 percent of both (Figure 3).

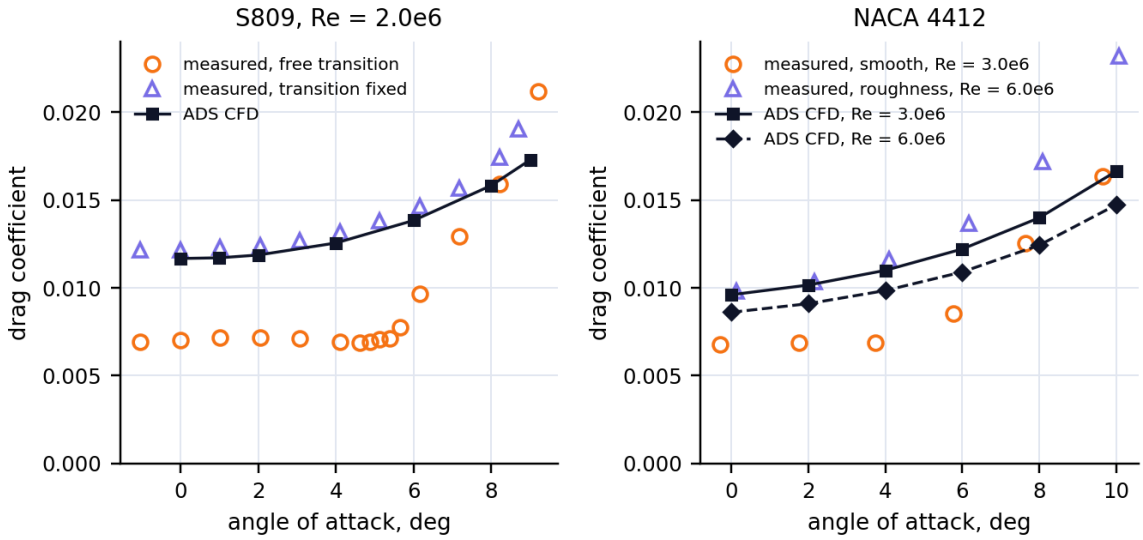


Figure 3. Drag coefficient of S809 and NACA 4412: measured with free transition and with a tripped boundary layer [7, 8], and ADS CFD.

4.4 High-lift sections at Reynolds numbers above 1 × 10^6

The sections of Sections 4.2 and 4.3 reach a lift coefficient of about 1 before their lift curves bend. The NASA GA(W)-1 [11] is the test at higher lift. It is 17 percent thick, with a blunt nose, most of its camber at the rear and a trailing edge 0.7 percent of chord thick, and it reaches maximum lift coefficients of 1.6 to 2.0. It was measured smooth and with transition fixed on both surfaces at 8 percent of chord by a narrow strip of sparse grit. A boundary layer tripped that far forward, by a strip that adds little drag of its own, is as close as a wind tunnel comes to the flow the computation describes. This is therefore the most direct test in this note.

The values were read from the figures of the report, to within 0.01 in lift coefficient, 0.1 degrees and 0.0002 in drag coefficient. The report applies no wall corrections, which it puts at about 2 percent of the coefficients, and the Mach number of the test, 0.15, adds about 1 percent to the measured lift that an incompressible computation does not have.

Table 7. ADS CFD, fully turbulent, against the NASA GA(W)-1 with transition fixed at 0.08 c [11].

Section	Alpha	C_l measured	C_l ADS CFD	Difference	C_d measured	C_d ADS CFD	Difference
Re = 2.1×10^6	0 deg	0.446	0.450	+0.9%	0.0131	0.0117	−10.8%
	2 deg	0.660	0.677	+2.7%	0.0136	0.0124	−9.1%
	4 deg	0.876	0.896	+2.3%	0.0145	0.0135	−6.9%
	6 deg	1.071	1.101	+2.9%	0.0169	0.0152	−10.1%
	8 deg	1.243	1.287	+3.5%	0.0212	0.0175	−17.3%
	10 deg	1.378	1.449	+5.2%		0.0212	
	12 deg	1.485	1.582	+6.6%		0.0268	
	mean, absolute			**3.4%**			**10.8%**
Re = 4.3×10^6	0 deg	0.461	0.465	+0.9%	0.0118	0.0104	−11.5%
	2 deg	0.697	0.695	−0.2%	0.0115	0.0110	−4.1%
	4 deg	0.929	0.917	−1.3%	0.0124	0.0120	−3.5%
	6 deg	1.126	1.130	+0.3%	0.0150	0.0134	−10.3%
	8 deg	1.322	1.322	0.0%	0.0178	0.0155	−13.1%
	10 deg	1.469	1.489	+1.3%	0.0219	0.0186	−14.8%
	12 deg	1.592	1.638	+2.9%	0.0272	0.0231	−15.0%
	mean, absolute			**1.0%**			**10.3%**
Re = 6.3×10^6	0 deg	0.474	0.475	+0.1%	0.0107	0.0098	−8.0%
	2 deg	0.718	0.705	−1.8%	0.0116	0.0104	−10.3%
	4 deg	0.946	0.927	−1.9%	0.0113	0.0113	−0.1%
	6 deg	1.157	1.145	−1.1%	0.0139	0.0126	−9.4%
	8 deg	1.361	1.336	−1.8%	0.0163	0.0145	−11.3%
	10 deg	1.528	1.508	−1.3%	0.0178	0.0173	−2.8%
	12 deg	1.660	1.662	+0.1%	0.0216	0.0216	−0.1%
	mean, absolute			**1.1%**			**6.0%**

