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**Validation of software for the calculation of
aerodynamic coefficients
with a focus on the software package *Tornado***

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Fluida och mekatroniska system



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ABOUT THIS DOCUMENT

This TGZD20 degree project executed during the 2009-2010 course at Linköping University determined the validity of various software used for the calculation of the aerodynamic properties of four different aircraft and two airfoils.

ABSTRACT

Several programs exist today for calculating aerodynamic coefficients that with some simplifications provide fast approximations of the values for a real aircraft.

Four different programs were analyzed for this report: Tornado, AVL, PANAIR and a handbook-type preliminary method. In addition, ANSYS CFX was used for airfoil validation. For calculation of the zero lift drag, an approximation was computed in order to calculate the remaining values that were not calculated by the software: drag contribution for fuselages, nacelles and some horizontal stabilizers and fins.

Different types of aircraft were selected for trial: two commercial aircraft (Boeing 747-100 and 777-300), a TF-8A research airplane (with area rule application: some additions were made to the fuselage to prevent large variations in the cross-section when the contribution of the wing is added), a Lockheed Constellation C-69 used as a military cargo airplane, a Boeing Stratocruiser used by the USAF with two configurations (basic and bomber), and an Aero Commander 680 Super, similar to a Cessna 162. Two airfoils (NACA2412, 0012) were also analyzed, to investigate the limitations of software designed for three-dimensional calculations.

The accuracy of the results showed that the validity of the software depends on the planform of the aircraft, as well as the simulation parameters Mach number and Reynolds number. The shape of the wing caused some of the methods to have serious difficulties in converging to valid results, or increased the simulation time beyond acceptable limits.

SAMMANFATTNING

Nu finns det olika program för beräkning av de aerodynamiska koefficienterna från en modell med vissa förenklingar som ger en snabb approximation av värdena för ett verkligt flygplan.

Fyra olika program har analyserats för denna rapport: Tornado, AVL, PANAIR och en handbok baserad preliminär metod. Dessutom användes ANSYS CFX för validering av vingprofiler. Vid beräkningen av noll-lyft motståndet, en approximation användes för de återstående delarna som inte beräknas av de andra metoderna: motståndsbidraget från flygkroppar, gondoler och vissa horisontella stabilisatorer och fenor.

Olika flygplaner har testats: två trafikflygplan (Boeing 747-100 och 777-300), ett TF-8A forskningsflygplan (med area regel användning: några tillägg gjordes på flygkroppen för att tvärsnitten inte har stora variationer när bidraget från vingen läggs), ett Lockheed Constellation C-69, ett Boeing Stratocruiser som används av USAF i två konfigurationer (den vanliga och bombplan), och ett Aero Commander 680 Super, som liknar ett Cessna 162. Två vingprofiler (NACA 2412, 0012) analyserades också, för att kontrollera begränsningarna av programmen avsedd för tredimensionella beräkningar. Riktigheten av resultaten visade att giltigheten av programmen beror på formen av flygplanernas vingar, samt de simulationernas parametrar: Mach nummer och Reynolds nummer. Formen på vingen orsakade några av de metoderna att ha stora svårigheter med konvergensen till giltiga resultat, eller ökat simulering tid över acceptabla gränser.

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IV. SYMBOLS

AR: Aspect Ratio
 $C_{L\alpha}$: Lift curve slope
 C_{D0} : Zero Lift Drag
 e : Oswald efficiency factor
 K_1 : Coefficient for the linear term
 K_2 : Coefficient for the quadratic term
MTOW: Maximum Take-Off Weight
RMS: Root Mean Square error
 RMS_{Lift} : Root Mean Square error on lift
 RMS_{Drag} : Root Mean Square error on drag
VLM: Vortex Lattice Method
WTT: Wind Tunnel Test
 α_{CL0} : Zero lift angle of attack
 Λ_{LE} : Sweepback of the leading edge.

1. INTRODUCTION

Drag and lift are two basic parameters when investigating the performance of an airplane. The engine needed and the MTOW that an aircraft can bear depend on them. In addition, the structural design depends on lift, drag and the other aerodynamic forces and moments and interacts with them. A balance has to be found as the weight of the structure can not be too high: if the structural weight is too great, the payload may not be large enough for the airplane to be profitable for any company or suitable for military missions, as the greater the weight the less fuel-economic the aircraft is.

The different values for lift, for drag and the other coefficients are traditionally measured in wind tunnels and during flight tests. Wind tunnels have special challenges, though: they are expensive, even for small models, and in order to make a flight test a first full-scale unit has to be built. It would be desirable for the project developer to have an idea of the aircraft's properties before actually building it. Above all, in the case of a high capacity aircraft (as for instance a Boeing 747), the cost of making a model airplane (with cost increasing with scale) would be extremely high (a full-scale airplane can cost hundreds of millions US\$).

The evolution of fluid dynamic models provided a first approximation of the calculation of aerodynamic coefficients and the appearance of computers made calculations faster and more accurate. Computer-aided design (CAD), the finite element method (FEM) applied to the calculation of the structures, and Computational Fluid Dynamics (CFD) are used nowadays in most engineering projects. However, before starting to use a program as a valid tool for aerodynamic calculations, it has to be proven to be reliable.

In this work, the validity of four different aerodynamic modeling software was tested by comparing their results with wind tunnel or flight test data for different aircraft. Also, a secondary validation on two airfoils was run in ANSYS CFX, which is used by the most important aeronautical companies (Boeing, Airbus). The methods are explained in section 4 and the models in section 5.

The results of wind tunnel and flight tests (references 1 to 7) were used as the actual values for the performance of the aircraft, although this may not hold if the experiments are set and/or run improperly. There are cases where the results obtained using different software are similar among themselves but where the wind tunnel data differs. It is from the analysis of the data, based on experience and possibly other similar previous aircraft, that a decision to accept the wind tunnel results is made.

The quality of the solution will not be the only factor taken into account: user-friendliness and time spent on the computation are also important. For instance, a test is run on an aircraft in two different programs and the results are very accurate (e.g. RMSs of 0.50% and 0.75%, respectively). If the computation time for the second simulation is half of the first, it would in some instances be advisable to use the second, although the RMS is higher. The selection of the best solution for the specific case is a choice that must be made by the working team depending on the errors they find acceptable for a basic calculation.

2. BACKGROUND

As the aim of this project is to compare software, the versions are the latest available for each program and method, i.e. Tornado v.135, AVL 3.27 and PANAIR 14. ANSYS CFX is run on ANSYS Workbench 12.

The comparisons are usually made by means of comparing the aerodynamic coefficient derivatives in forces and moments for both angle of attack and sideslip. The validations are usually done by comparing commercial software that has been proven to be reliable in the specific case with the ones that are being tested.

In this report only lift and drag were computed for aircraft and lift and pitching moment for the airfoil analysis, and the results from the different software were compared to decide the most appropriate for each validation case, checking the results against the wind tunnel data.

3. EXPERIMENTAL SETUP

The wind tunnel tests were performed at the NASA facilities Langley Research Center in Hampton, Virginia, and Ames Research Center at Moffett Field, California. Depending on the size of the model used, either the 8-, 11- or 16-foot wing tunnel was used, in addition to the full scale testing wind tunnel. The computational calculations were made at Linköping University. Additional corrections needed to be made to the preliminary results for some models. The angles of attack and sideslip (and therefore, lift and drag measured) depend on the facilities and how the model plane is mounted in the tunnel. However, in most cases the corrections for the wind tunnel results are already made by the test staff. For the Boeing 747-100, the angle of attack is decreased by 2.5 degrees to balance the test bench attitude^[1]. The Mach number is 0.85 under cruise conditions. The Reynolds number in this test is $2.4 \cdot 10^7$ for both wind tunnel and models.

The Boeing 777-300 has no additional corrections^[2]. The conditions are at cruise altitude and Mach 0.84, with a resulting Reynolds number of $8.7 \cdot 10^5$.

The TF-8A research airplane^[3] has a correction of 1.5 degrees due to the mounting system. The two cases are at M0.5 and $Re = 2.0 \cdot 10^5$ and M0.8 and $Re = 3.5 \cdot 10^5$.

The Lockheed C-69^[4] has no corrections. The Mach number is 0.5 and the Reynolds number is $3.6 \cdot 10^5$.

The Boeing Stratocruiser^[5] has the corrections already computed on the results used in both cases. The transport version operates at Mach 0.775 and $Re = 6.3 \cdot 10^5$ while the bomber version was tested at Mach 0.6 and $Re = 4.9 \cdot 10^5$.

The Aero Commander 680 Super^[6] has no further corrections. The Mach number is 0.2 at $Re = 6.8 \cdot 10^5$.

The NACA2412 and NACA0012 airfoils have no corrections. The Mach number is 0.3 and the tests are at a Reynolds of $6 \cdot 10^6$. The curves used for the comparison are taken directly from [7].

4. METHODS

4.1. PANEL METHOD

A general panel method^[8] can be used for both incompressible and compressible flows, in both two and three-dimensional cases, but always inviscid (ideal fluid, not real application cases), or when the viscous effect can be considered negligible. It solves the Laplace ($\nabla^2\phi = 0$) or the Prandtl-Glauert equations depending on the Mach number (Laplace for low Mach numbers, incompressible flow and Prandtl-Glauert when compressible). The surface is divided into N parts, called panels, as shown in figure 1. Each panel has a "singularity" (algebraic functions that are solutions to the equations) where the Laplace equation is applied. This provides a linear set of algebraic equations. An extra equation is needed as there are $N+1$ unknowns and N equations ($N+1$ nodes and N panels). The remaining equation is the Kutta condition: the flow has to leave the trailing edge smoothly. The tangential velocity on the first and the last panels has to be the same, but for this condition to be satisfied, the two panels need to have the same length. With the equation for the Kutta condition plus the Laplace or Prandtl-Glauert equations for the panels, the model can be solved.

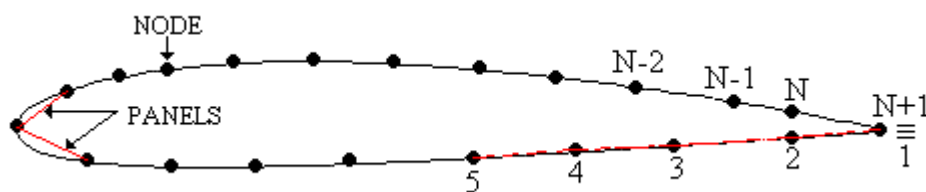


Figure 1. An N -panel airfoil model

4.2. VORTEX LATTICE METHOD

The vortex lattice method (VLM) has basic similarities with the panel method, but it is easier to implement. It is based on solutions to Laplace's Equation. The fact that the method is totally numerical made the VLM difficult to use for practical problems until the development of computers. The method divides the lifting areas into panels and each panel has a horseshoe vortex (see figure 2). Along a vortex line, the circulation Γ remains constant. The vortex line is extended to infinity or ends at a solid boundary.

A big difference between the panel method and VLM is in the treatment of the boundary conditions. They are applied at a mean surface and not the actual one; it is usually developed into a "thin airfoil boundary condition" which means that the actual layer surface becomes a flat plate parallel to the local chord. Some simplifications can be made because of the linearity of the Laplace equation applied. Calculations using VLM are oriented towards thin airfoils, unlike the panel method which has no thickness limitations. Flow conditions are an important aspect: in VLM the flow has to be steady and inviscid.

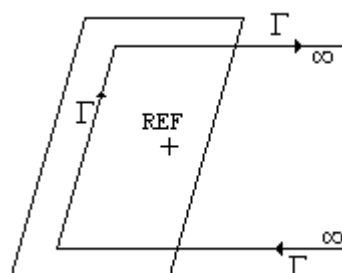


Figure 2. A horseshoe vortex. The finite line is situated at the quarter line, and the calculation point at three quarters.

4.3. WIND TUNNEL TESTING

This is the traditional way of obtaining data from aircraft. The results should be the most accurate if the aircraft model is scaled to be aerodynamically similar, and if the size of the tunnel is sufficient to conduct a simulation as if it were an outdoor flight test. In this report, the results obtained from wind tunnel tests were taken as the actual values and the basis on which to calculate the errors in the numerical models. The Mach and Reynolds numbers also have to fulfill the similarity conditions. All tests in this work were conducted by NASA at Langley Research Center (Hampton, VA) or at Ames Research Center (Moffett Field, CA). As different size models were tested, the size of the tunnels used also varied. The Mach numbers ranged from Mach 0.2 (on the Aero Commander 680 Super) to Mach 0.85 (Boeing 747-100), and the Reynolds numbers varied between $2 \cdot 10^5$ on the TF-8A at Mach 0.5, and $2.4 \cdot 10^7$ on the Boeing 747-100. The wind tunnels used were the 8-by-8 ft (for the TF-8A), 11-by-11 ft (Boeing 777-300), 16-by-16 ft (Lockheed C-69, Boeing Stratocruiser) and full scale 30-by-60 ft (Aero Commander 680 Super) wind tunnels at the named centers, and a flight test was performed with the Boeing 747-100.

4.4. TORNADO

The Tornado software is a vortex lattice method based code. It has two solver methods, depending on the type of the wake: it can be fixed wake (a normal vortex lattice) or the Tornado method^[9]. The main difference is in the wake created, as the Tornado method has a free stream following wake, that is, the wake is influenced by the angles of attack and sideslip. The wing modeling is done by partitions, and a blunt body model of the fuselage can be computed. A partition is a section of the wing where the geometric characteristics do not change. The end of the partition can be a point with geometry or airfoil changes. The modeling of the intersection zone of the wing occupied by the fuselage is done by regarding it as an actual part of the wing, but with a flat plate in the corresponding partition; it can also be a thin symmetric airfoil, like a NACA0006, or 0008, to take into account the presence of some lifting forces from the fuselage.

Tornado is a MATLAB-implemented code published under GNU-General Public License. The Tornado software calculates numerous variables, such as lift, drag (and their non-dimensional coefficients), bending moment, and shear forces. It calculates aerodynamic forces on wing-like surfaces (that is, wing and tail group) but not fuselage or nacelles. For the drag case, an estimation of the zero lift drag of the fuselage can be made from a blunt body approximation.

4.5. ATHENA VORTEX LATTICE

AVL uses an extended vortex lattice method (according to Drela, reference 10) for the calculation of lifting surfaces (wing, tail group) and a slender body model for fuselage-like surfaces (the fuselage itself, nacelles). The wing is modeled in the geometry file by selecting the coordinates of the leading edge of the desired sections (changes on the plan view of the wing, changes on airfoil). Experience of the slender body model is very limited and the results may therefore not be as expected. Modeling using slender bodies implies the cross-section to be round. The angles of attack have to be low for the vortex lattice to work properly. The flow is treated as quasi-steady, where the unsteady motion is sufficiently slow. The angular velocities also need to be low, being limited to 0.1 in roll (multiplied by the span), 0.03 in pitch (multiplied by the MAC) and 0.25 in yaw (span). The movement is actually very violent if the rate is outside the limits. AVL applies a Prandtl-Glauert transformation to model compressibility due to Mach number. An unswept wing can apply this transformation at Mach numbers below 0.6 to ensure that the model works properly. At M0.7, the model is liable to be wrong due to the possibility of transonic points, at M0.8 it is totally unreliable and above M0.8 it is hopeless inaccurate. These limits are increased if swept wings are used.

In the analyzed cases, only the wing-type surfaces are modeled, to obtain a better comparison with Tornado and to avoid the possible errors on the fuselage modeling mentioned above. The fuselages in the validation cases do not have not round cross-sections, which further justifies not using fuselage modeling.

The code was developed by Mark Drela and Harold Youngren and is published under the GNU-General Public License.

Simulations on airfoils were run with XFOIL, software developed by the same authors and focused on calculations on airfoils.

4.6.- PANEL AERODYNAMICS (PANAIR)

PANAIR^[11] can solve potential flow problems using a high-order panel method. Up to four different conditions can be solved in one run. The flow cannot be transonic, but can be either sub- or supersonic if the flow is attached. The viscous effects are not modeled, so cases where viscosity or boundary layer separation are dominant will not have the expected results. The cases where the panel method is not reliable are also likely to produce inaccurate results as well. The cases run in PANAIR have to be within the linearized potential flow conditions to achieve valid solutions. The total pressure and total temperature should be constant, although an implementation for solving flows with different total conditions than the free stream has been developed and added to this version.

The solutions shown include an analysis of the flow field for all input cases and a flow description of streamlines in the desired cases.

PANAIR is a code developed by Boeing in the early 1990s, also known by its code name A502. It can solve the whole aircraft, but once again only the wing will be modeled in these examples.

4.7.-ANSYS CFX ®

ANSYS CFX and ANSYS FLUENT are two of the most used programs for calculating the aerodynamic characteristics of aircraft in the industry: both Boeing and Airbus use them. They can solve laminar and turbulent cases, using different models for turbulence. ANSYS FLUENT can solve 2-dimensional states, but CFX cannot do so. This is a problem when airfoils are tested, but it can be resolved by using extremely high aspect ratios (over 100). ANSYS CFX calculates forces and moments for fluid areas; the bodies where the parameters are calculated are “holes” in the fluid domain.

In this document, only airfoils are to be solved with CFX, but obviously whole aircraft can be solved with it. The memory needed for the simulations may be a problem when using it: a simulation of an aircraft would be too large for a standard computer, although the results would be best if the mesh is done well and the appropriate boundary conditions are set. The difficulty with CFX is that the results have to be proven to be mesh-independent and the boundary conditions need to be positioned so as not to interfere with the results. For instance, the inlet and outlet have to be fairly distant from the model to prevent any non-disturbed flow on them. At the outlet in particular, this can be extremely difficult to accomplish, as the best results are achieved with the outlet more than 5 mean aerodynamic chords (around it) from the trailing edge of a wing and all this space needs to be meshed, which requires a great many elements and, therefore, memory.

4.8. PRELIMINARY METHOD

The preliminary method^[12] is very simple, and can be used for a first approximation of the wing, only. It calculates the lift slope and the second-grade coefficient of the polar (see equation 1) having to be complemented by a zero-lift drag value and a point of the lift curve. As a first approximation, a lift calculation could be made with initial flight conditions. Also, there is no linear term on the drag polar, meaning that zero-lift drag will always be the minimum, which is not true in most real cases (see section 6 Results). It makes no difference what airfoils are used on the wing, so having a symmetric airfoil would give the same result as a high-cambered airfoil. The results depend only on the top view, speed not even being considered. This can lead to problems if an aircraft flies at an obviously compressible Mach number.

The formulas used for the calculations according to the reference are equation 2 (lift slope) and equation 3 (polar second grade coefficient). AR stands for Aspect Ratio, e is the Oswald efficiency factor and Λ_{LE} is the sweepback of the leading edge. In equation 1, CD0 is the zero-lift drag.

$$C_D = K_2 \cdot C_L^2 + C_{D0} \dots \dots \dots (1)$$

$$C_{L\alpha} = \frac{2\pi \cdot AR}{2 + \sqrt{4 + \left(\frac{AR}{\cos(\Lambda_{LE})}\right)^2}} \dots \dots \dots (2)$$

$$K_2 = \frac{1}{\pi \cdot AR \cdot e} \dots \dots \dots (3)$$

4.9. ZERO LIFT DRAG CALCULATION

A first approximation of the zero lift drag has to be made for the aircraft as most of the methods need either a whole value for C_{D0} or an addition to it. For instance, Tornado calculates the C_{D0} for the parts modeled, but needs the fuselage drag. AVL needs the whole aircraft value, and so does the preliminary method.

The method used to calculate the zero lift drag was a Hoerner-Raymer combination [13, 14]. The final result is extremely good in most cases, with an error of less than 5%.

5. VALIDATION CASES

A) AIRCRAFT MODELS

A.1) Boeing 747-100

The Boeing 747 is easily recognized by its double deck configuration, and it is a classic aircraft that is even today widely used by operators. The first flight took place on 1969, and it entered service in 1970.

It was selected for this study because it is representative of very long-range aircraft, like the Airbus A340 or the Airbus A380. The range of the Boeing 747-100 (the one used in the study) is around 9,000 km at MTOW. A three-view drawing of the aircraft is shown in figure 3. Figures 9 and 10 are the respective simulation models in Tornado and AVL. The Mach number of this flight test is 0.85 (cruise speed) and the Reynolds is $2.4 \cdot 10^7$.

A.2) Boeing 777-300

The Boeing 777 first flew in 1994 and entered service in 1995. The range of the 300 version is around 7,000 km.

It was chosen as an example of a long-range airplane, so the results can be compared with other long-rangers with similar characteristics (for instance, Airbus A320, A330 and Boeing 757). The three-view drawing is shown in figure 4 and the simulation in figures 11 and 12. The Reynolds is $8.7 \cdot 10^5$ and the Mach is 0.84 in this test, that was performed in the 11 ft wind tunnel.