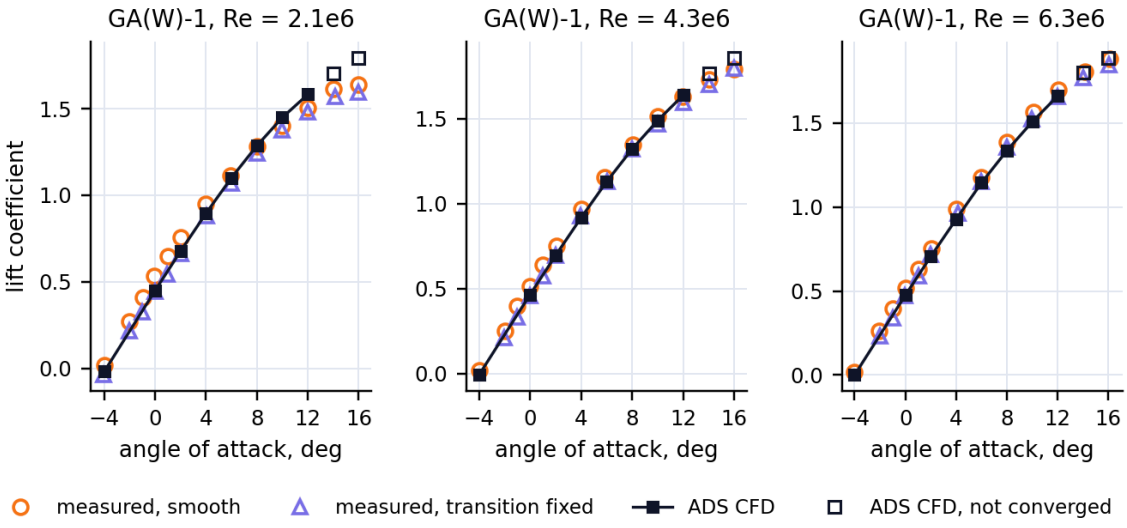


Figure 4. Lift coefficient of the NASA GA(W)-1: measured smooth and with transition fixed [11], and ADS CFD.

With transition fixed, the computed lift is within 4 percent of the measurement from 0 to 8 degrees at all three Reynolds numbers (between 2 percent below and 4 percent above it). At 10 and 12 degrees the measured lift curve has left the straight line, because the flow separates at the rear of the upper surface. There the computed lift is within 3 percent at the two higher Reynolds numbers and 5 to 7 percent above the measurement at the lowest, where the model is nearest to its maximum lift.

The computed drag is lower than the measured one, by 0 to 17 percent from 0 to 8 degrees and by 9 percent on average (Figure 5). The strip of grit has a drag of its own and the tunnel walls are not corrected for; the computation has neither, and the rest of the difference belongs to the turbulence model. The change with the Reynolds number is reproduced: from 2.1×10^6 to 6.3×10^6 the drag at 0 degrees falls by 18 percent in the measurement and by 16 percent in the computation.

The smooth model confirms what Section 4.3 shows for the drag: in its low-drag range the computation is 13 to 70 percent higher. For the lift it shows something new. The strip costs this section lift, 0.09 in lift coefficient at 0 degrees at the lowest Reynolds number and 0.04 at the highest, because the section carries much of its load at the rear, where a thicker boundary layer takes camber away. The computation follows the tripped model, so it lies below the smooth one: 6 to 16 percent below the measurement up to 4 degrees at the lowest Reynolds number, and 3 to 8 percent below it up to 8 degrees at the highest. A smooth wing of this kind in clean air has more lift than the computation gives it.