A.3) TF-8A research airplane

This research model is an example of an area-ruled airplane. Two different Mach numbers were tested: Mach 0.5 and 0.8. This is an example of a high-sweep airplane (the leading edge sweep is almost 45 degrees) and the average aspect ratio 7. Figure 5 shows a top view of the aircraft, with all dimensions in centimeters, with inches in brackets. The simulation models are shown in figures 13 and 14. The two wind tunnel tests performed in the 8 ft wind tunnel have Reynolds numbers of $2.0 \cdot 10^5$ and $3.5 \cdot 10^5$ respectively for Mach numbers 0.5 and 0.8.

A.4) Lockheed Constellation C-69 model

This is an example of a cargo-designed model. It can be used as comparison to some large transport aircraft, as the span is around 40 meters. For instance, the Airbus A400M has a span of 42 meters and is also a 4-propeller airplane. It is also similar to the Tupolev Tu-95.

The three-view drawing is shown in figure 6. Dimensions are in inches. Figures 15 and 16, show the simulation configurations. The tests were run in the 16 ft wind tunnel and the Mach number is 0.5 at a Reynolds of $3.6 \cdot 10^5$.

A.5) Boeing Stratocruiser

Two configurations were tested. The wing is the same in both models, but the tail group and the fuselage are not equal and thus give different performance. The Mach and Reynolds numbers also change, and the results from the software will thus change even for the same wing.

Figure 7 is a three-view drawing of the transport version. Figures 17 and 18 are the models for the simulations. This example could be representative of any large civil or military jet aircraft. The tests were conducted in the 16 ft wind tunnel; the transport version parameters are Mach 0.775 and $Re=6.3 \cdot 10^5$ and for the bomber M0.6 at Reynolds $4.9 \cdot 10^5$

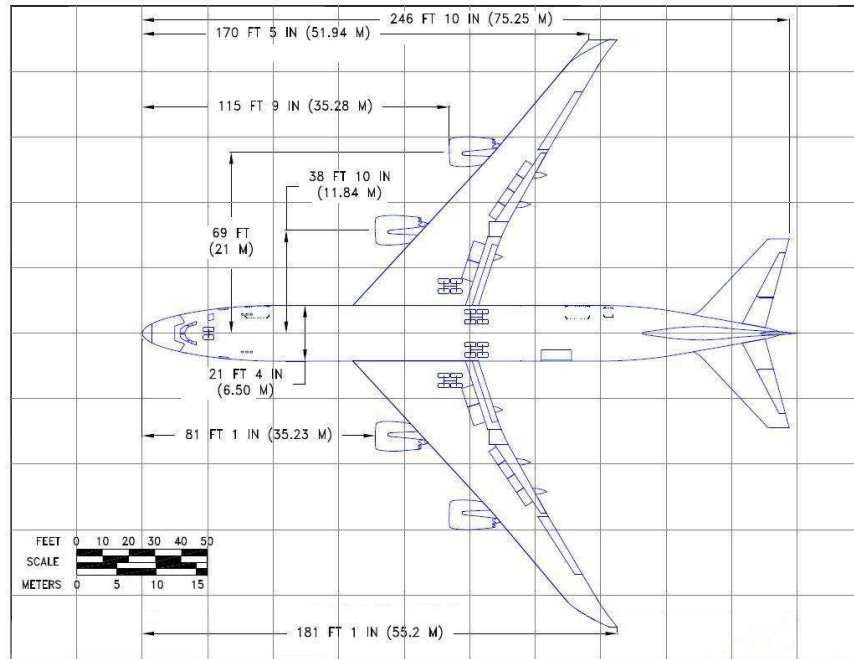


Figure 3. Top view of the Boeing 747-100

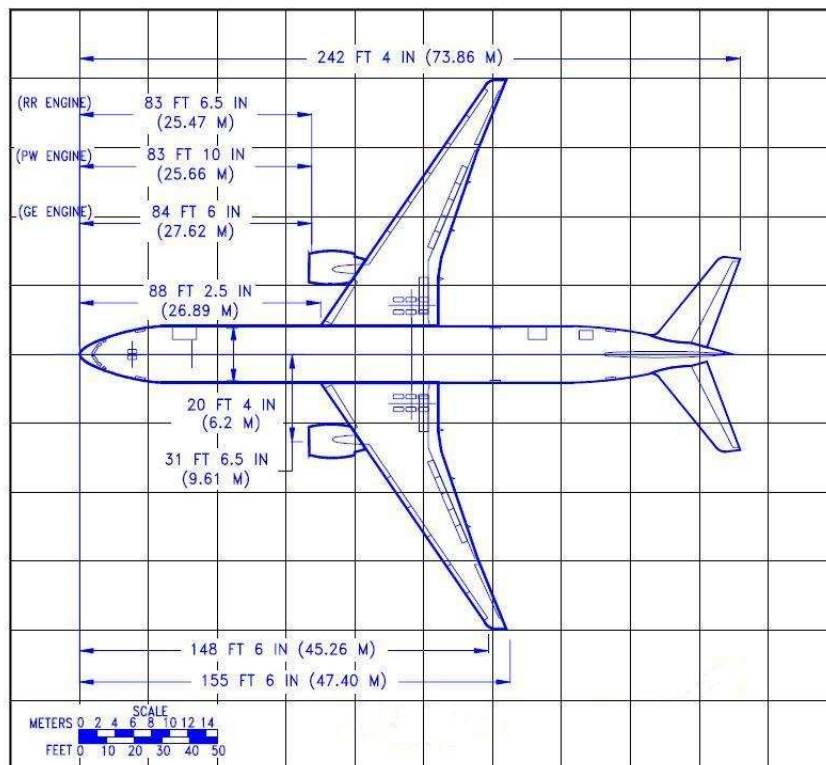


Figure 4. Top view of the Boeing 777-300^[15]

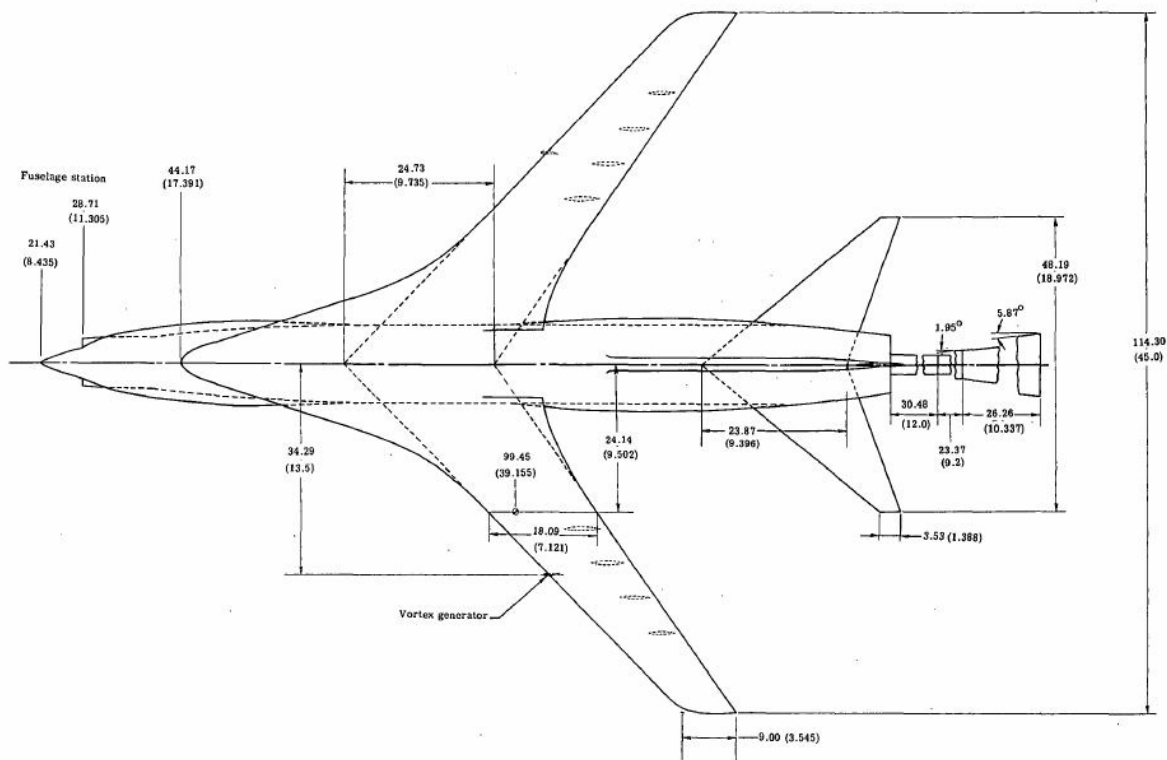


Figure 5. Top view of the TF-8A research airplane

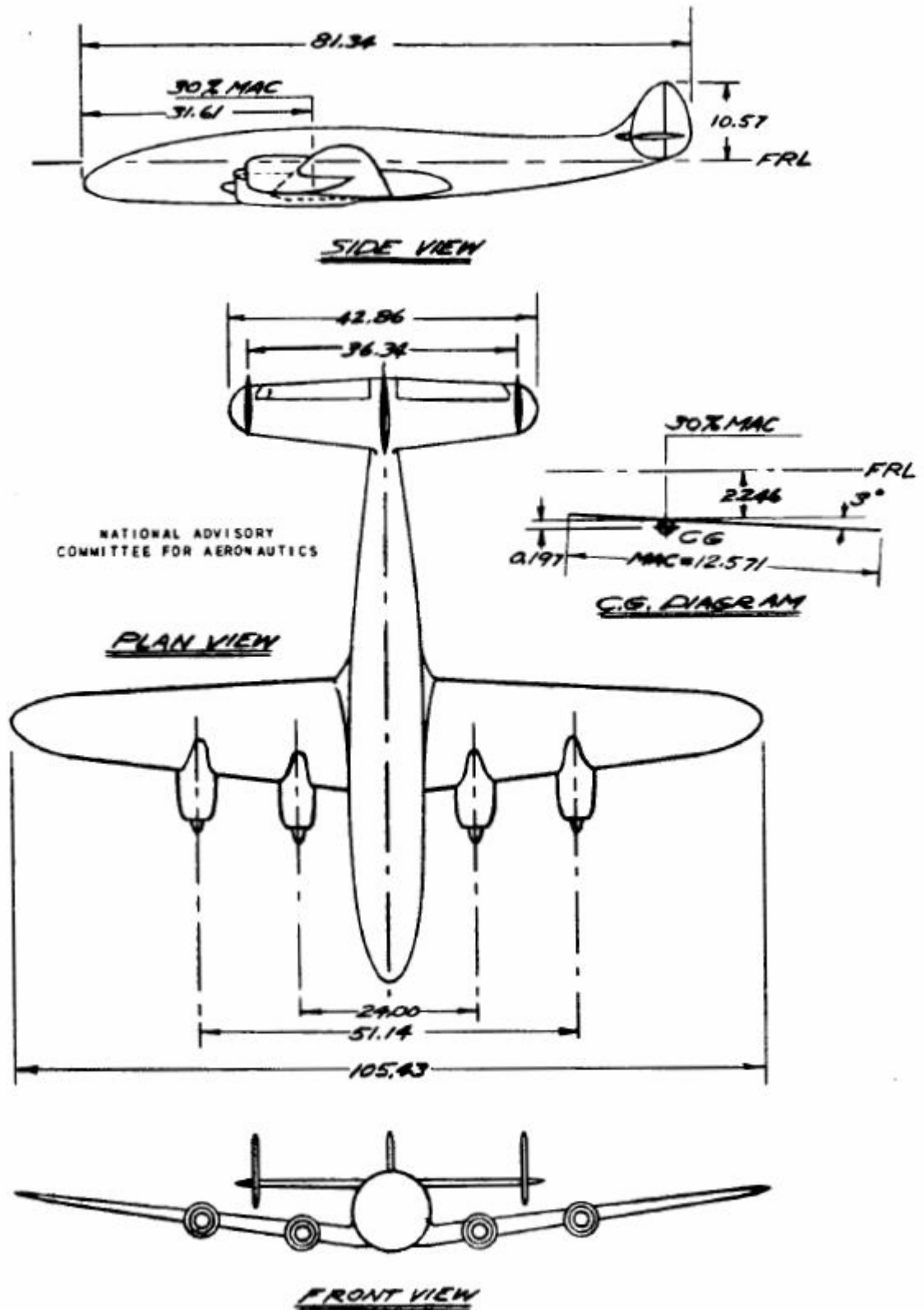


Figure 6. Three view drawing of the Lockheed C-69 model

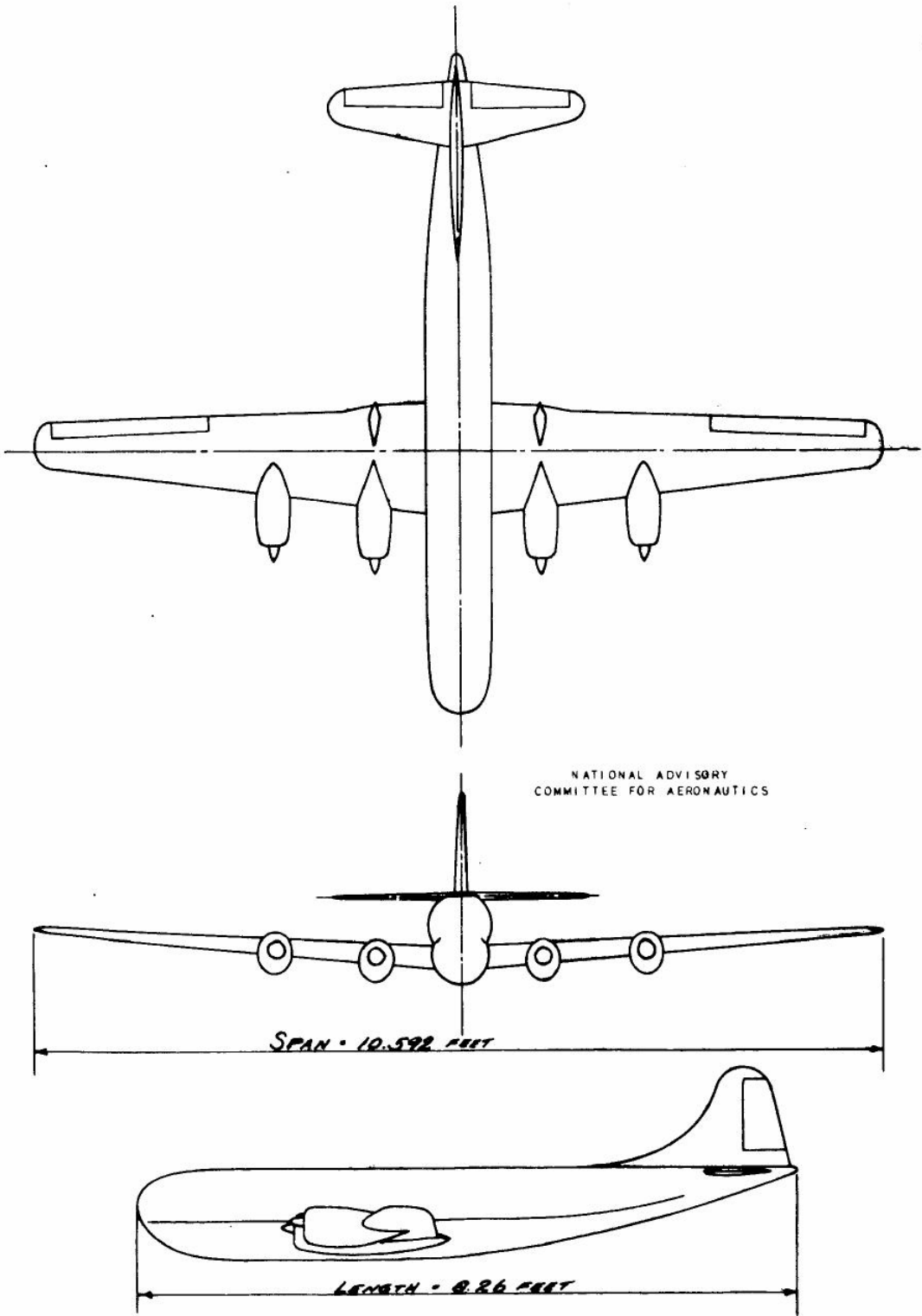


Figure 7. – Three-view drawing of a Boeing Stratocruiser, conventional configuration

A.6) Aero Commander 680 Super

This aircraft was selected as an example of a general aviation propeller airplane. Its wingspan is 10.97 meters. Figure 8 shows the actual aircraft and figures 19 and 20 the ones used at code simulations. The full-scale test conditions are Mach 0.2 and Reynolds number $6.3 \cdot 10^5$.