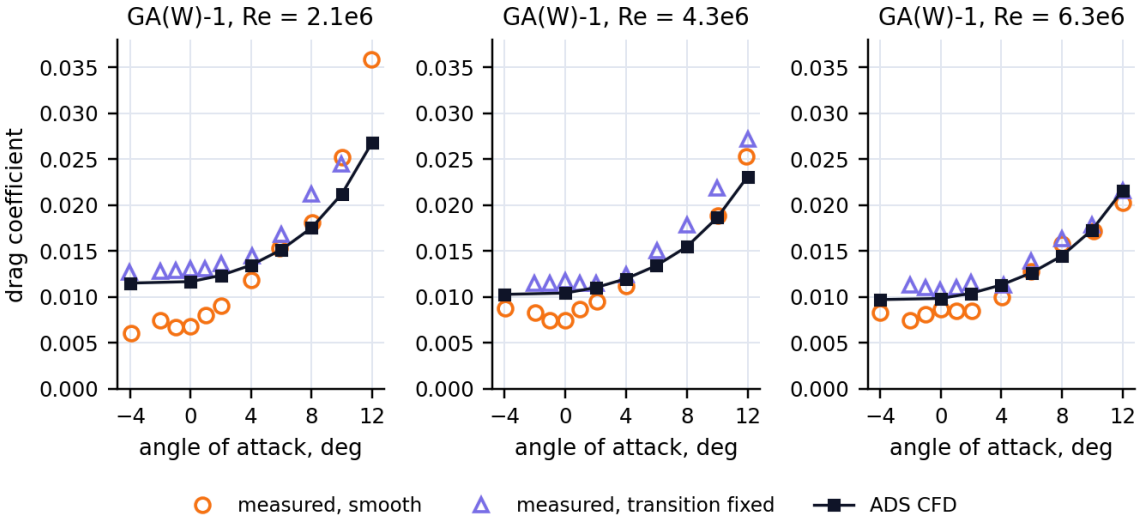


Figure 5. Drag coefficient of the NASA GA(W)-1: measured smooth and with transition fixed [11], and ADS CFD.

The UI-1720 [12] was designed for maximum lift. The pressure on its upper surface is flat over the first fifth of the chord and then rises as steeply as a turbulent boundary layer can follow without separating. A boundary layer that is turbulent from the leading edge arrives at that rise thicker than the one the designers counted on, so this is the hardest case for the fully turbulent mode. The measurement is also the weakest in this note: a model of aspect ratio 0.67 between side walls with blowing, eight points, and a drag that the authors themselves call optimistic at the higher angles. The computation is compared at the measured angles, on the line between its neighbouring points.

> These differences are not numerical errors: the model in the tunnel has laminar flow, the computation does not.

Table 8. ADS CFD, fully turbulent, against the UI-1720 at Re = 1.8 × 10^6 [12].

Section	Alpha	C_l measured	C_l ADS CFD	Difference	C_d measured	C_d ADS CFD	Difference
UI-1720	−4.2 deg	0.056			0.0104		
	0.0 deg	0.482	0.484	+0.3%	0.0093	0.0107	+14.8%
	3.6 deg	0.814	0.879	+8.0%	0.0107	0.0123	+15.1%
	5.1 deg	1.000	1.041	+4.1%	0.0121	0.0134	+11.0%
	8.0 deg	1.317	1.350	+2.5%	0.0125	0.0166	+32.4%
	11.7 deg	1.637	1.676	+2.4%	0.0188	0.0246	+31.1%
	13.3 deg	1.803	1.741	−3.4%	0.0230	0.0343	+49.3%
	15.2 deg	1.959			0.0282		
	mean, absolute			**3.4%**			