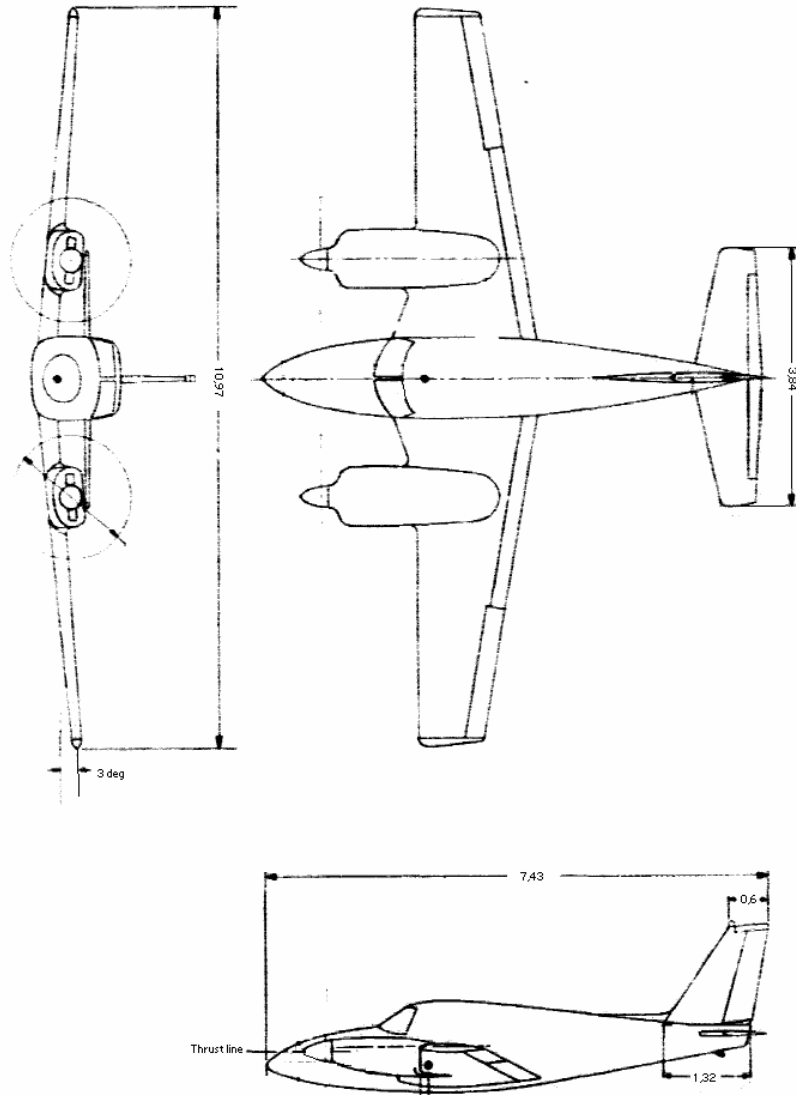


Figure 8. Three-view drawing of the model

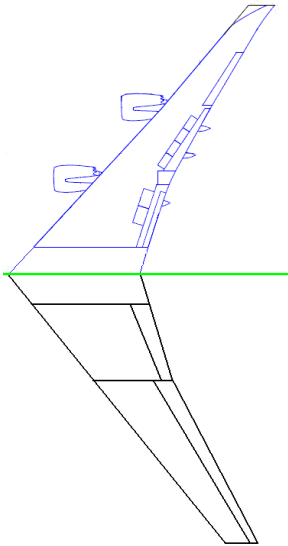


Figure 9. Tornado model Boeing 747-100

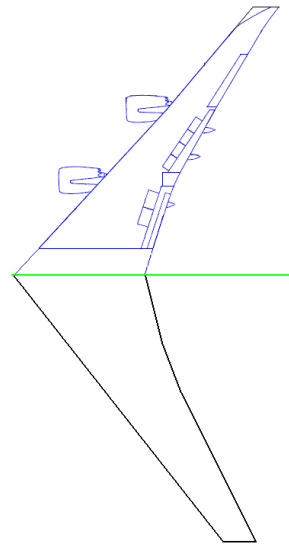


Figure 10. AVL model Boeing 747-100

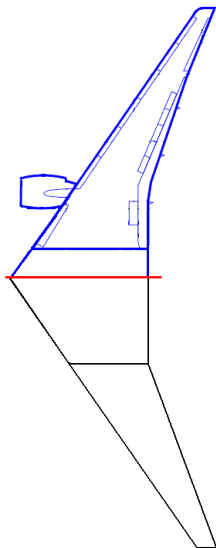


Figure 11. Tornado model Boeing 777-300

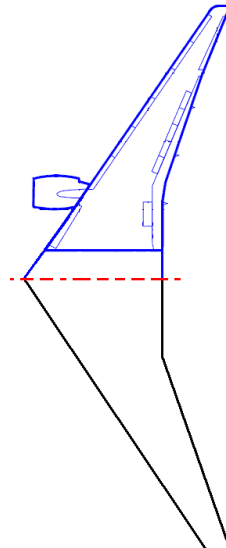


Figure 12. AVL model Boeing 777-300

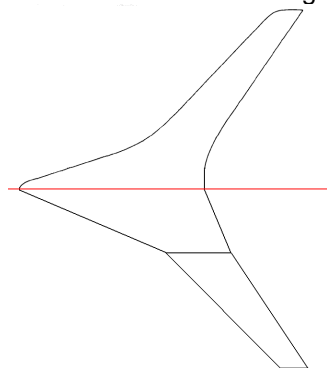


Figure 13. Tornado model TF-8A airplane

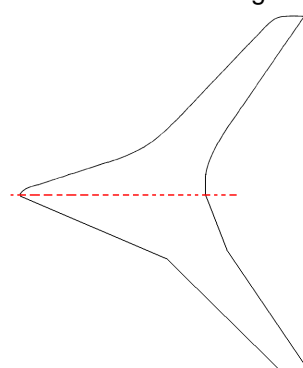


Figure 14. AVL model TF-8A airplane

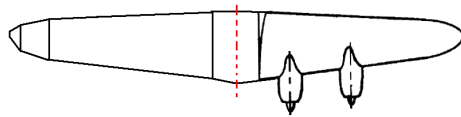


Figure 15. Tornado model Lockheed C-69

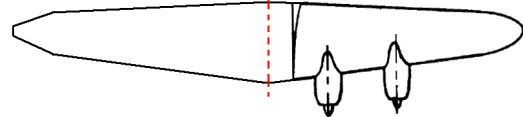


Figure 16. AVL model Lockheed C-69

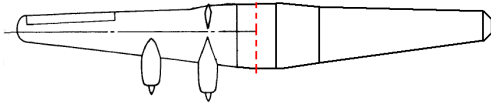


Figure 17. Tornado model Boeing Stratocruiser

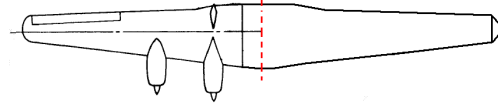


Figure 18. AVL model Boeing Stratocruiser

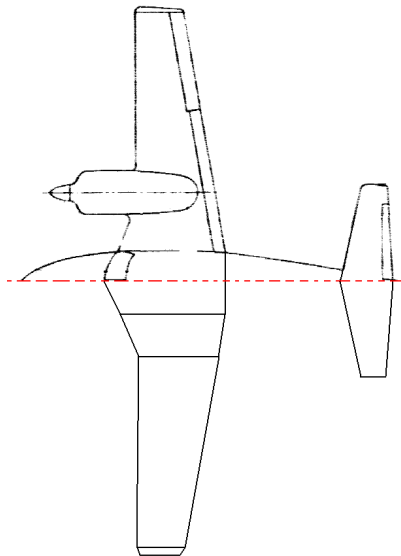


Figure 19. Tornado model AC680S

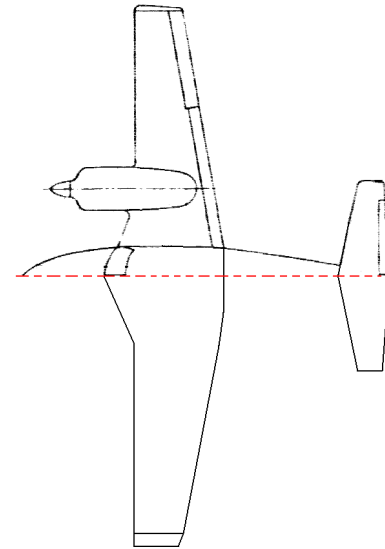


Figure 20. AVL model AC680S

B) AIRFOILS

B.1) NACA 2412

This is a classic among general aviation airfoils and has been studied extensively, which is why it was chosen. A normalized model is shown in figure 19.



Figure 21. Standard view of the NACA 2412 airfoil

B.2) NACA 0012

The NACA 0012 airfoil is the most used symmetric airfoil. It is usually seen at the tail, on the horizontal stabilizer. It was also used to check the balance of the wind tunnels, which is the main reason for its inclusion here.



Figure 22. - Standard view of the NACA 0012 airfoil

6. RESULTS

6.1) AIRCRAFT

The following section will show the results of the study for the 6 defined airplanes, both propeller and jet aircraft, of different sizes (ranging from an Aero Commander 680 Super to a Boeing 747) and missions (military, civil). The tables show the values of different coefficients for polar and lift calculations. In the case of experimental data, an approximation was made. In most of the codes, the approximation coefficients are calculated by the software itself. Where they are not, a MATLAB or Excel calculation can be performed using the obtained results.

The comparison between the different results and the wind tunnel data is shown in different figures for the lift and drag coefficients, viz. figures 23 to 38. In addition to the actual error values (figures 39 to 54), mean square root values have been calculated using lift and drag data and are shown in the tables. Errors are computed as the difference between the approximation result and the experimental value. The errors in the approximations of the experiments were also computed and are shown in the figures.

To check which calculation gives the closest values to the actual results, the RMS_{Drag} (root mean square error for drag) and RMS_{Lift} (root mean square error for lift) columns need to be analyzed in the tables for each case. The Experimental error analysis can be used as a way to check if the curves are shaped as theory suggests. That is, the lift is a straight line and the drag polar is a second grade curve. In the case of the Lockheed C-69, this is proven to be wrong (see section 7 Discussion)

The lift line is modeled as a straight line. That means that the angles of attack cannot be too high or too low as the stall will not be taken into account. By high angle of attack is meant any angle above 10 degrees, possibly above 12 degrees in some cases. The lift approximation is shown in equation 4, the angle of attack being α_{CL0} where C_L is zero, and $C_{L\alpha}$ is the lift slope. The drag polar is modeled as a second grade polynomial curve (see equation 5), C_{D0} being the zero lift drag.

$$C_L = C_{L\alpha} \cdot (\alpha - \alpha_{CL0}) \dots \dots \dots (4)$$

$$C_D = K_2 \cdot C_L^2 + K_1 \cdot C_L + C_{D0} \dots \dots \dots (5)$$

DATA

Boeing 747-100

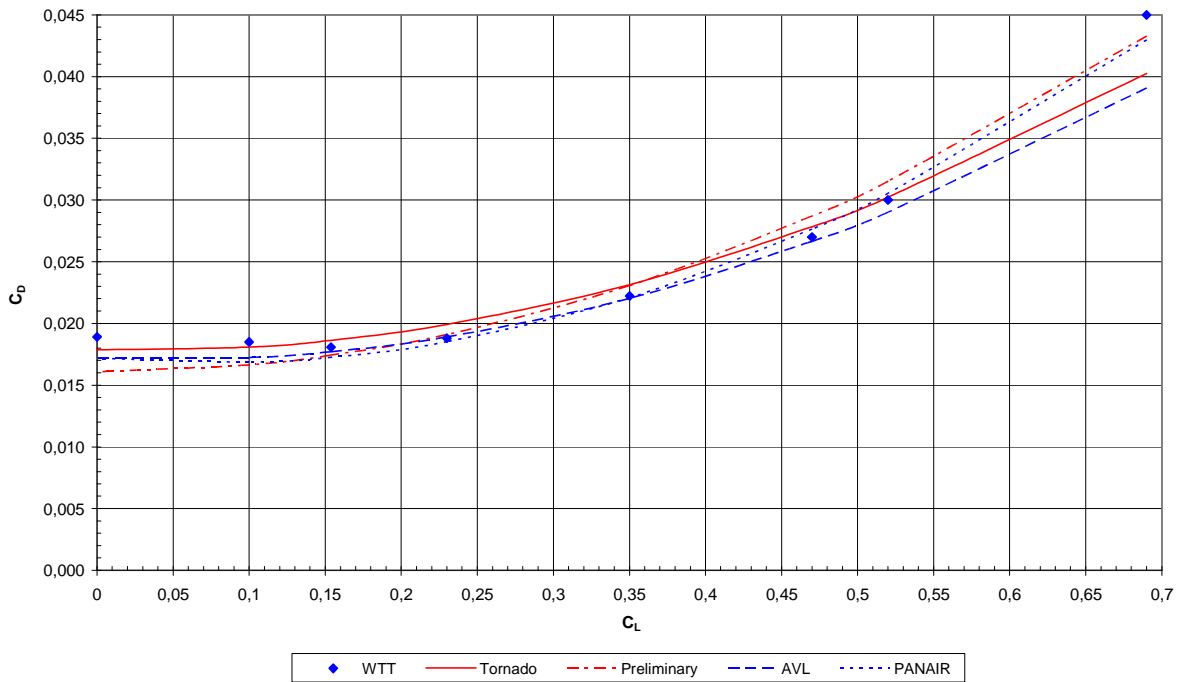


Figure 23. Drag Polar, Boeing 747-100

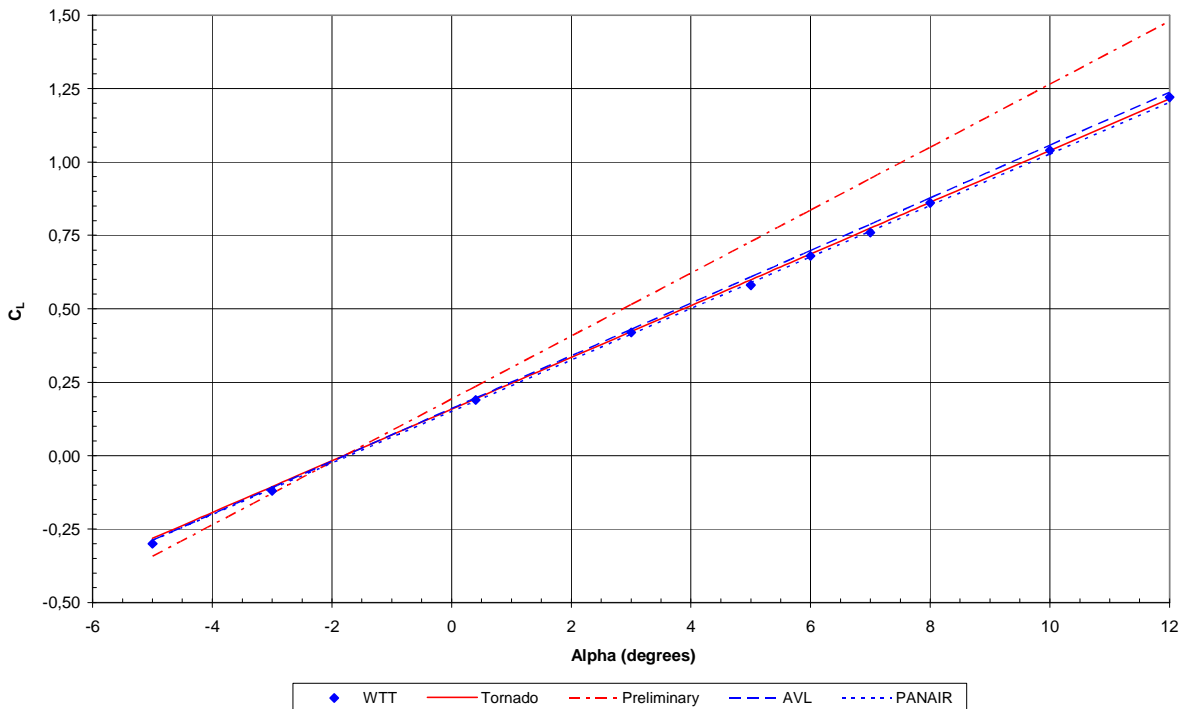


Figure 24. Lift coefficient vs. Angle of attack, Boeing 747-100

	$C_{L\alpha}$	C_{D0}	$\alpha_{CL=0}$ (°)	K_2	K_1	RMS_{Lift}	RMS_{Drag}
Experimental	5,1	0,019	-1,7	0,082	-0,021	2,8%	3,7%
Tornado	5,0	0,018	-1,8	0,051	-0,003	4,6%	4,5%
Preliminary	6,1	0,016	-1,8	0,057	0,000	32,0%	7,5%
AVL	5,1	0,017	-1,8	0,053	-0,005	4,0%	6,7%
PANAIR	5,0	0,017	-1,7	0,069	-0,010	3,4%	6,0%

Table 1. Data for the Boeing 747-100

Boeing 777-300

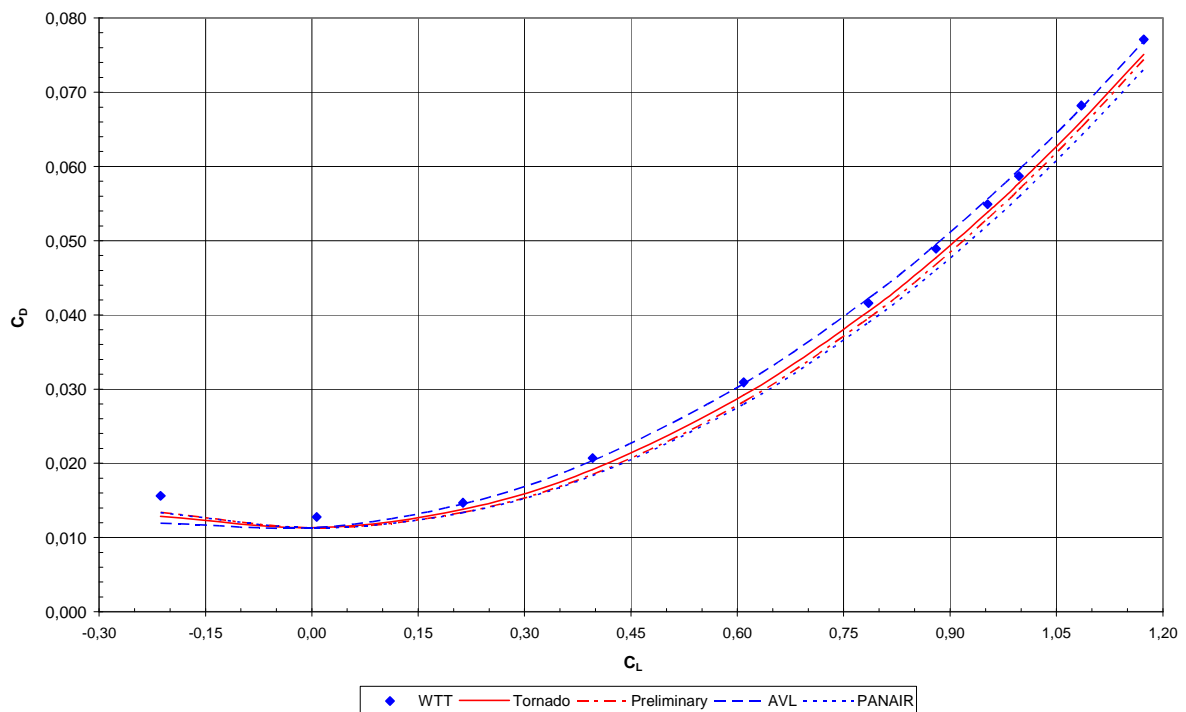


Figure 25. Drag Polar, Boeing 777-300

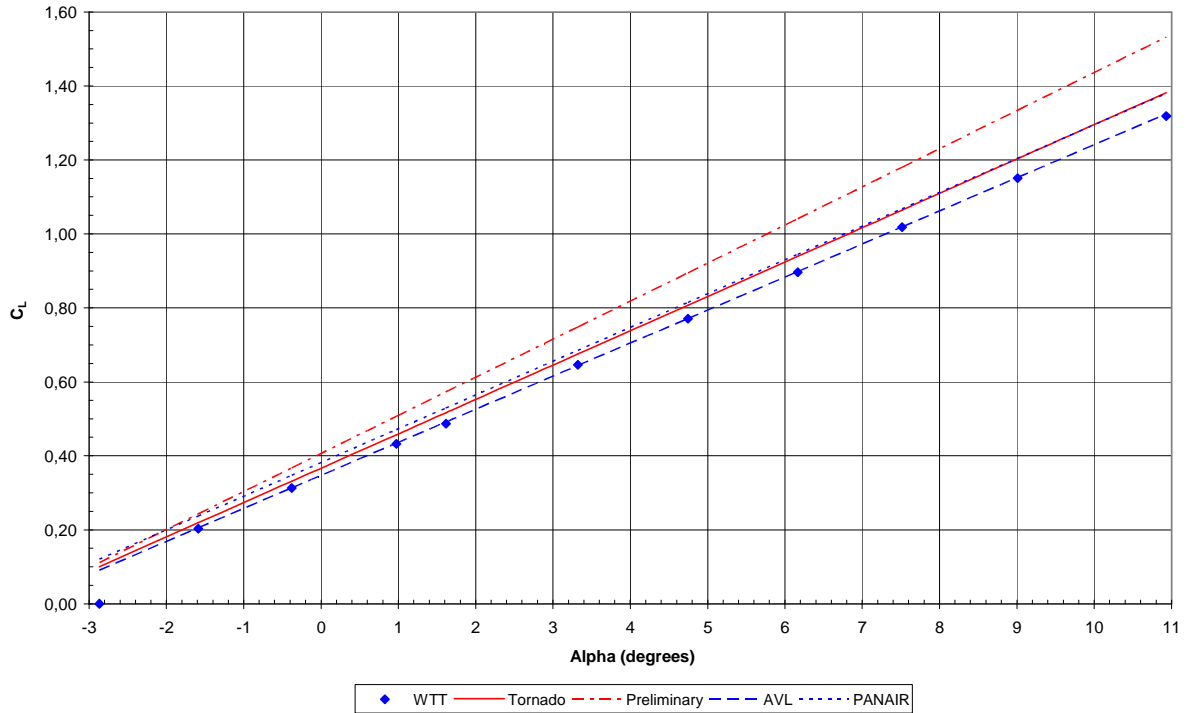


Figure 26. Lift coefficient vs. Angle of attack, Boeing 777-300

	$C_{L\alpha}$	C_{D0}	$\alpha_{CL=0}$ (°)	K_2	K_1	RMS_{Lift}	RMS_{Drag}
Experimental	5,1	0,013	-2,8	0,047	0,000	1%	3,3%
Tornado	5,3	0,011	-2,9	0,044	0,002	6%	6,7%
Preliminary	5,9	0,011	-2,9	0,046	0,000	14%	7,2%
AVL	5,1	0,011	-2,8	0,043	0,006	2%	7,2%
PANAIR	5,2	0,011	-2,8	0,045	0,001	3%	8,1%