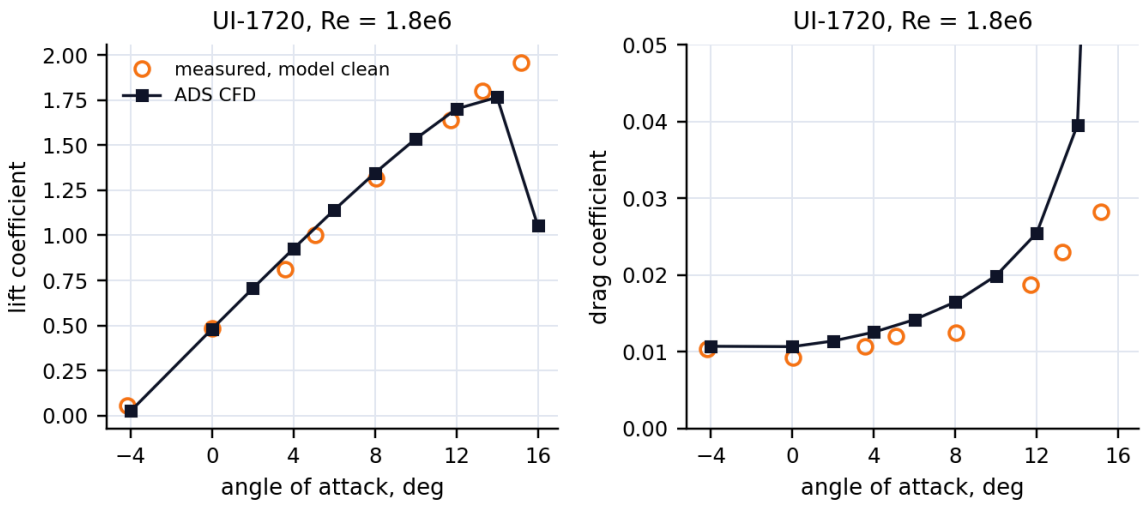


Figure 6. Lift and drag coefficient of the UI-1720 at Re = 1.8 × 10^6: measured [12] and ADS CFD. The computed drag of the stalled point at 16 degrees lies outside the frame.

Up to its maximum, the computed lift is between 3 percent below and 8 percent above the measurement, and 3 percent from it on average. The maximum itself comes early. The computation reaches a lift coefficient of 1.77 at 14 degrees and has stalled at 16 degrees (1.05), where the model reaches 1.96 at 15.2 degrees and stalls just above 16 degrees. A boundary layer that is turbulent from the leading edge gives way on the pressure rise sooner than the boundary layer of the test did. The computed drag is 11 to 49 percent above the measurement, as with the other smooth models.

4.5 Against smooth models at a Reynolds number of 2×10^5

> These differences are not numerical errors: the model in the tunnel has laminar flow, the computation does not.

Table 9. ADS CFD, fully turbulent, against the UIUC measurements [9, 10] at Re = 2.0×10^5.

Section	Alpha	C_l measured	C_l ADS CFD	Difference	C_d measured	C_d ADS CFD	Difference
S1223	2 deg	1.253	1.303	+4.0%	0.0240	0.0240	−0.2%
	4 deg	1.416	1.495	+5.6%	0.0263	0.0269	+2.3%
	6 deg	1.566	1.674	+6.9%	0.0312	0.0309	−0.9%
	8 deg	1.704	1.820	+6.8%	0.0367	0.0369	+0.6%
	10 deg	1.833	1.919	+4.7%	0.0419	0.0468	+11.6%
	mean, absolute			**5.6%**			
E423	2 deg	1.108	1.131	+2.0%	0.0240	0.0254	+5.6%
	4 deg	1.282	1.271	−0.8%	0.0248	0.0314	+26.5%
	6 deg	1.444	not converged		0.0272	not converged	
	8 deg	1.597	not converged		0.0309	not converged	
	10 deg	1.739	not converged		0.0335	not converged	
	mean, absolute			**1.4%**			
NACA 2414	2 deg	0.377	0.391	+3.8%	0.0115	0.0158	+37.1%
	4 deg	0.599	0.587	−2.0%	0.0132	0.0170	+29.0%
	6 deg	0.772	0.772	0.0%	0.0147	0.0190	+29.2%
	8 deg	0.929	0.945	+1.7%	0.0175	0.0222	+27.0%
	10 deg	1.047	1.080	+3.2%	0.0233	0.0281	+20.6%
	mean, absolute			**2.1%**			