Table 2. Data for Boeing 777-300

TF-8A at Mach 0.5

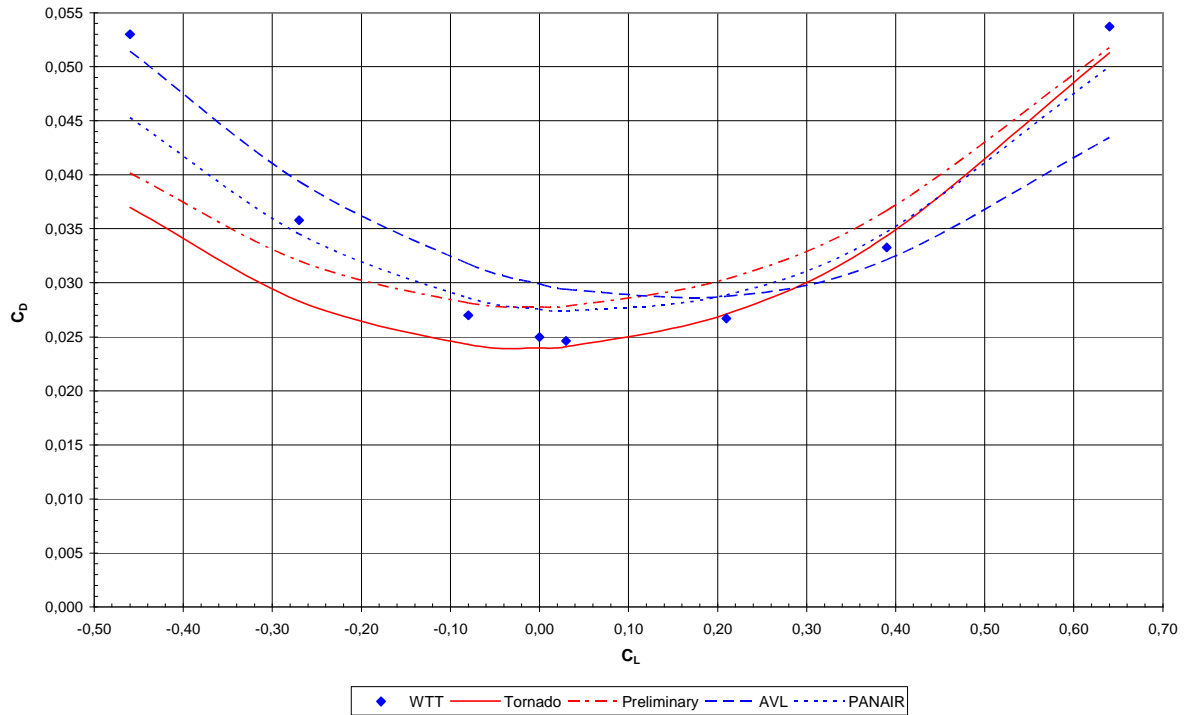


Figure 27. Drag Polar, Supercritical wing airplane at Mach 0.5

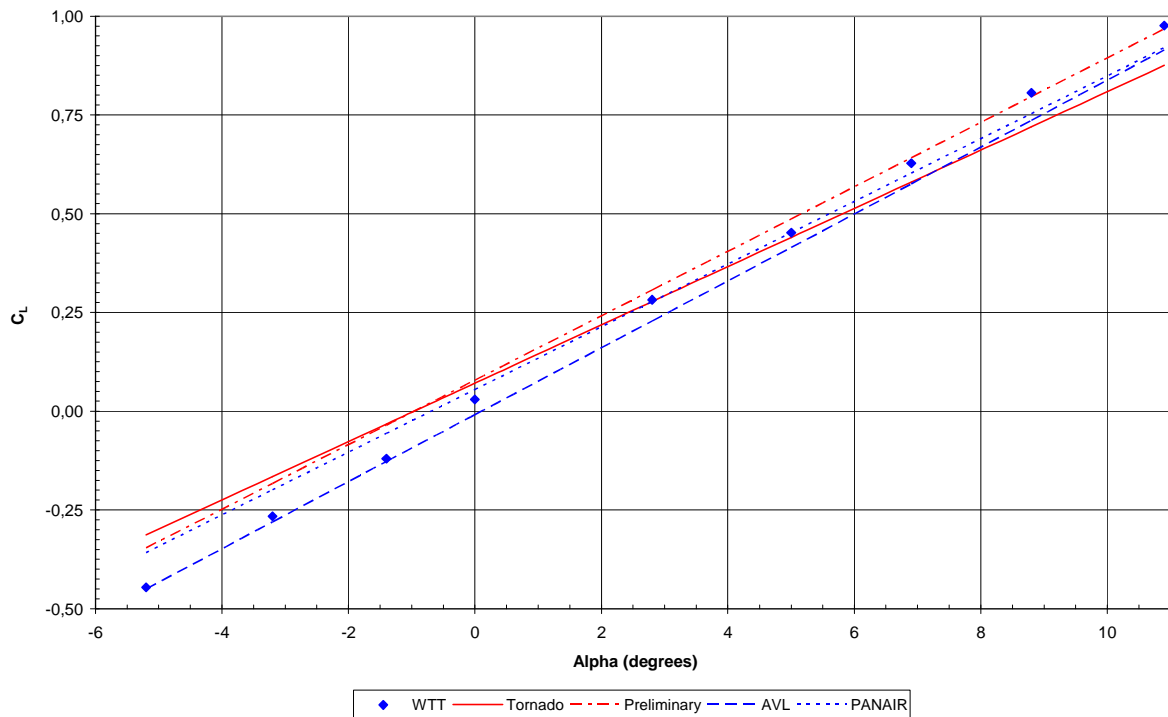


Figure 28. Lift vs. Angle of attack, Supercritical wing airplane at Mach 0.5

	$C_{L\alpha}$	C_{D0}	$\alpha_{CL=0}$ (°)	K_2	K_1	RMS_{Lift}	RMS_{Drag}
Experimental	5,0	0,026	-0,3	0,091	-0,014	4%	2%
Tornado	4,2	0,024	-1,0	0,065	0,001	5%	10%
Preliminary	4,7	0,028	-1,0	0,059	0,000	11%	13%
AVL	4,9	0,030	0,1	0,062	-0,018	10%	12%
PANAIR	4,6	0,028	-0,7	0,067	-0,008	13%	7%

Table 3. Data for Supercritical wing airplane at Mach 0.5

TF- 8A at Mach 0.8

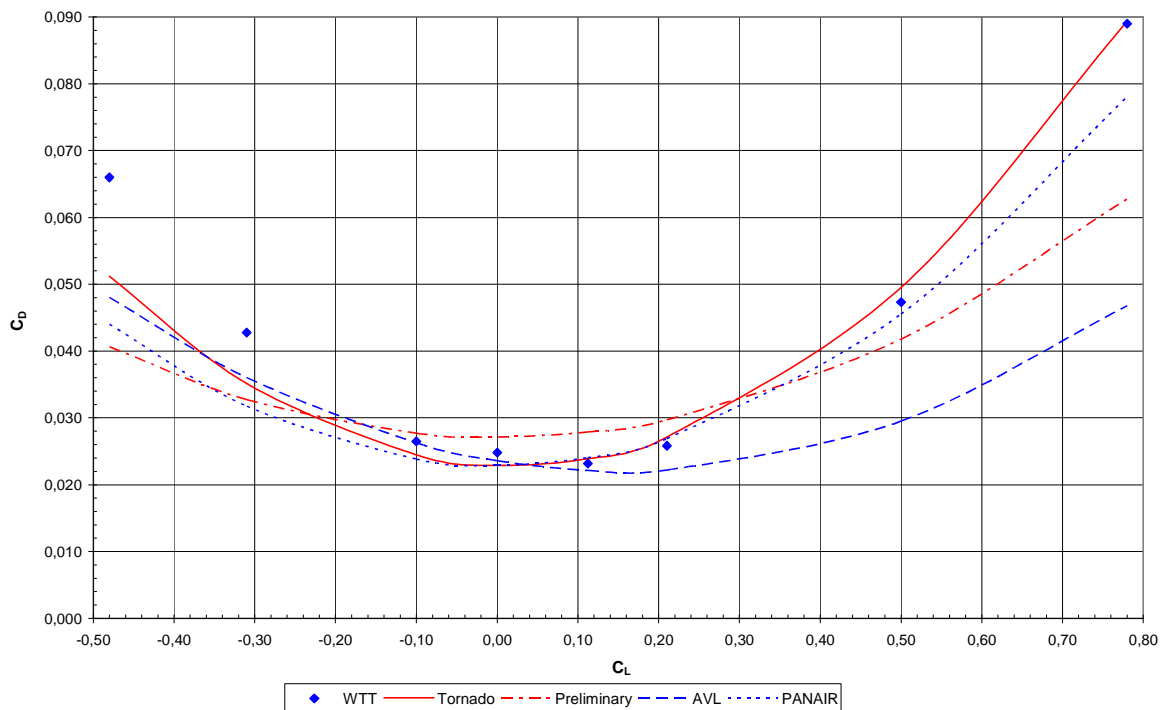


Figure 29. Drag Polar, Supercritical wing airplane at Mach 0.8

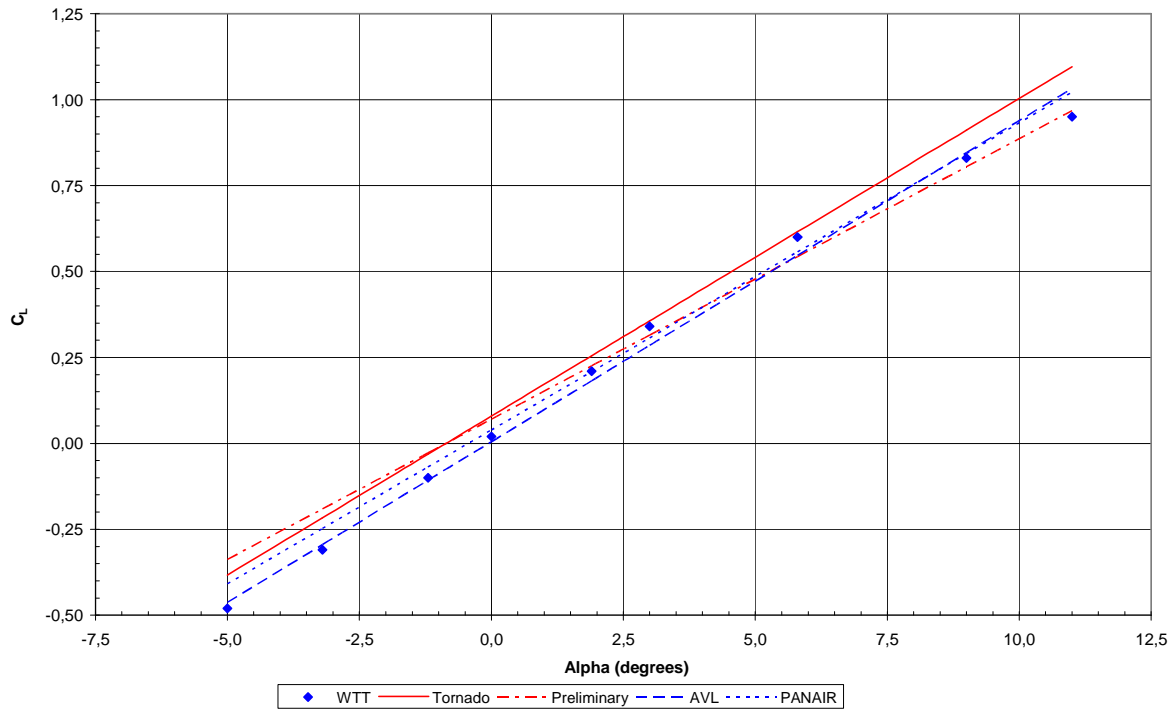


Figure 30. Lift vs. Angle of attack, Supercritical wing airplane at Mach 0.8

	$C_{L\alpha}$	C_{D0}	$\alpha_{CL=0}$ (°)	K_2	K_1	RMS_{Lift}	RMS_{Drag}
Experimental	5,2	0,024	-0,2	0,133	-0,023	5%	2%
Tornado	5,3	0,023	-0,9	0,114	-0,004	6%	11%
Preliminary	4,7	0,027	-0,9	0,059	0,000	13%	21%
AVL	5,4	0,024	0,0	0,064	-0,020	10%	22%
PANAIR	5,1	0,023	-0,4	0,091	0,000	11%	15%

Table 4. Data for Supercritical wing airplane at Mach 0.8

Lockheed Constellation C-69

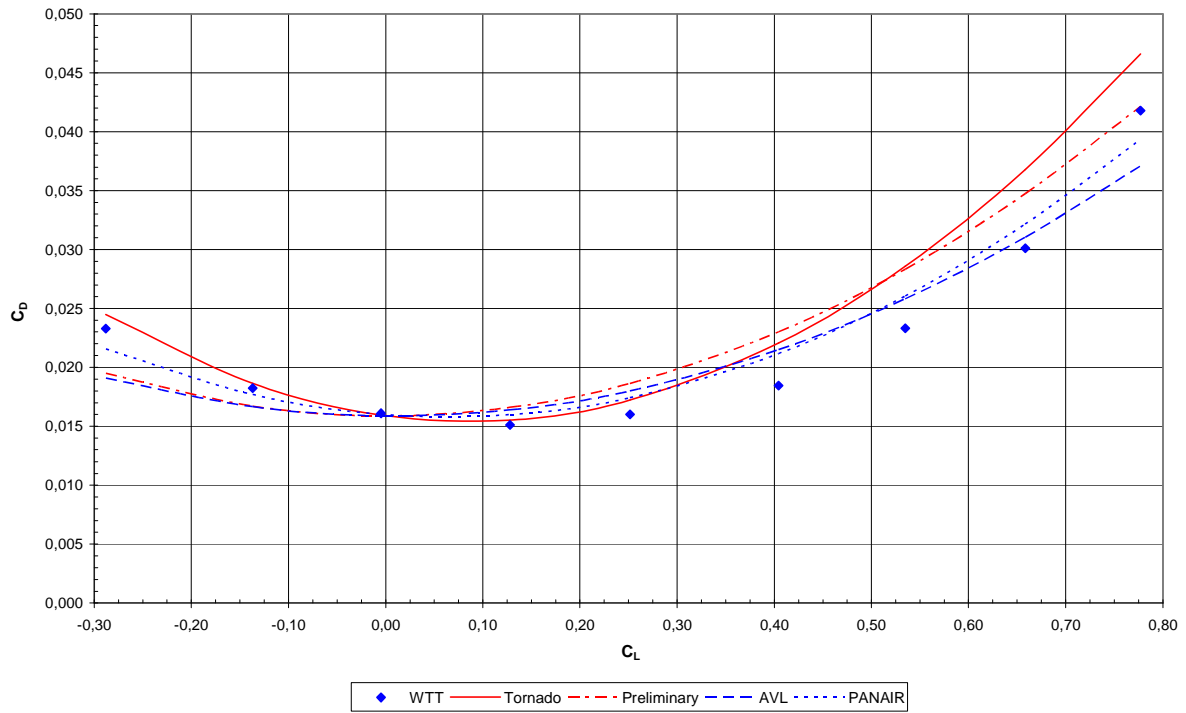


Figure 31. Drag Polar, Lockheed C-69

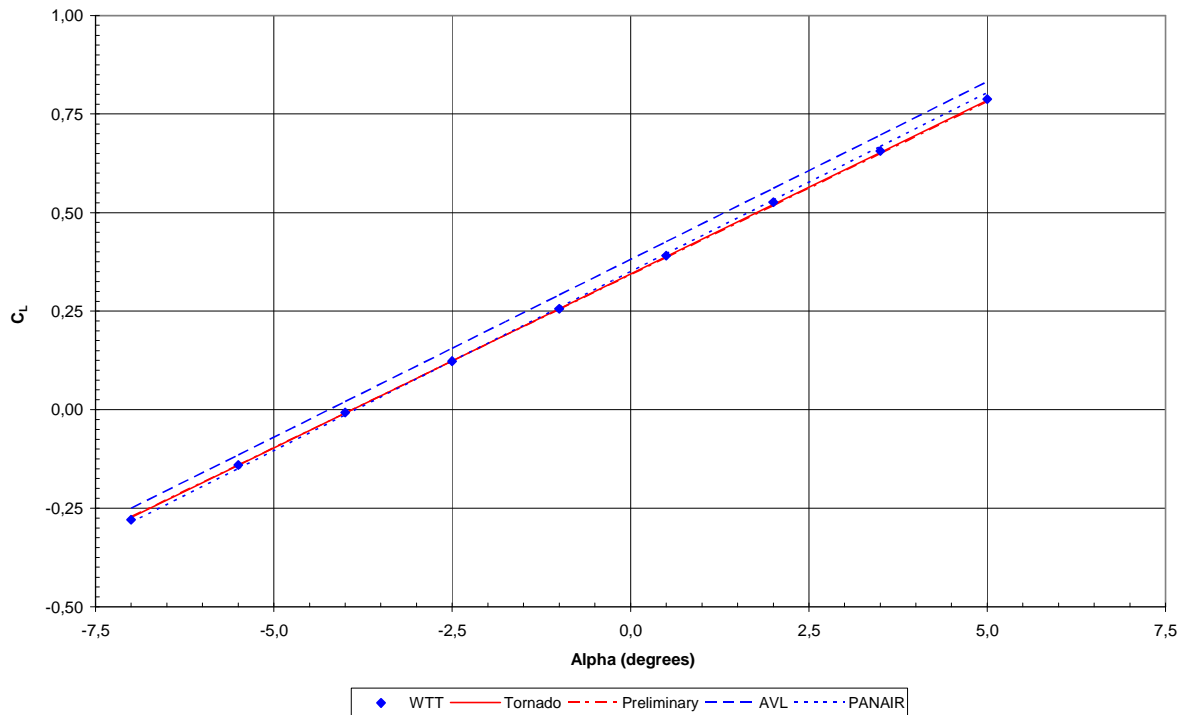


Figure 32. Lift vs. Angle of attack, Lockheed C-69

	$C_{L\alpha}$	C_{D0}	$\alpha_{CL=0}$ (°)	K_2	K_1	RMS_{Lift}	RMS_{Drag}
Experimental	5,1	0,015	-3,9	0,060	-0,015	0,9%	4%
Tornado	5,1	0,016	-3,9	0,065	-0,011	1,0%	13%
Preliminary	5,0	0,016	-3,9	0,043	0,000	1,3%	15%
AVL	5,2	0,016	-4,2	0,036	-0,001	14%	11%
PANAIR	5,2	0,016	-3,9	0,046	-0,006	2,7%	8%

Table 5. Data for the Lockheed C-69

Boeing Stratocruiser - Conventional configuration

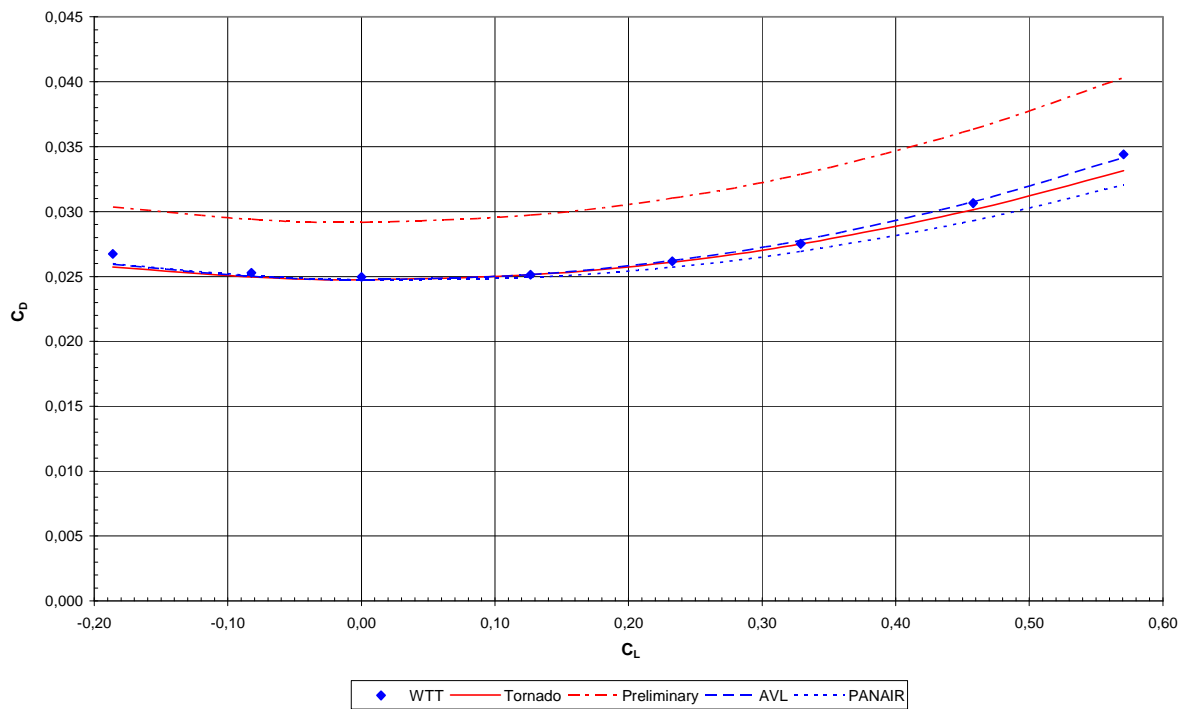


Figure 33. Drag Polar, Boeing Stratocruiser, conventional configuration

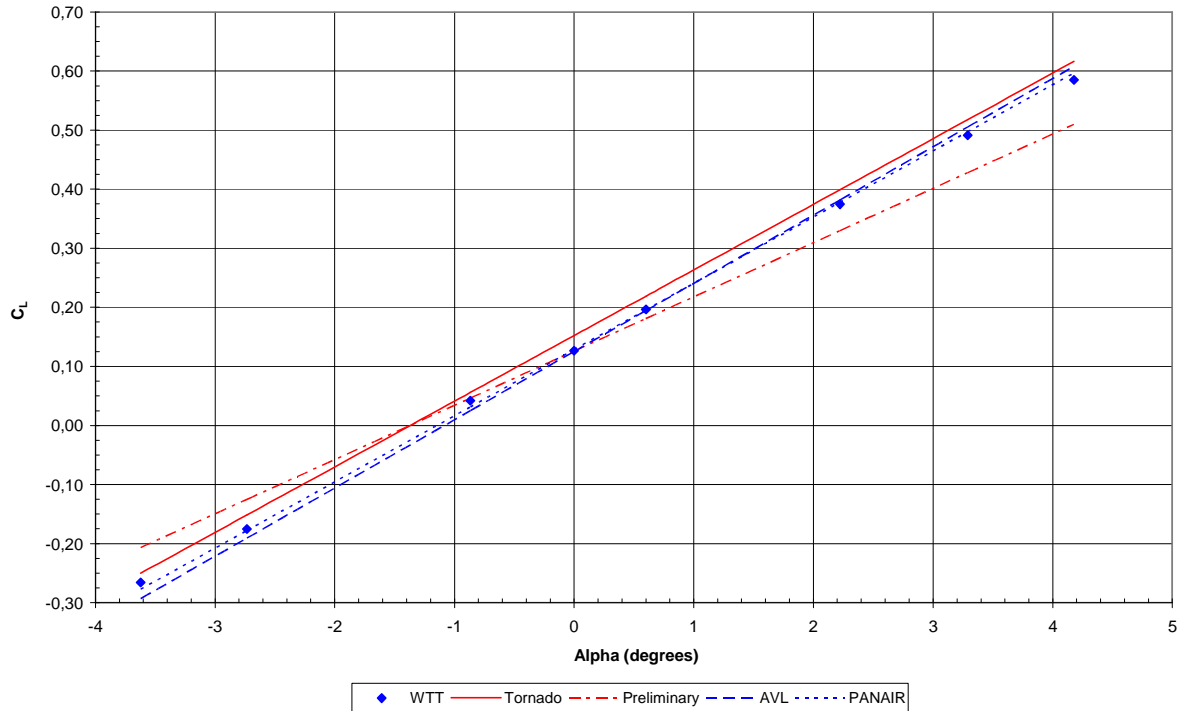


Figure 34. Lift vs. Angle of attack, Boeing Stratocruiser, conventional configuration

	$C_{L\alpha}$	C_{D0}	$\alpha_{CL=0}$ (°)	K_2	K_1	RMS_{Lift}	RMS_{Drag}
Experimental	6,3	0,025	-1,2	0,034	-0,003	1%	0%
Tornado	6,4	0,025	-1,4	0,026	0,000	11%	2%
Preliminary	5,3	0,029	-1,4	0,034	0,000	16%	17%
AVL	6,6	0,025	-1,1	0,030	-0,001	6%	1%
PANAIR	6,4	0,025	-1,1	0,026	-0,002	2%	3%

Table 6. Data for the Boeing Stratocruiser, conventional configuration

Boeing Stratocruiser - Bomber configuration

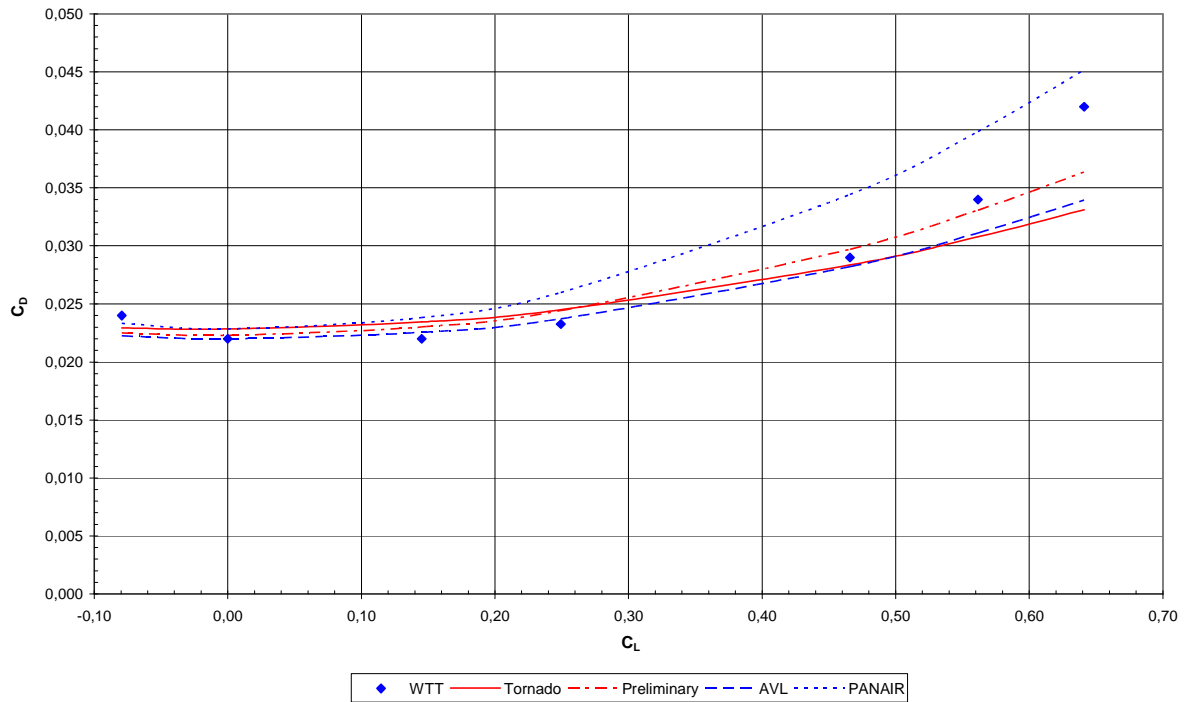


Figure 35. Drag Polar, Boeing Stratocruiser, bomber configuration

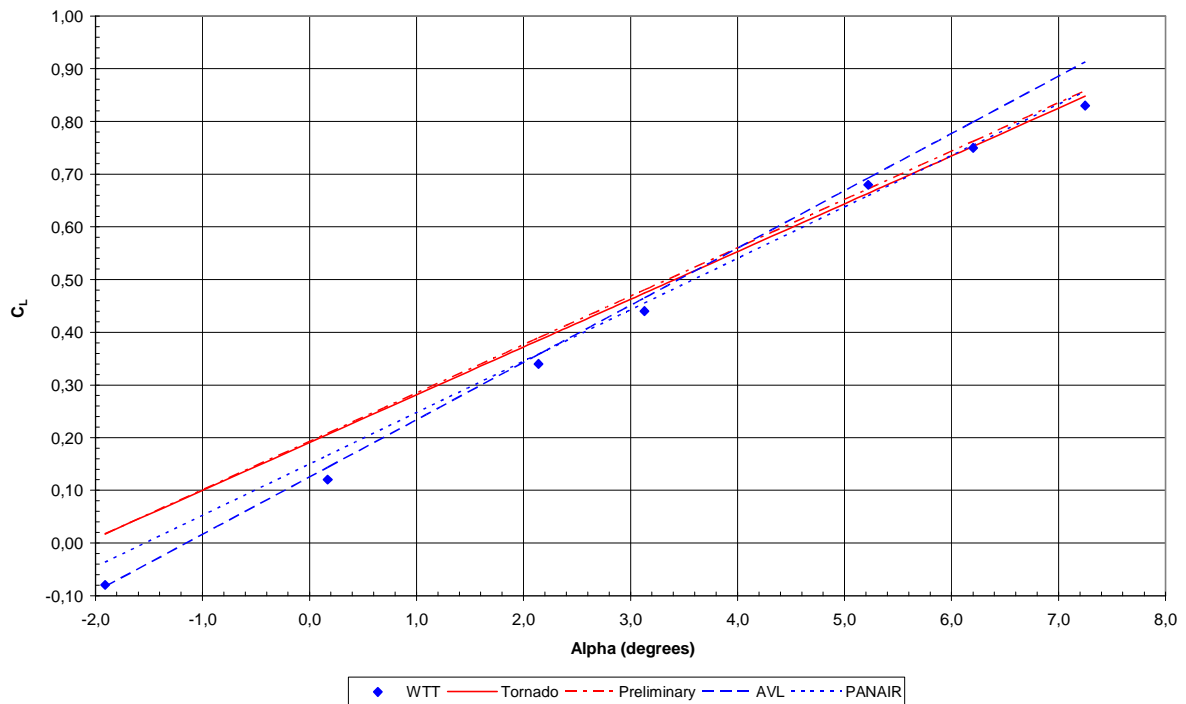


Figure 36. Lift vs. Angle of attack, Boeing Stratocruiser, bomber configuration

	$C_{L\alpha}$	C_{D0}	$\alpha_{CL=0}$ (°)	K_2	K_1	RMS _{Lift}	RMS _{Drag}
Experimental	5,9	0,022	-1,2	0,070	-0,017	3%	3%
Tornado	5,2	0,023	-2,1	0,024	0,001	7%	10%
Preliminary	5,3	0,022	-2,1	0,034	0,000	8%	6%
AVL	6,2	0,022	-1,1	0,030	-0,001	6%	9%
PANAIR	5,6	0,023	-1,5	0,057	-0,002	4%	11%

Table 7. Data for the Boeing Stratocruiser, bomber configuration

Aero Commander 680 Super

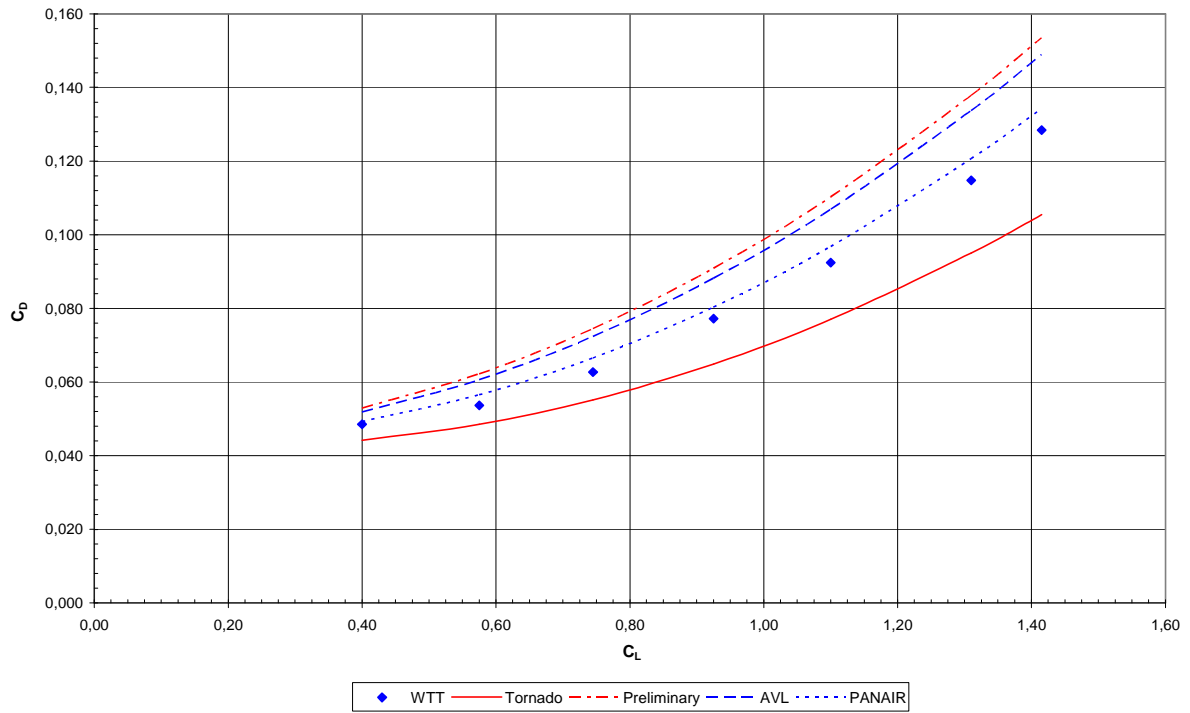


Figure 37. Drag Polar, Aero Commander 680 Super

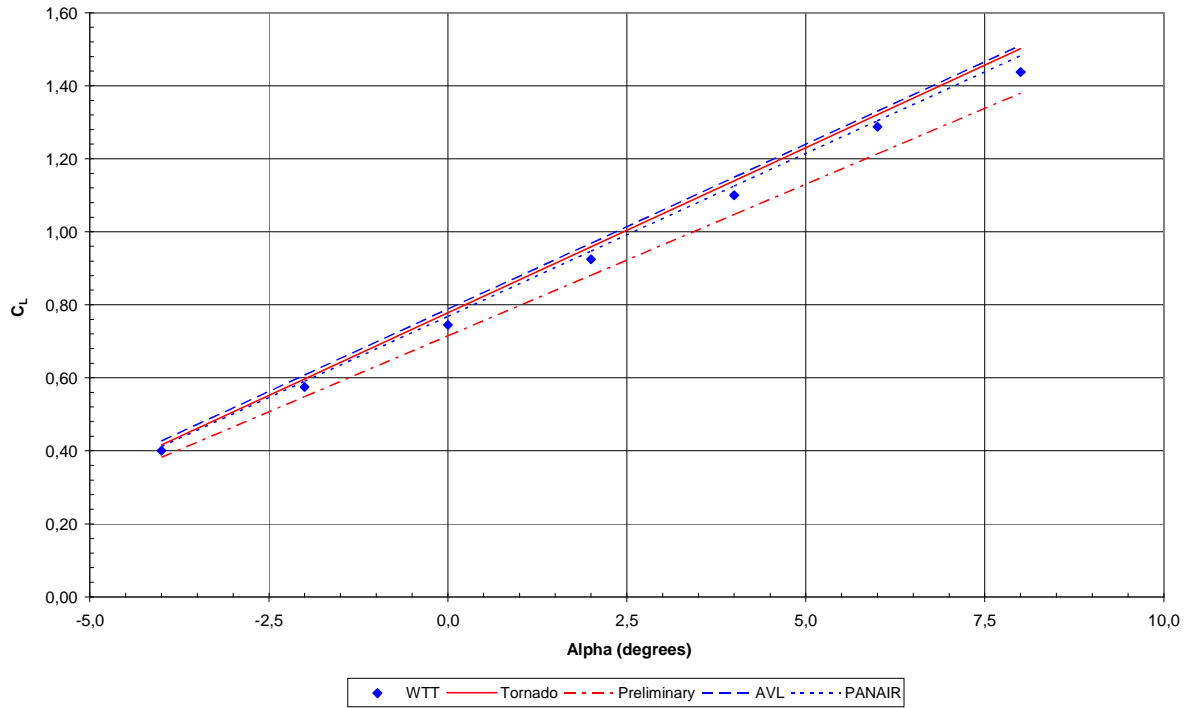


Figure 38. Lift vs. Angle of attack, Aero Commander 680 Super

	$C_{L\alpha}$	C_{D0}	$\alpha_{CL=0}$ (°)	K_2	K_1	RMS_{Lift}	RMS_{Drag}
Experimental	5,0	0,044	-8,6	0,050	-0,011	1%	1%
Tornado	5,2	0,044	-8,6	0,043	-0,017	4%	14%
Preliminary	4,8	0,044	-8,6	0,055	0,000	5%	18%
AVL	5,2	0,044	-8,7	0,054	-0,003	5%	14%
PANAIR	5,1	0,044	-8,6	0,050	-0,007	2%	5%