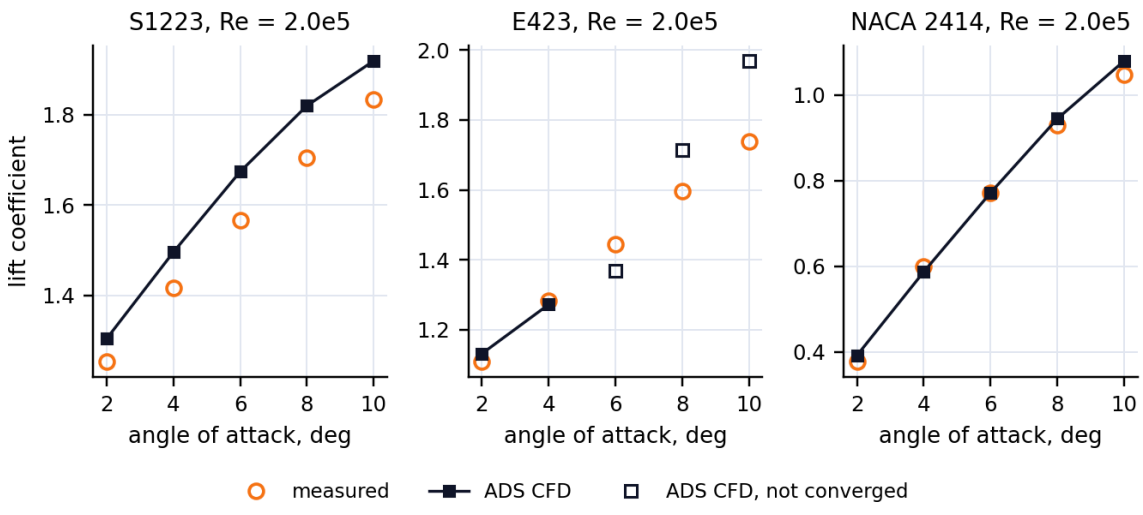


Figure 7. Lift coefficient at Re = 2.0×10^5: UIUC measurements [9, 10] and ADS CFD. Hollow squares: runs that did not converge (Section 6.1).

The computed lift is 4 to 7 percent above the measurement for the S1223 and within 4 percent of it for the NACA 2414. For the E423 it is within 2 percent at 2 and 4 degrees; from 6 degrees on the runs did not converge, which Section 6.1 describes.

The drag depends on the section. For the S1223 the fully turbulent drag is within 2.4 percent of the measurement from 2 to 8 degrees and 12 percent above it at 10 degrees. For the NACA 2414, a conventional section with a long laminar run at this Reynolds number, it is 21 to 37 percent above the measurement, and for the E423 6 and 26 percent above it at 2 and 4 degrees (Figure 8). The good agreement on the S1223 is therefore not a general statement about drag at low Reynolds numbers.

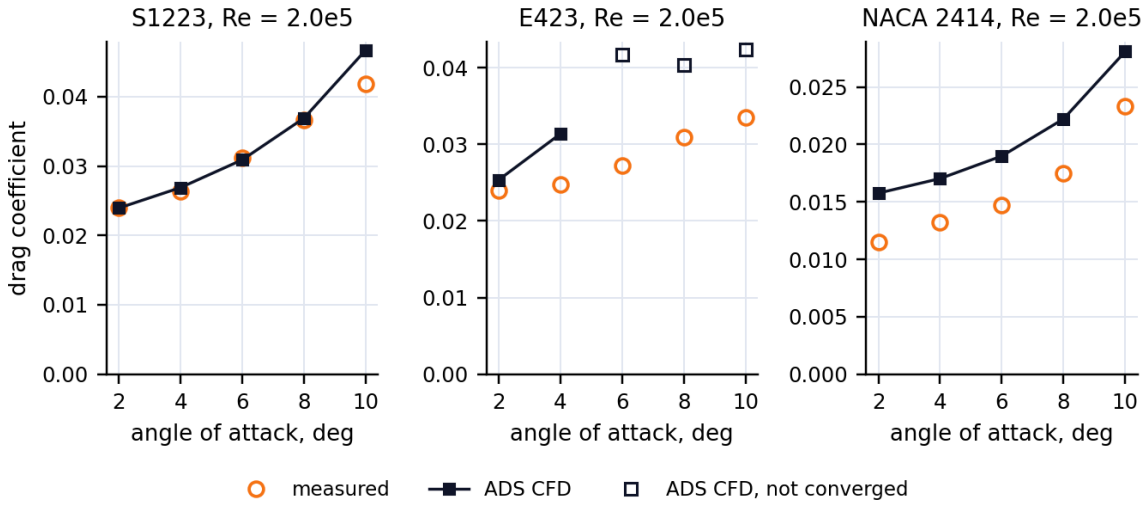


Figure 8. Drag coefficient at Re = 2.0 × 10^5: UIUC measurements [9, 10] and ADS CFD.

5. Numerical uncertainty

Grid. In addition to the grid the application uses, every case of Table 10 was also computed on a coarser and a finer grid. At Reynolds numbers of 2 × 10^6 and above, the finer grid changes the lift by 1.6 percent or less and the drag by 1.5 percent or less. At a Reynolds number of 2 × 10^5, 3 of the 5 cases change just as little (0.4 percent in lift, 1.0 percent in drag), and 2 change more: S1223 at 8 degrees (lift +2.4 percent, drag −4.6 percent) and NACA 2414 at 6 degrees (lift +5.7 percent, drag −4.9 percent). In these two the coarse grid and the grid in use agree, and it is the finer grid that gives more lift and less drag, which is what a smaller separation near the trailing edge does.

We checked that these two runs had really finished. Computed again on both grids with a convergence criterion ten times stricter, they changed by 0.2 percent in lift and 0.3 percent in drag at most, so the difference comes from the grid. What differs between the grids is where the flow leaves the upper surface: at 91 percent of chord on the grid in use and at 94 percent on the finer one for the NACA 2414, at 87 and 89 percent for the S1223. At this Reynolds number a turbulent boundary layer is thick and separates ahead of the trailing edge already at moderate angles, and the lift follows the place of that separation closely.

Table 10. Lift and drag coefficient on three grids. Change: from the grid in use to the finer one.

Section	Alpha	C_l coarse	C_l in use	C_l fine	Change	C_d coarse	C_d in use	C_d fine	Change
NACA 0012, Re = 6.0 × 10^6	10 deg	1.0743	1.0804	1.0833	+0.27%	0.01273	0.01252	0.01250	−0.17%
S809, Re = 2.0 × 10^6	4 deg	0.5934	0.5984	0.6040	+0.93%	0.01266	0.01255	0.01244	−0.91%
S809, Re = 2.0 × 10^6	8 deg	1.0128	1.0230	1.0346	+1.13%	0.01631	0.01583	0.01559	−1.48%
NACA 4412, Re = 3.0 × 10^6	4 deg	0.8688	0.8697	0.8746	+0.56%	0.01107	0.01099	0.01089	−0.92%
NACA 4412, Re = 3.0 × 10^6	8 deg	1.2587	1.2659	1.2855	+1.55%	0.01416	0.01398	0.01387	−0.79%
S1223, Re = 2.0 × 10^5	4 deg	1.5067	1.4954	1.4979	+0.17%	0.02674	0.02691	0.02686	−0.17%
S1223, Re = 2.0 × 10^5	8 deg	1.8187	1.8200	1.8635	+2.39%	0.03714	0.03694	0.03525	−4.56%
NACA 2414, Re = 2.0 × 10^5	2 deg	0.3918	0.3915	0.3911	−0.09%	0.01581	0.01576	0.01562	−0.90%
NACA 2414, Re = 2.0 × 10^5	6 deg	0.7749	0.7717	0.8158	+5.71%	0.01927	0.01899	0.01806	−4.92%
E423, Re = 2.0 × 10^5	2 deg	1.1401	1.1305	1.1341	+0.32%	0.02526	0.02535	0.02539	+0.14%

Repeated runs. Computed a second time, the 28 points of the validation set came back with the same lift within 0.02 percent and the same drag within 0.06 percent. Continued to more than three times its normal length, a run of the reference case returned the same lift and drag within 0.1 percent. Of the 28 points of the validation set, 25 converged.

Taken together: for attached flow at Reynolds numbers of 2 × 10^6 and above, the numerical uncertainty of a converged result is 1 to 2 percent in lift and 2 to 3 percent in drag. That is smaller than the differences from the measurements in Section 4, which therefore belong to the turbulence model and to the measurements, not to the grid. At a Reynolds number of 2 × 10^5 the same holds at low angles. At the higher angles of that Reynolds number the result depends on the grid by up to 6 percent in lift and 5 percent in drag, as much as it differs from the measurements, so the agreement shown in Section 4.5 at those angles is that of the grid in use.

6. Limits

6.1 Cases without a steady solution

The E423 at a Reynolds number of 2 × 10^5 did not converge at 6, 8 and 10 degrees. On this section, with its strongly curved rear upper surface, the fully turbulent solution moves slowly back and forth between a state with the flow separated over the rear of the upper surface and an attached one, however the run is started. Run much longer, the points at 8 and 10 degrees settled on the attached state, with a lift 13 and 14 percent above the measurement; the point at 6 degrees did not settle at all. Even at 4 degrees, where the run converged, a second run started differently gave a lift 1.6 percent and a drag 3.6 percent away from the first.

Such points are not hidden. The convergence check flags them, the report says that no steady solution was reached and why, and their coefficients should not be used. A steady solver cannot average a flow that does not settle. The remedy is an unsteady solver: the application lists it as "URANS (unsteady)", and it is in development.

6.2 Near and beyond maximum lift

Close to maximum lift the differences grow. For the S809 at 9 degrees, where the measured lift curve has already bent over, the computed lift is 12 percent above that of the smooth model (Table 6). For the NACA 4412 at 13.87

degrees it is 3.4 percent above the reference codes that use the same turbulence model (Table 3). The UI-1720, a section designed to work at the edge of separation, stalls in the computation at a lift coefficient of 1.77 where the model reaches 1.96 (Table 8). Values near and beyond maximum lift should be treated as indicative.

We also took two sections through the stall. Run the way the application runs them, the NACA 4412 at a Reynolds number of 3×10^6 converged up to 14 degrees, where its lift coefficient of 1.73 is 15 percent above the measured one; the model had reached its maximum of 1.50 at 13.9 degrees [8]. From 15 degrees on, the runs were still changing when they ended, and they were reported as not converged. The S809 converged at 10 and 11 degrees, 23 and 35 percent above the model with fixed transition [7]. It was reported as not converged from 12 to 16 degrees and at 20 degrees, and it was accepted as converged at 18 degrees with a lift coefficient of 1.47.