Table 8. Data for the Aero Commander 680 Super

ERRORS

Boeing 747-100

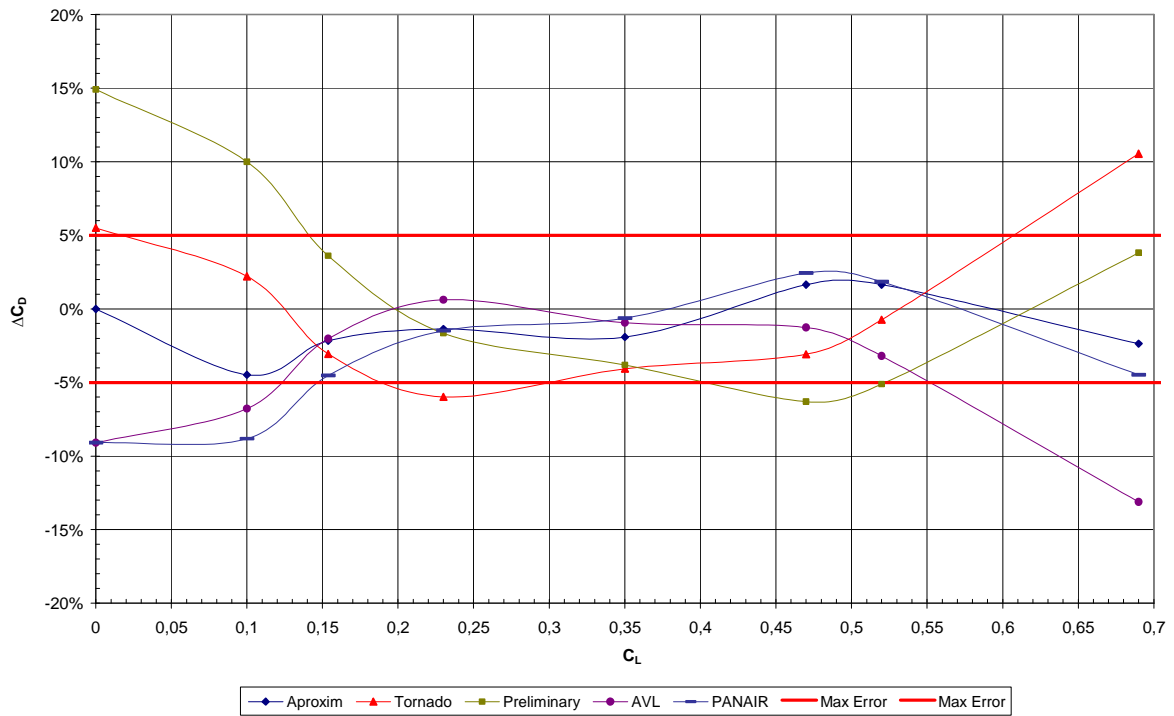


Figure 39. - Differences on polar-Boeing 747-100

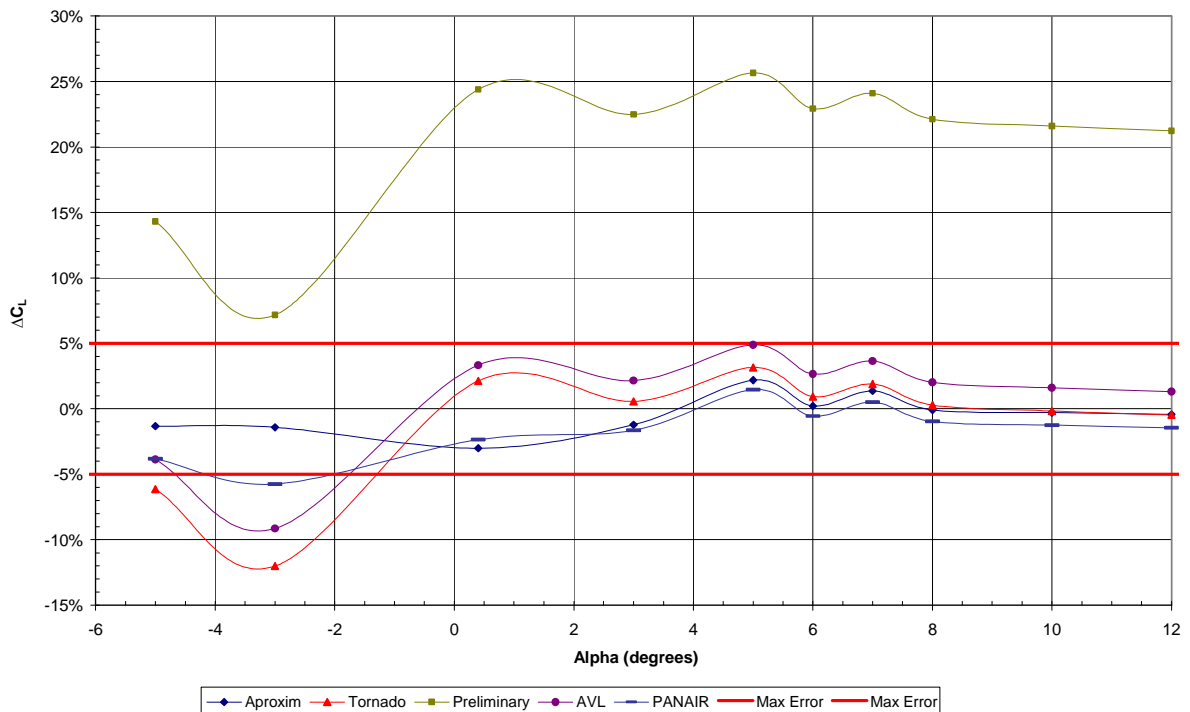


Figure 40. - Differences on lift- Boeing 747-100

Boeing 777-300

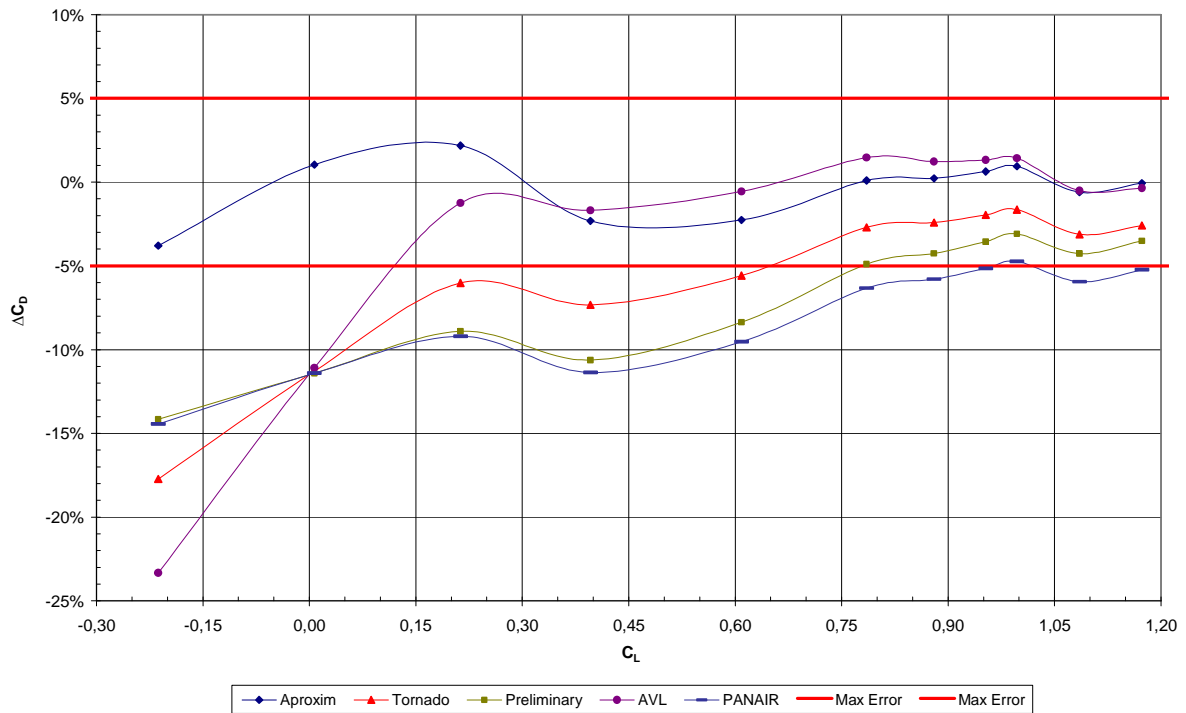


Figure 41. Differences in polar, Boeing 777-300

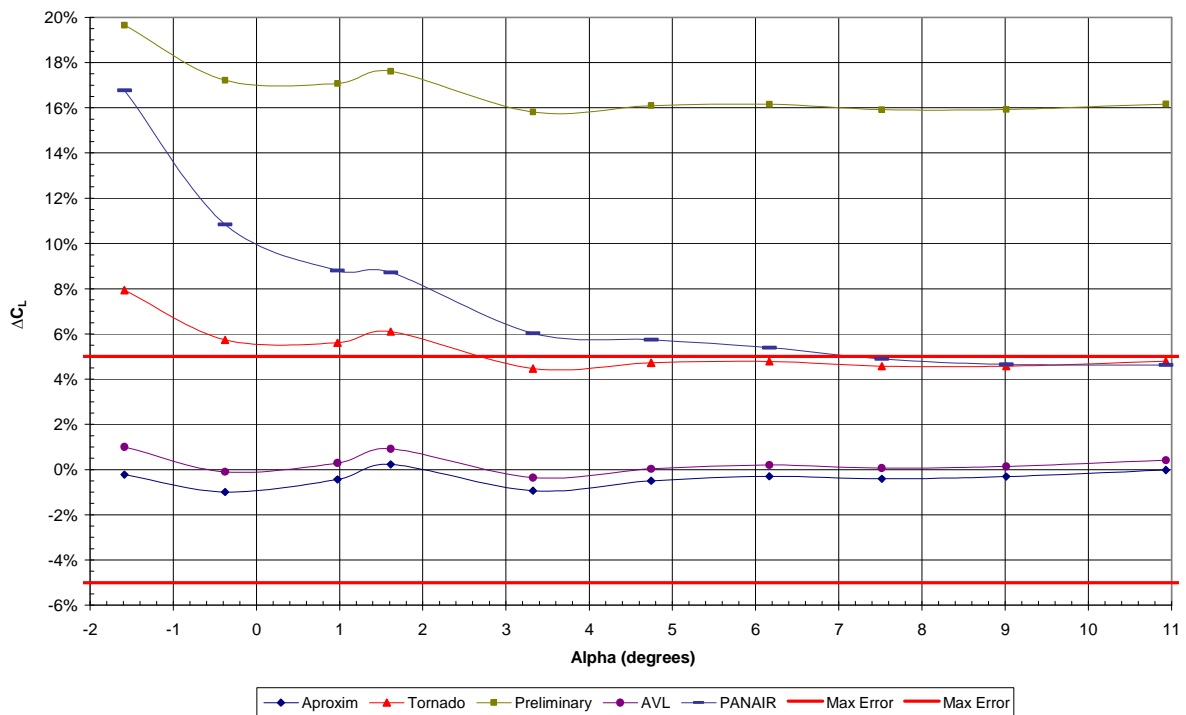


Figure 42. Differences in lift, Boeing 777-300

TF-8A at Mach 0.5

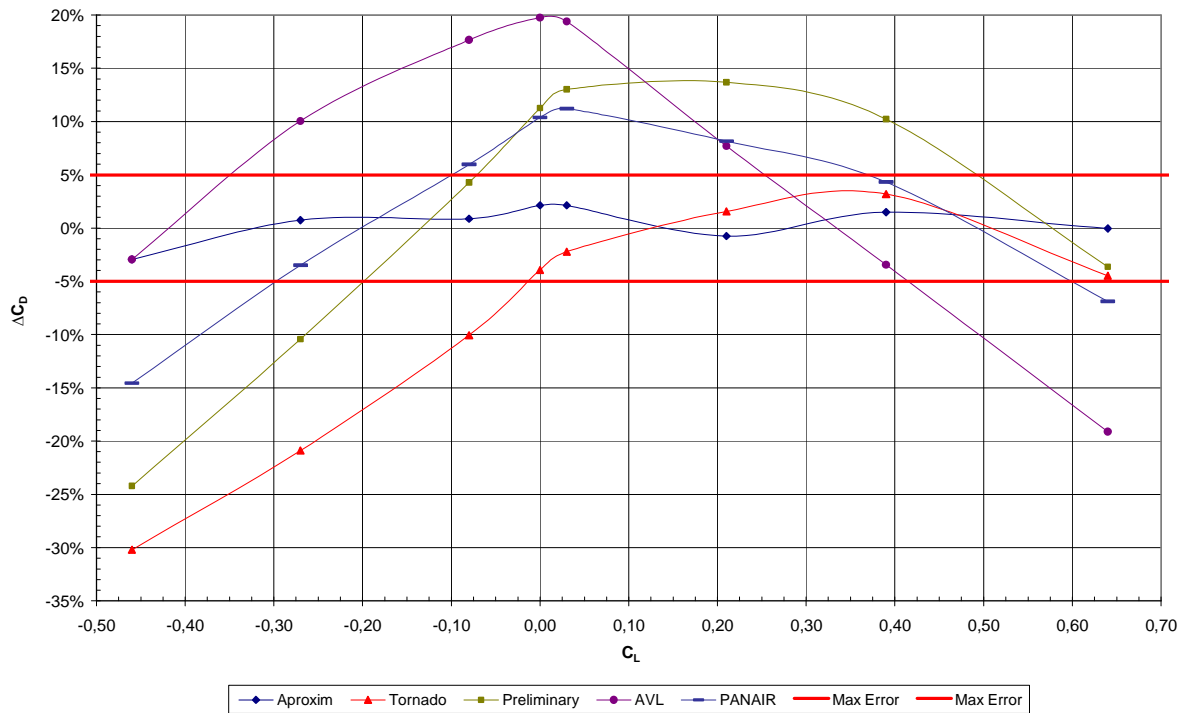


Figure 43. Differences in polar, Supercritical wing airplane at Mach 0.5

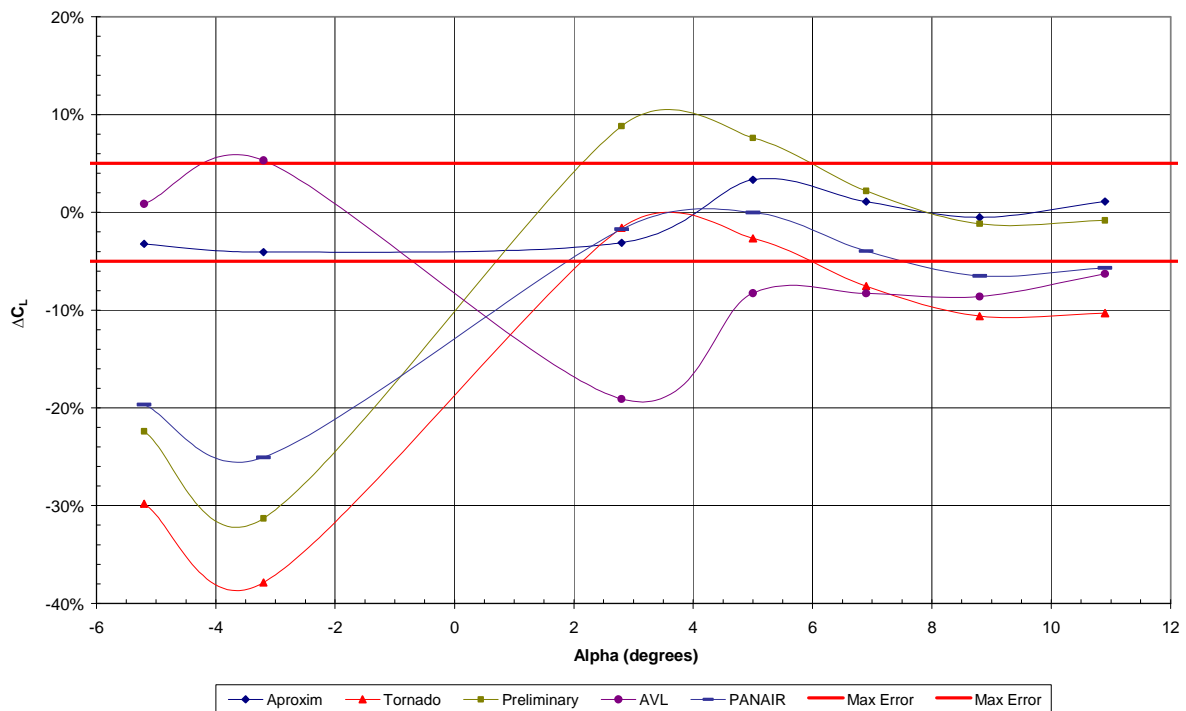


Figure 44. Differences in lift, Supercritical wing airplane at Mach 0.5

TF- 8A at Mach 0.8

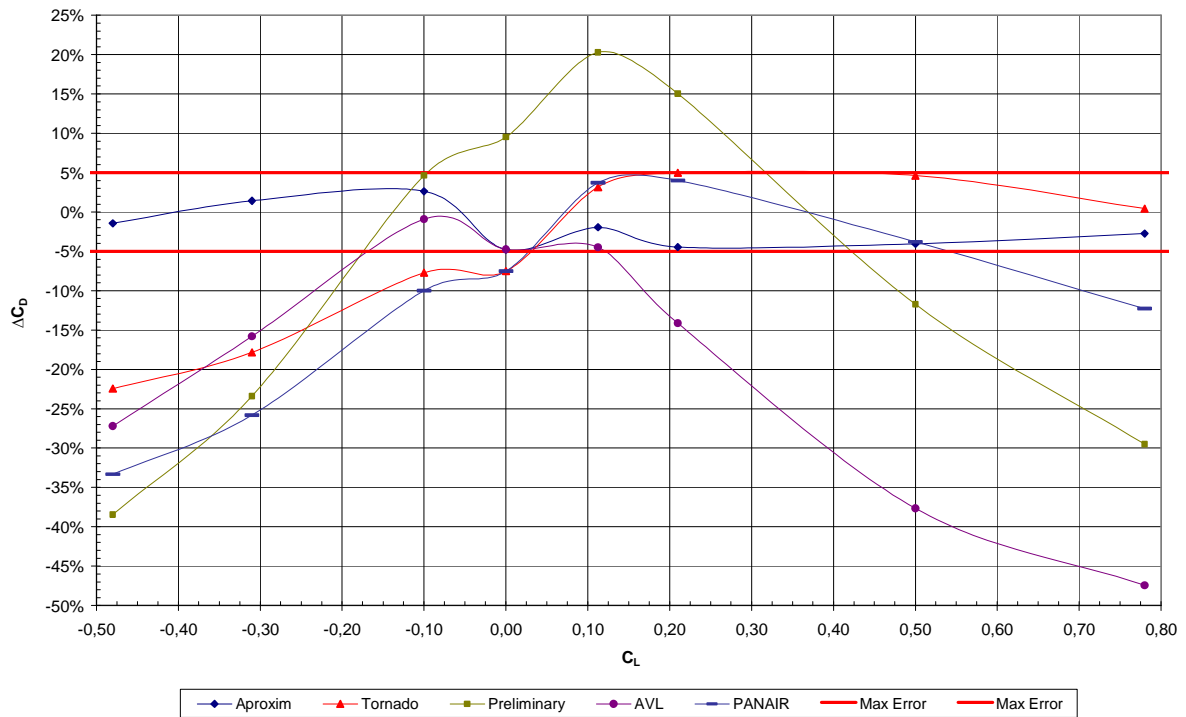


Figure 45. Differences in polar, Supercritical wing airplane at Mach 0.8

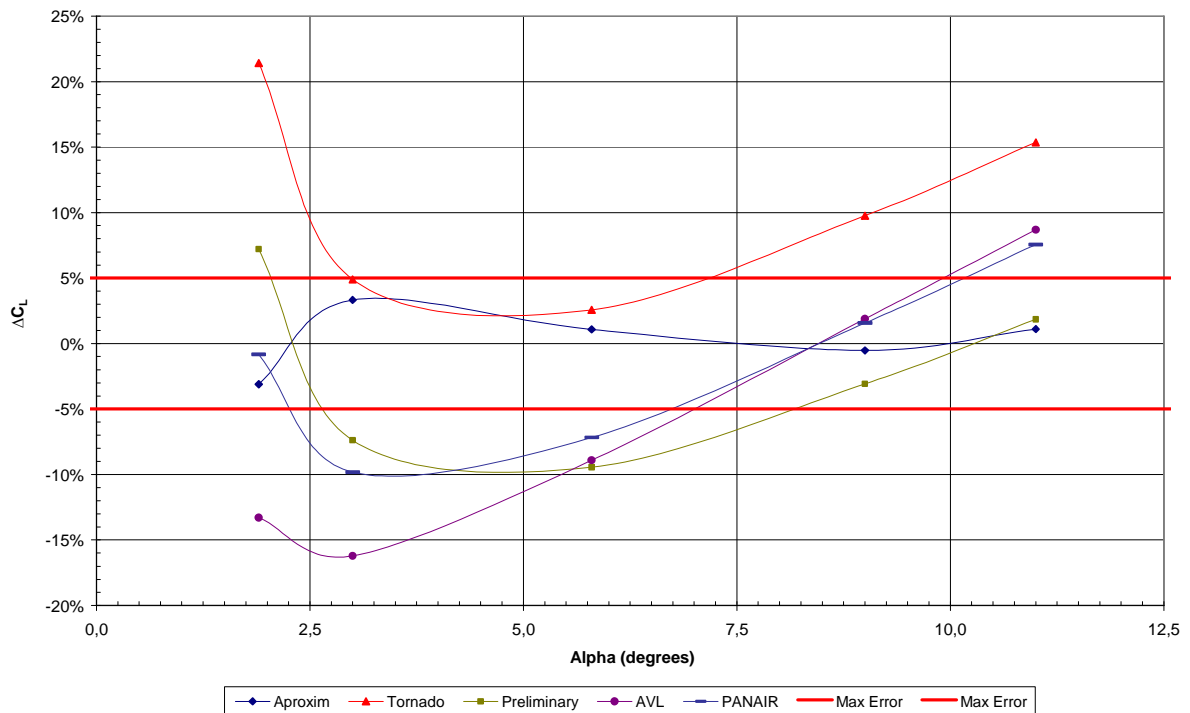


Figure 46. Differences in lift, Supercritical wing airplane at Mach 0.8

Lockheed Constellation C-69

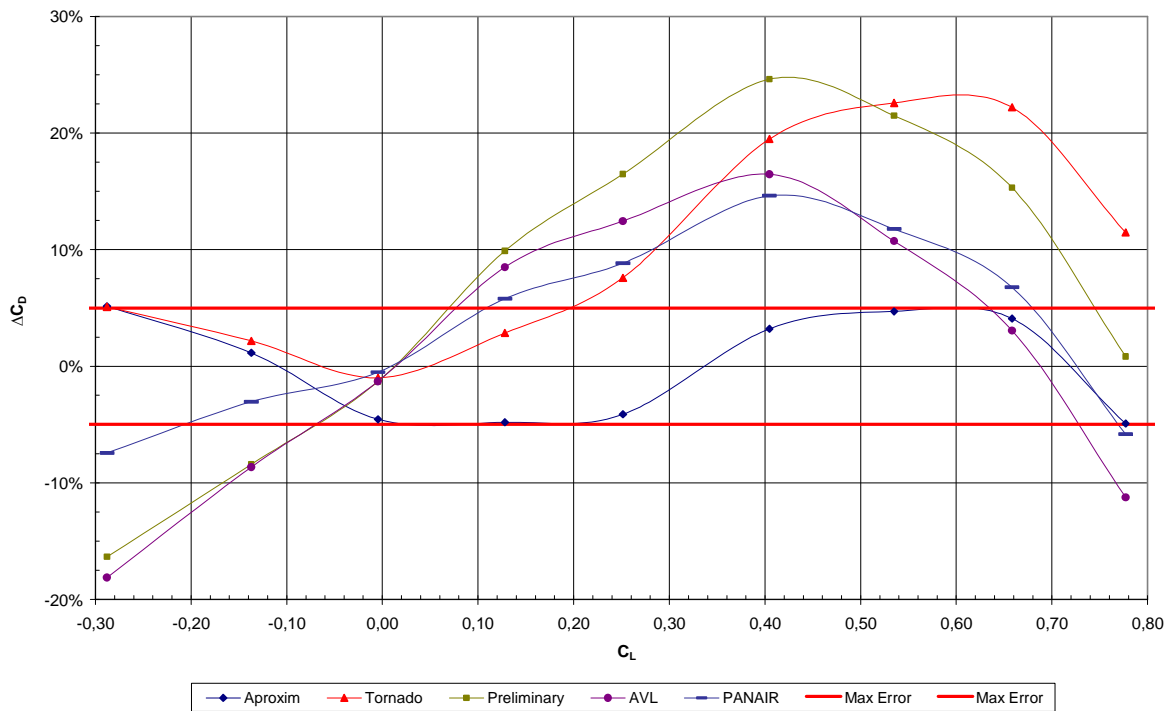


Figure 47. Differences in polar, Lockheed C-69

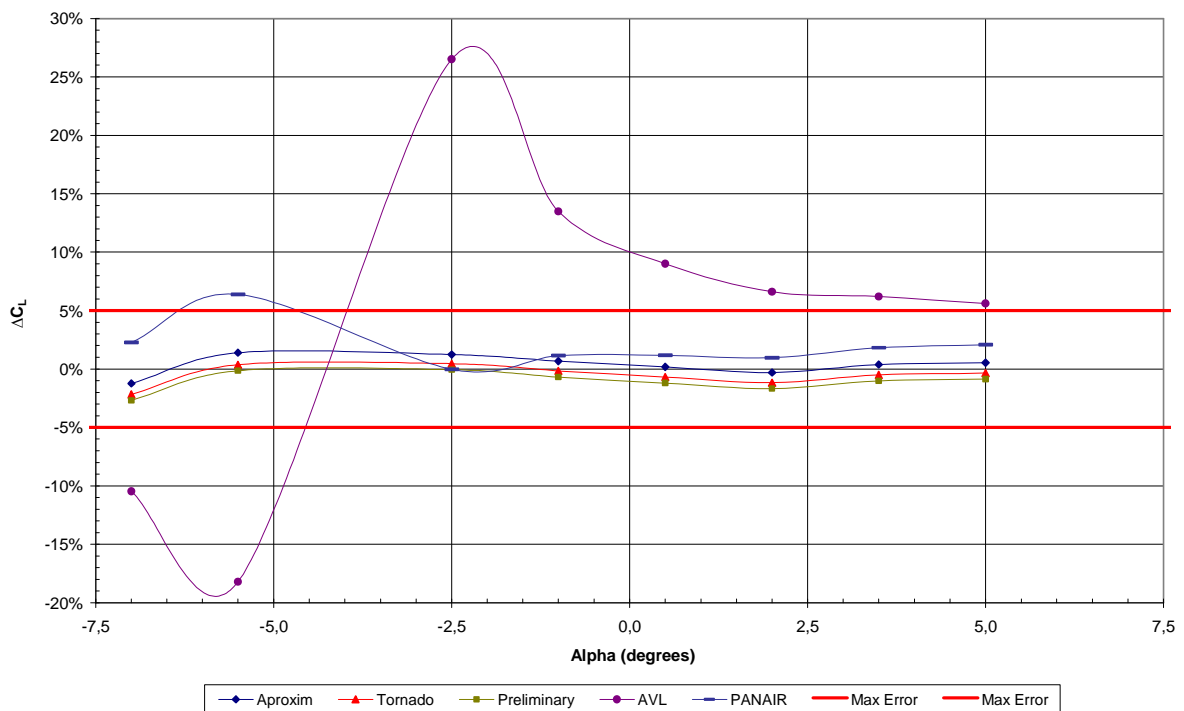


Figure 48. Differences in lift, Lockheed C-69

Boeing Stratocruiser - Conventional configuration

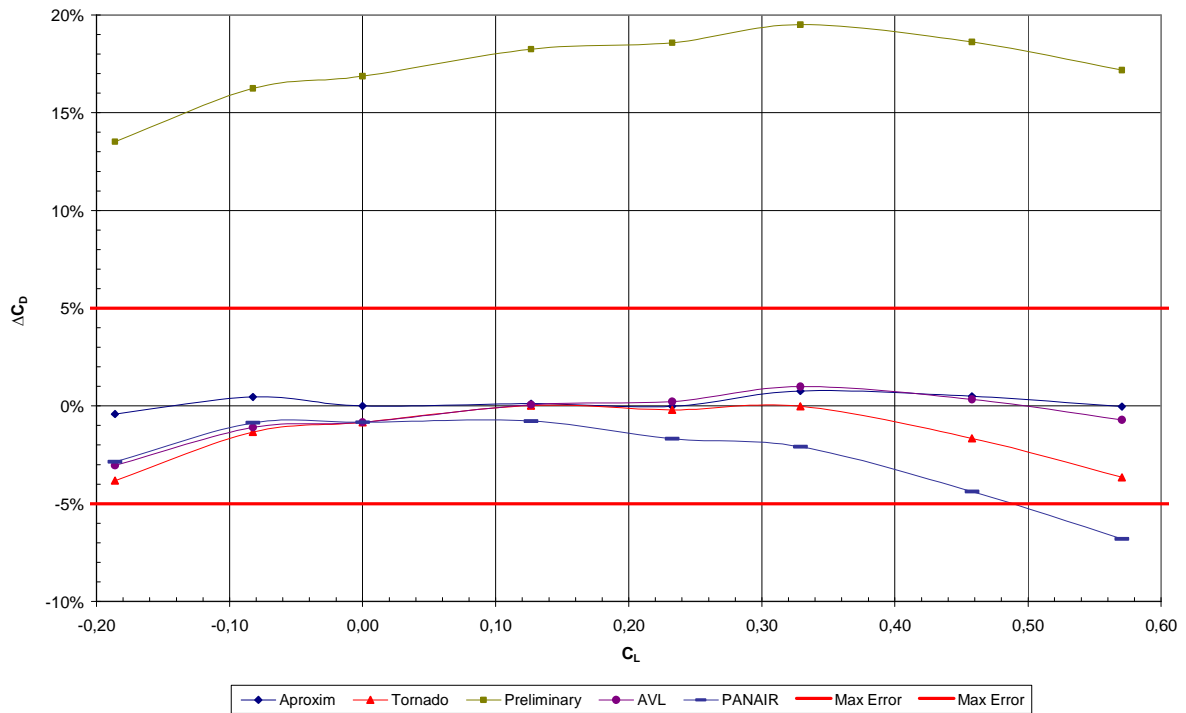


Figure 49. Differences in polar, Boeing Stratocruiser, conventional configuration

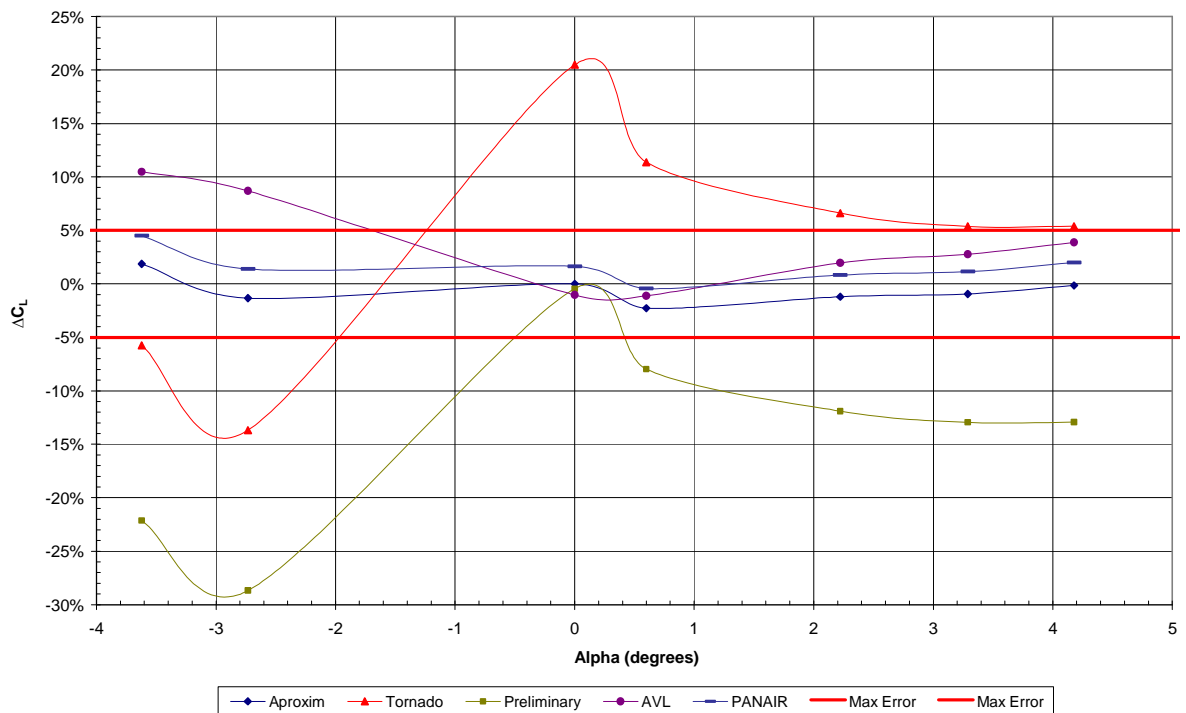


Figure 50. Differences in lift, Boeing Stratocruiser, conventional configuration

Boeing Stratocruiser - Bomber configuration

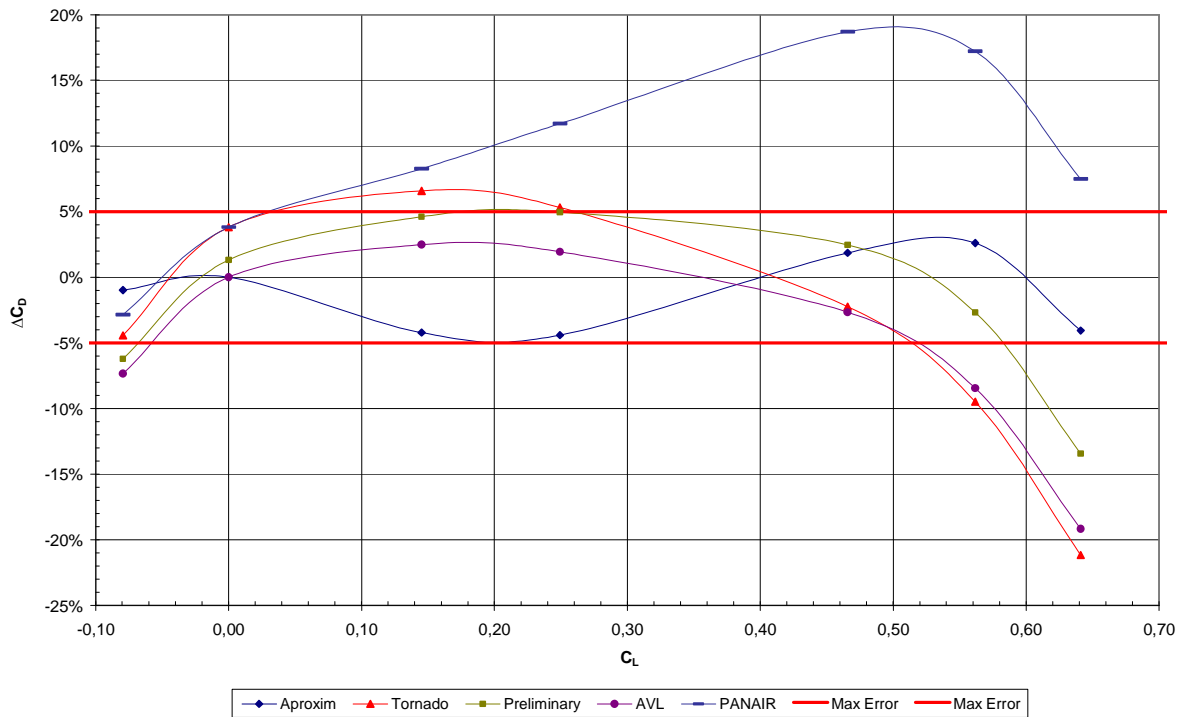


Figure 51. Differences in polar, Boeing Stratocruiser, bomber configuration

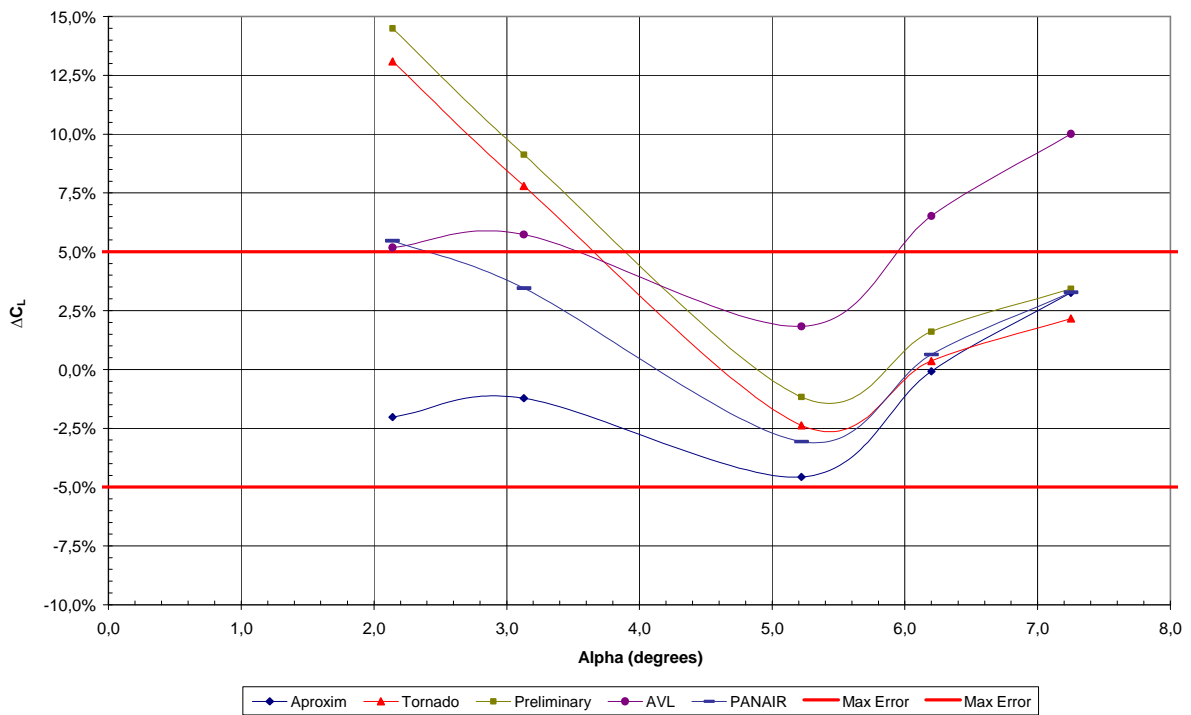


Figure 52. Differences in lift, Boeing Stratocruiser, bomber configuration

Aero Commander 680 Super

Validation of software for the calculation of aerodynamic coefficients

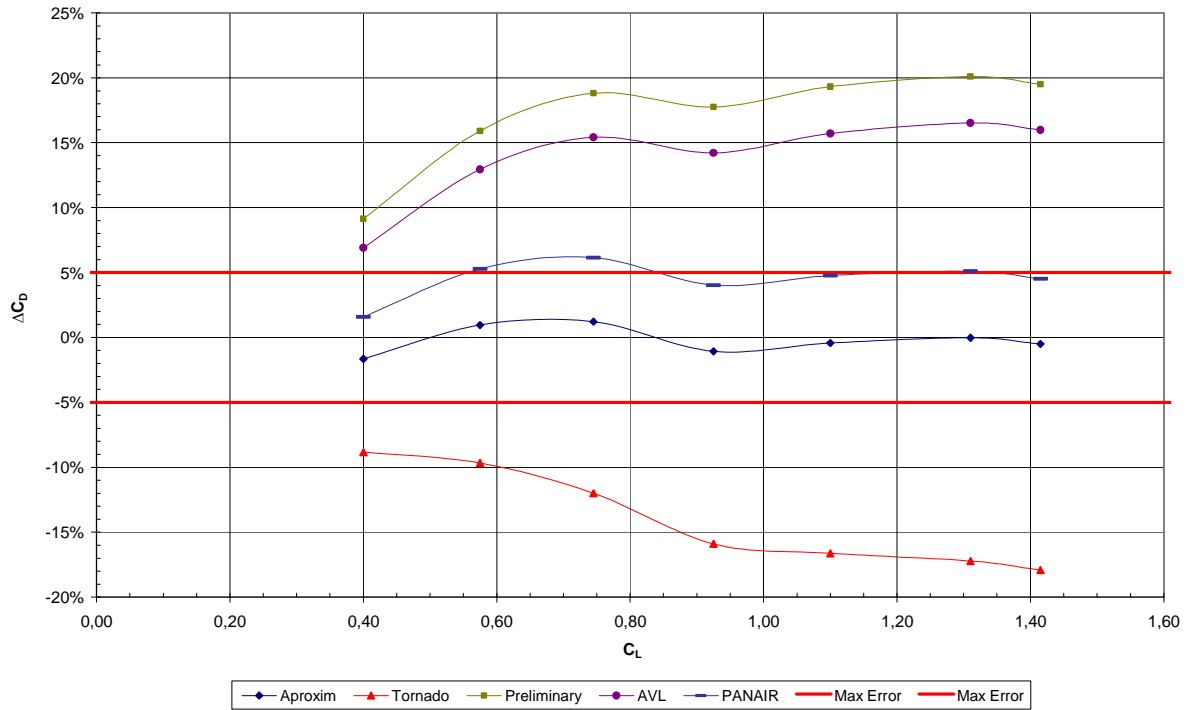


Figure 53. Differences in polar, Aero Commander 680 Super

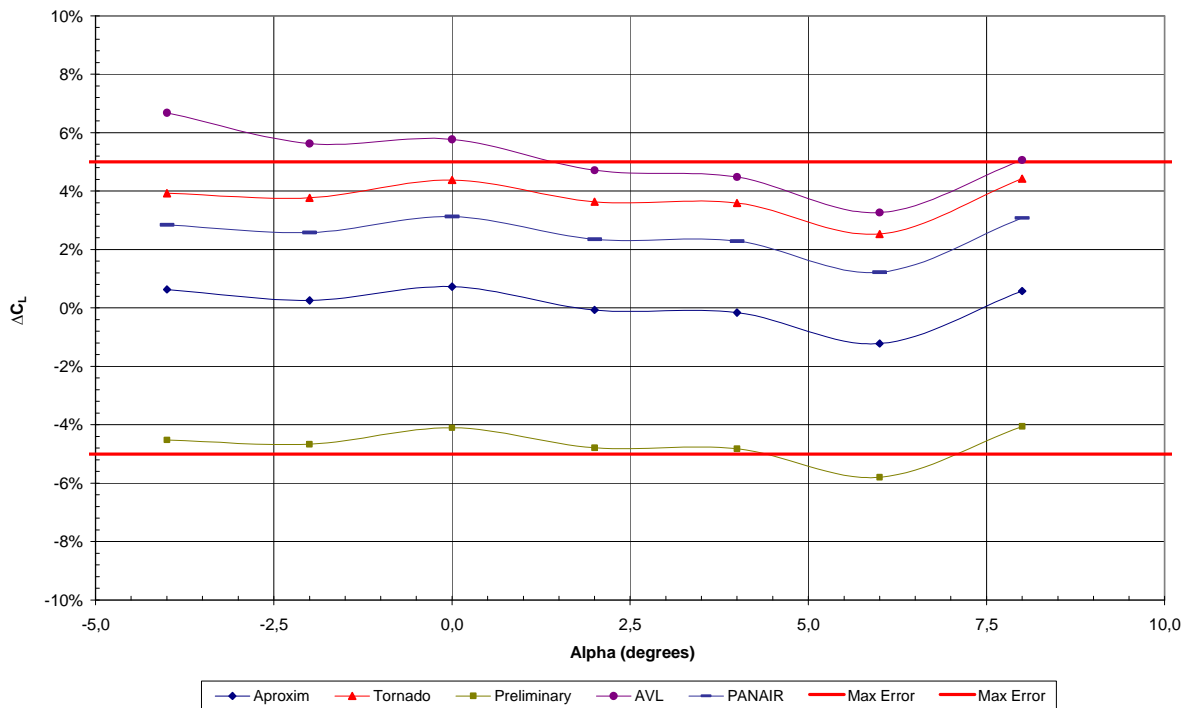


Figure 54. Differences in lift, Aero Commander 680 Super

6.2) AIRFOILS

In this section, the drag polar has been substituted by the pitch moment coefficient C_M . As the preliminary method does not calculate the moment, it is not included in the solutions. The ANSYS CFX software is used in these cases for both lift and moment. The reference point is the quarter chord point, that is, the aerodynamic center. The pitching moment is assumed to be constant.

In the NACA 0012, the pitch is $C_M=0$ at all angles of attack. The errors are therefore not computed.

The codes used are not intended to be used to calculate airfoil performance but these tests were made to check their accuracy even in calculations for which they are not designed. In order to accomplish this, the airfoils need to be set up as very high aspect ratio wings, and in this case the aspect ratio used is 100. The XFOIL software is used for these comparisons as well, as a reliable source on the calculation of airfoil characteristics.