Computed in a second way, as one continuous sweep through the angles with longer runs, both sections do reach steady states beyond those angles, but other ones. The lift coefficient of the NACA 4412 is then largest at 16 degrees with 1.73, 15 percent above the maximum of the model and about 2 degrees later. That of the S809 stays between 1.21 and 1.32 from 10 to 18 degrees, 19 to 33 percent above the model with fixed transition where that was measured, and at 18 degrees it settles at 1.32 instead of 1.47. So past maximum lift the steady solution depends on how it is reached, and either way the computed flow keeps more of the upper surface attached than the flow on the models did. A value near or beyond maximum lift is indicative only, also where the run is reported as converged.

6.3 The transition mode

The application lists two further modes that are not open yet. "RANS with transition" adds the correlation-based transition model of Langtry and Menter [2], which predicts where the boundary layer turns turbulent. In steady computations its results did not settle down as the grid was refined: on the S809 the drag in the low-drag range changed by tens of percent from one grid to the next finer one, and at a Reynolds number of 2×10^5 most points on the finer grids reached no steady state at all. The laminar separation bubbles that govern the flow at such Reynolds numbers are unsteady, and a steady solver cannot average them. We therefore do not offer that mode for single-element airfoils, and nothing in this note applies to it. We will take it up again together with the unsteady solver of Section 6.1.

6.4 Two dimensions

Results are two-dimensional. They do not include tip vortices or any other three-dimensional effect of a finite wing, and the flow is incompressible.

6.5 Outside the validation set

The comparisons in this note lie between Reynolds numbers of 2×10^5 and 6.3×10^6, and between 0 degrees and the neighbourhood of maximum lift. Outside that range we ran the tool without a measurement to compare with. The NACA 4412 at 4 and 8 degrees converged at every Reynolds number tried from 5×10^4 to 1×10^7. From the lowest to the highest, its lift coefficient at 4 degrees rises from 0.69 to 0.89 and its drag coefficient falls from 0.0246 to 0.0091, as the friction of a turbulent boundary layer does. Below a Reynolds number of about 2×10^5, a smooth wing in clean air carries long laminar runs and separation bubbles that this mode does not contain: its results there are those of a wing whose boundary layer has been made turbulent. At negative angles the NACA 4412 converged at −4 and −8 degrees, and at −12 degrees only with a longer run than the application allows. The S1223 and the E423 at −4 degrees did not converge. Sections with this much camber stall on their lower surface at a small negative angle (the S1223 in the wind tunnel between −1.5 and −2.8 degrees [9]), and the run reports that no steady solution was reached.

7. What the CFD tool adds

- **Full flow fields.** Pressure, velocity and turbulence around the section, not just the integrated coefficients: where the flow accelerates, where it separates and how the wake develops (Figure 9).

- **Separated flow.** A RANS solver stays usable where extensive separation makes integral boundary-layer methods unreliable, within the limits of Section 6.
- **Any geometry.** Blunt trailing edges, Gurney flaps, hand-drawn or digitised sections and other shapes outside the assumptions of panel methods.
- **A route to what matters in motorsport.** Multi-element wings and wings in ground effect [13, 14], where the interaction between the elements, or with the ground, decides the performance.
- **Two tools in one place.** ADS offers both XFOIL and CFD: screen designs quickly with the panel method, and use CFD where the flow physics matters.

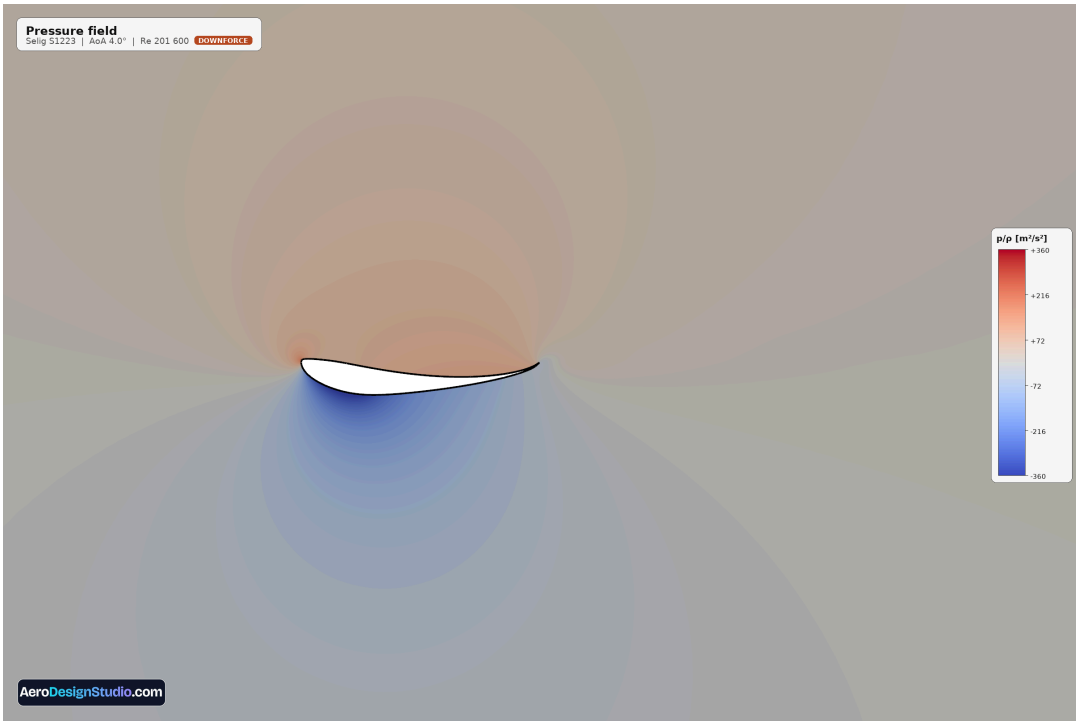


Figure 9. Pressure field around the S1223 at 4 degrees, Re = 2.0 × 10^5, in the downforce orientation, as delivered in an ADS CFD report.

8. Accuracy and recommendations

Table 1, at the start of this note, sums up the accuracy of the mode. Two remarks help to read it.

Lift. Where the boundary layer of the model was tripped by a narrow strip, which is the flow the computation describes, the computed lift is within 4 percent of the measurement up to 8 degrees at Reynolds numbers of 2.1 × 10^6 to 6.3 × 10^6 (Table 7). Against the smooth models of the five other sections it is within 8 percent for attached flow at every Reynolds number covered here, and 4 percent from them on average. Two things move a real wing away from that. A smooth wing of a section that carries its load at the rear has more lift than computed, by up to 16 percent on the GA(W)-1 at the lowest Reynolds number. And a wing with heavy roughness has less lift than a turbulent boundary layer on a smooth wall gives it, so less than computed (Table 5).

Drag. The computed drag is that of a boundary layer that is turbulent from the leading edge on a smooth wall. For a wing in that state, behind a trip or in the disturbed air around a car, it is the right estimate: it agrees with the tripped measurement of the S809 within 8 percent and lies 0 to 17 percent below that of the GA(W)-1, 9 percent on average. For a smooth wing in clean air it is an upper bound, and the more laminar flow the wing carries, the further it lies above the real drag: by up to 80 percent on the sections of this note.

Recommendations.

- Read the drag as that of a wing whose boundary layer is turbulent. That fits a wing on a car. For the drag polar of a smooth wing in clean air, use the XFOIL tool of ADS, which predicts transition.

- Check the convergence note of every point. A point without a steady solution is reported as such, and its numbers should not be used.
- Treat values near and beyond maximum lift as indicative, also where the run converged.
- At a Reynolds number of 2×10^5 and at moderate angles, allow for a few percent of numerical uncertainty on top of the differences of Section 4 (Section 5).
- Use the CFD tool for what a polar alone does not give you: the flow field, separated flow, and shapes outside the assumptions of a panel method.

9. Conclusions

The fully turbulent mode of the ADS CFD tool returns the reference solutions of the NASA Turbulence Modeling Resource for the NACA 0012 within 0.1 percent in lift and 1.4 percent in drag. On the NASA GA(W)-1, the wind-tunnel model closest to the flow the tool computes, the lift is within 4 percent of the measurement up to 8 degrees and the drag 9 percent lower on average, and both follow the Reynolds number as the measurement does. On five smooth models from 1 to 10 percent camber, at Reynolds numbers from 2×10^5 to 3×10^6, the computed lift is within 8 percent of the measurement between 0 and 8 degrees wherever the computation converges, and 25 of 28 points do. The computed drag is that of a turbulent boundary layer: close to the measurement on tripped models, and above it on smooth models by as much as their laminar flow saves. Points without a steady solution are reported as such, and values near maximum lift are indicative.

Future versions of this note will add sections with the camber of racing-car wings at Reynolds numbers above 1×10^6, once a measurement with a tripped boundary layer is available, multi-element wings, and the transition mode once an unsteady solver carries it.

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Notice

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