DATA

NACA 2412

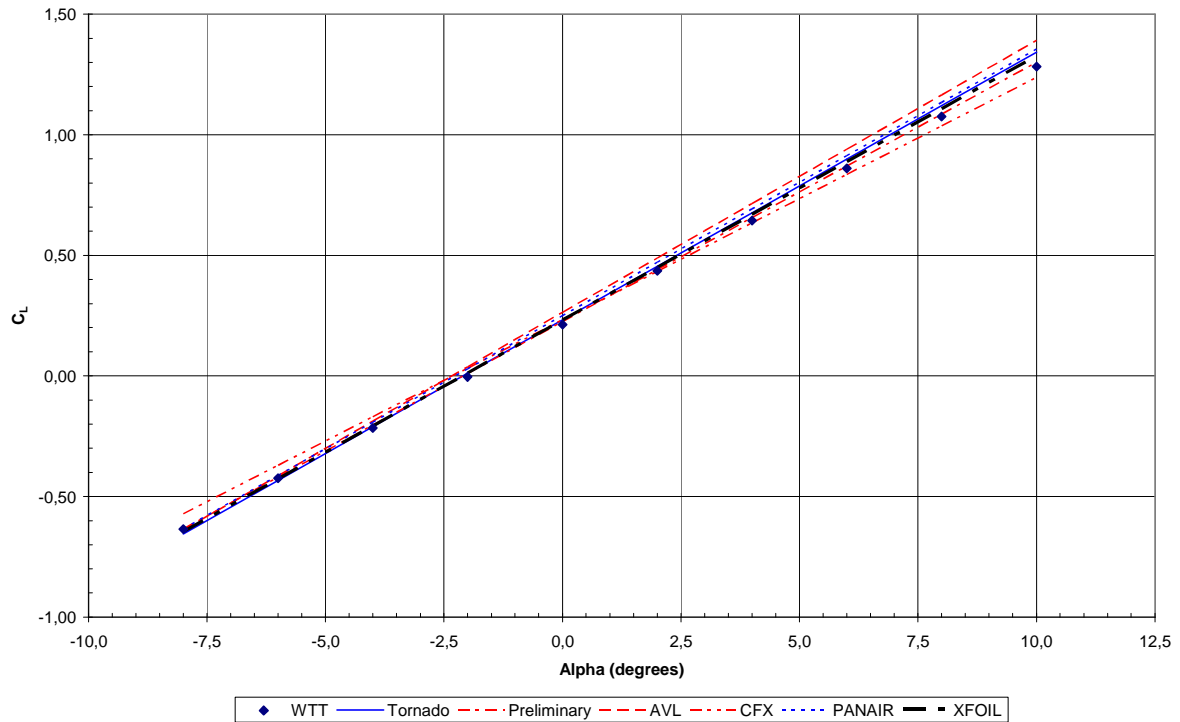


Figure 55. Lift vs. Angle of attack, NACA 2412

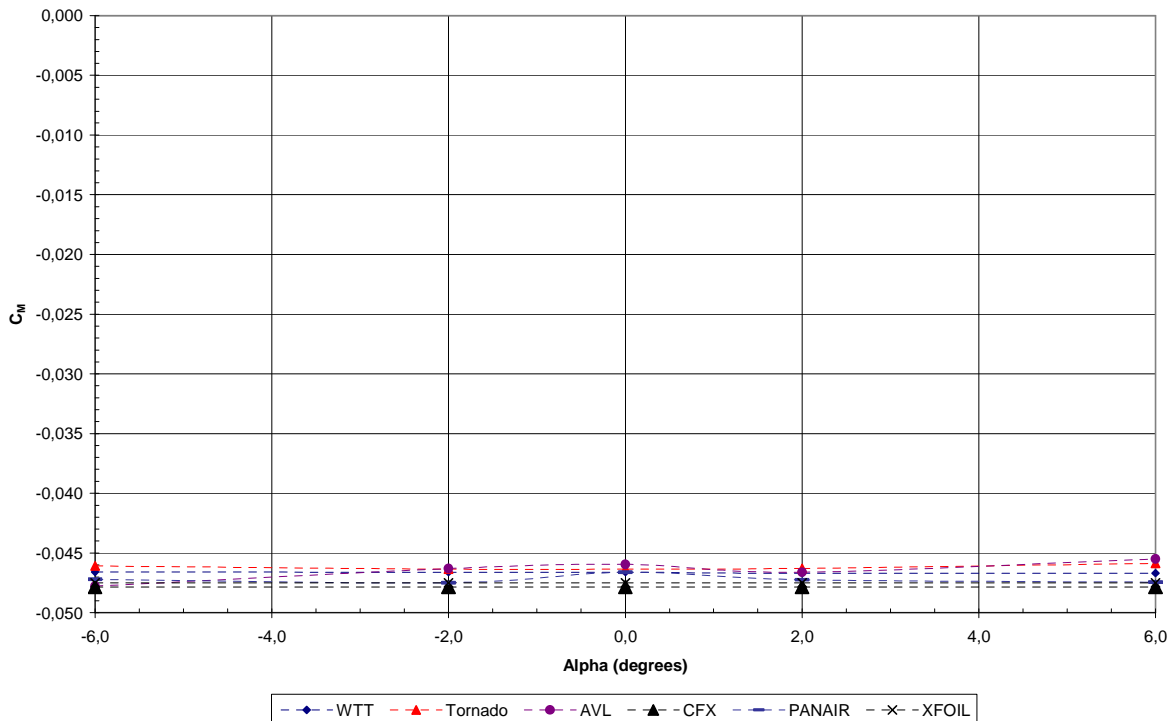


Figure 56. Pitching moment vs. Angle of attack, NACA 2412

	$C_{L\alpha}$	α_{CL0} (deg)	RMS _{Lift}	RMS _{Pitch}
Experimental	6,1	-2,0	1%	5%
Tornado	6,4	-2,1	5%	5%
Preliminary	6,2	-2,1	3%	N/D
AVL	6,5	-2,3	12%	5%
CFX	5,8	-2,3	10%	3%
PANAIR	6,3	-2,3	9%	5%
XFOIL	6,3	-2,1	4%	5%

Table 9. Data for the NACA2412 airfoil

NACA 0012

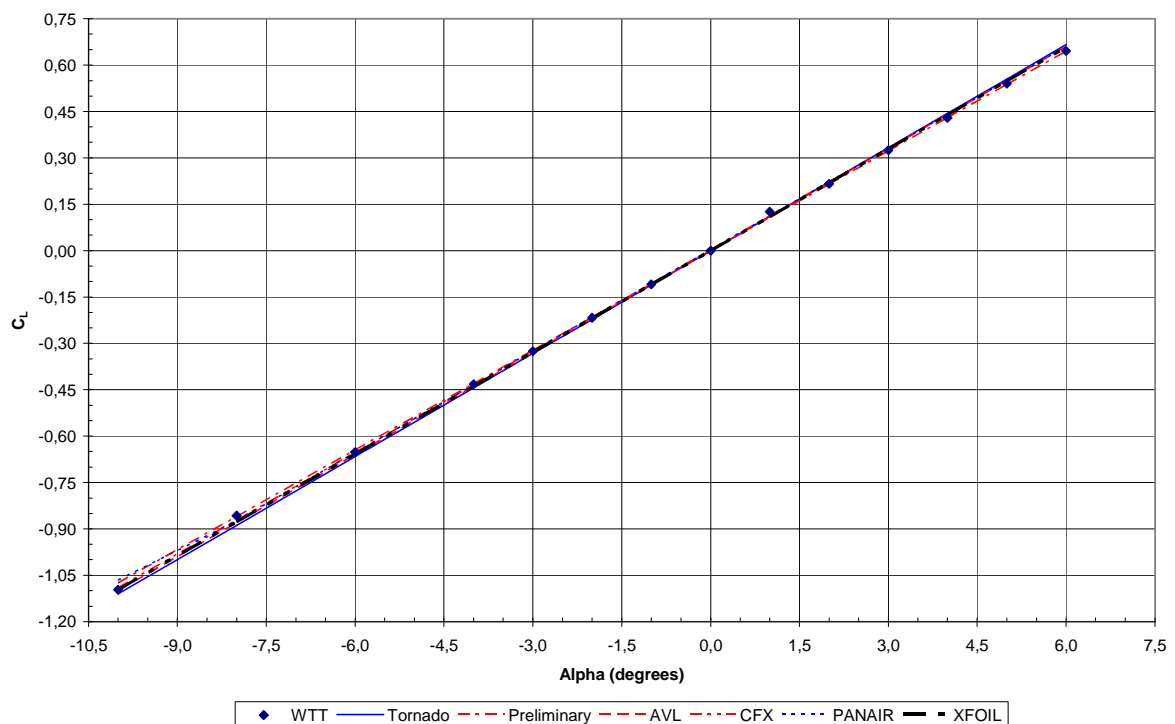


Figure 57. Lift vs. Angle of attack, NACA 0012

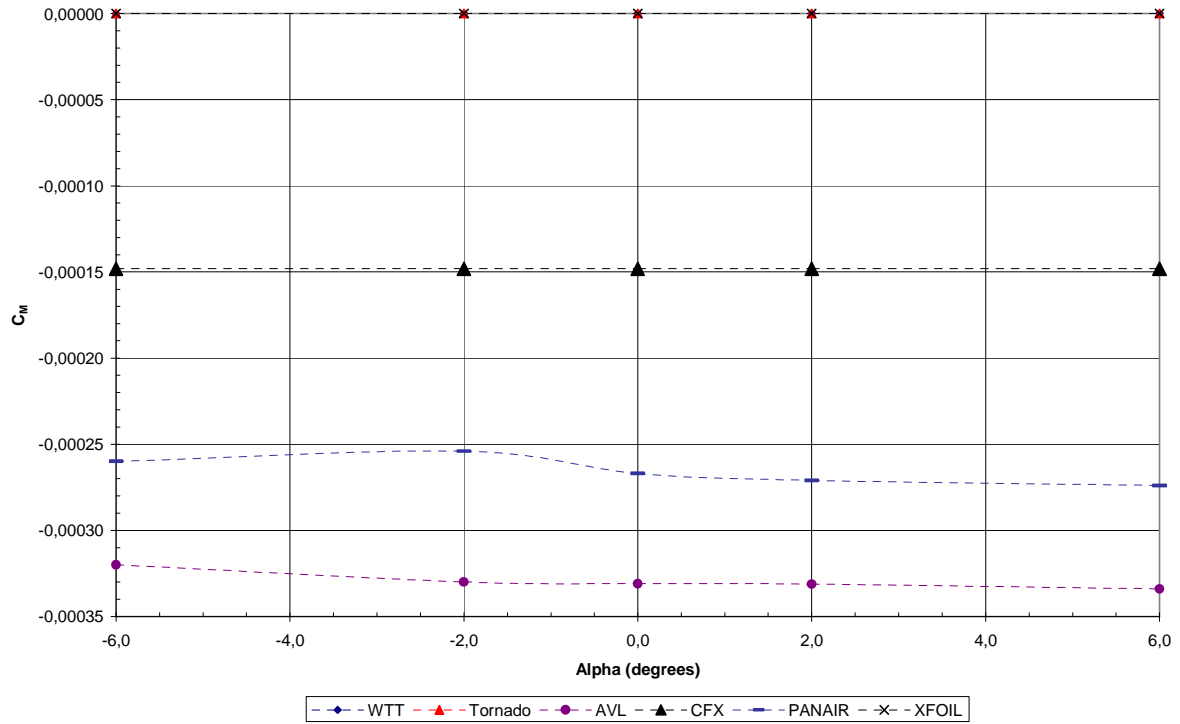


Figure 58. Pitching moment vs. Angle of attack, NACA 0012

	$C_{L\alpha}$	α_{CL0} (deg)	RMS_{Lift}
Experimental	6,2	0,0	0,6%
Tornado	6,4	0,0	2,7%
Preliminary	6,2	0,0	0,9%
AVL	6,3	0,0	1,8%
CFX	6,3	0,0	1,7%
PANAIR	6,1	0,0	1,9%
XFOIL	6,3	0,0	1,5%

Table 10. Data for the NACA0012 airfoil

ERRORS

NACA 2412

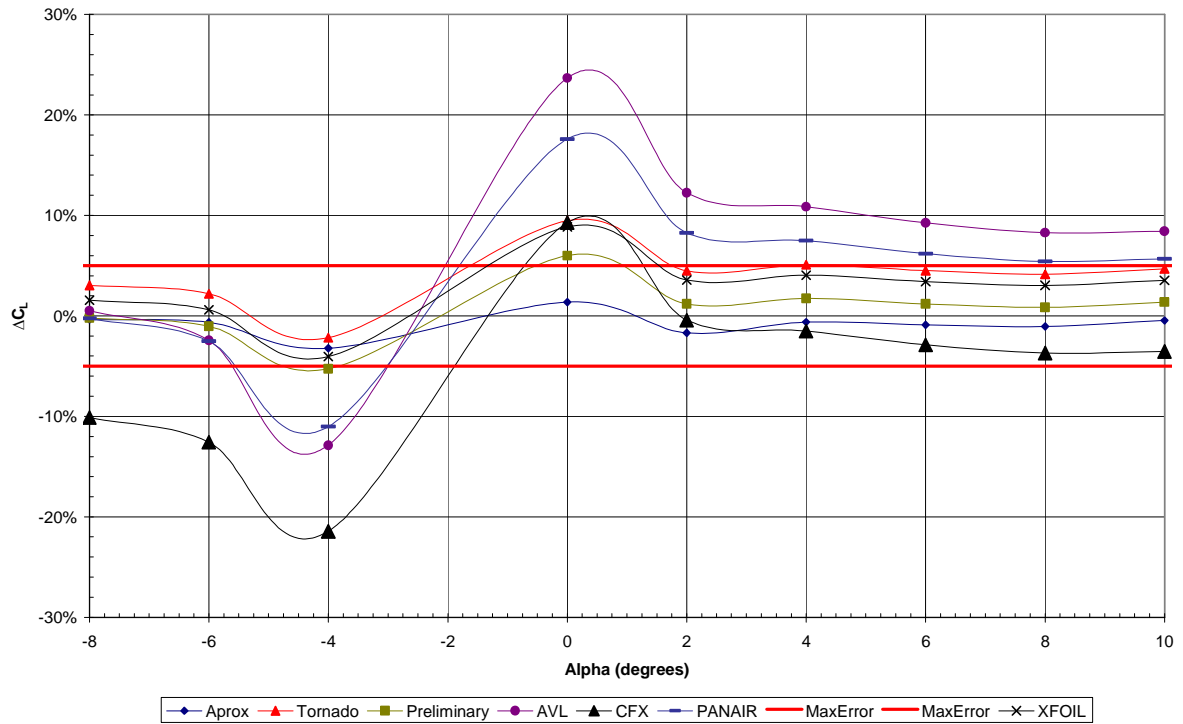


Figure 59. Differences in lift, NACA 2412

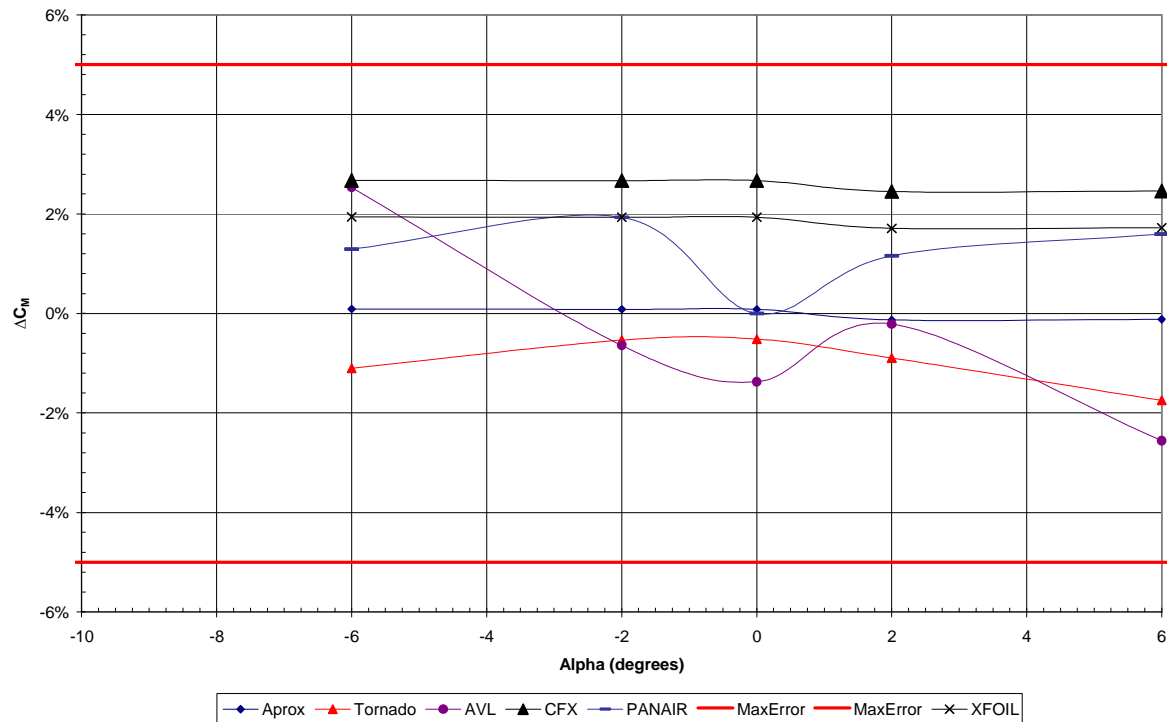


Figure 60. Differences in pitch, NACA 2412

NACA 0012

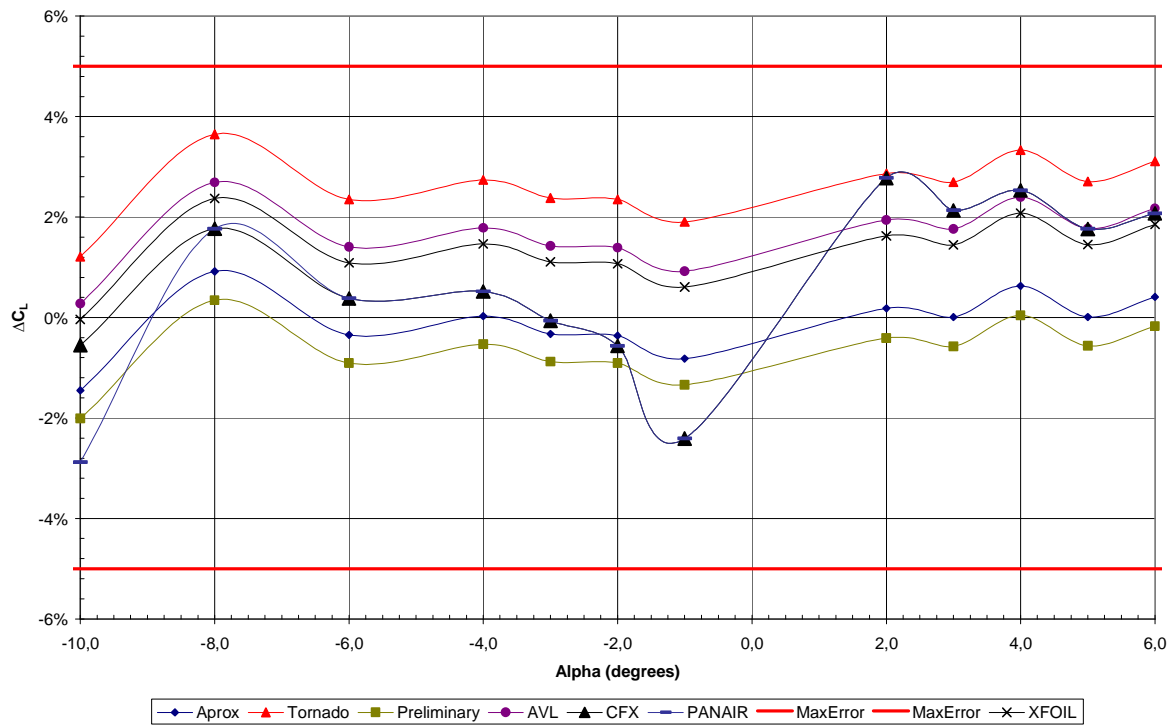


Figure 61. Differences in lift, NACA 0012

7. DISCUSSION OF THE RESULTS

The accuracy of the solutions depends on what is important in each specific case. Sometimes lift is the variable under investigation, but in other cases it is drag, and this is a decision to be made by the working team in order to apply the best software for the model being tested. Each method has weak points in different areas: more computational time on an elliptical wing for Tornado and AVL as a result of the necessary increase in the number of partitions, problems with calculation of airfoils etc. The methods would complement each other if different areas of study are analyzed. Depending on the kind of aircraft which is to be designed, one code or another should be used. Which software is the most appropriate for which type of aircraft will be discussed in the following chapters.

Grid Convergence

Something to take into account is that the number of panels in Tornado is limited by the memory used by MATLAB. That is, it is not possible to set an extremely high value for the number of panels. And anyway, it is not worth doing so: the variation in the results decreases as the number of panels increases until grid convergence is achieved. Grid convergence is the condition at which the variation of results obtained when increasing the complexity of the model (that is, more panels) is less than a limit value. In this report, a convergence limit of 1% was selected. The following figure shows the grid convergence in the method for the Boeing 747-100, one of the validation cases on this report. The number of panels varies from a 6-panel model (1 panel chord wise and 1 span wise on each partition) to a more complex 496-panel model with a high density of panels at the tip. For the convergence to be more precise, the variations have been calculated for the three aerodynamic coefficients: lift, drag, and pitch moment. Using this, increasing the number of panels to over 416 on the wing (or to round the number, 400) is a waste of memory, computational time and analysis time for this case. The convergence of the coefficients can be seen in figure 62, and the time consumption is summarized in figure 63. Even though the time for 496 panels is only 6.378 seconds, with a more complex geometry or for several tests (for instance, for different angles of attack), reducing the time to conduct one test implies less total time. As can be seen from figure 63, the increase in time with the number of panels follows a second grade curve, and using too many panels can therefore mean a loss of too much time with no improvement in the precision of the results. The limit for a usual example in a conventional computer and MATLAB R.2008, using RAM memory, is around 1,400 panels for a whole aircraft.

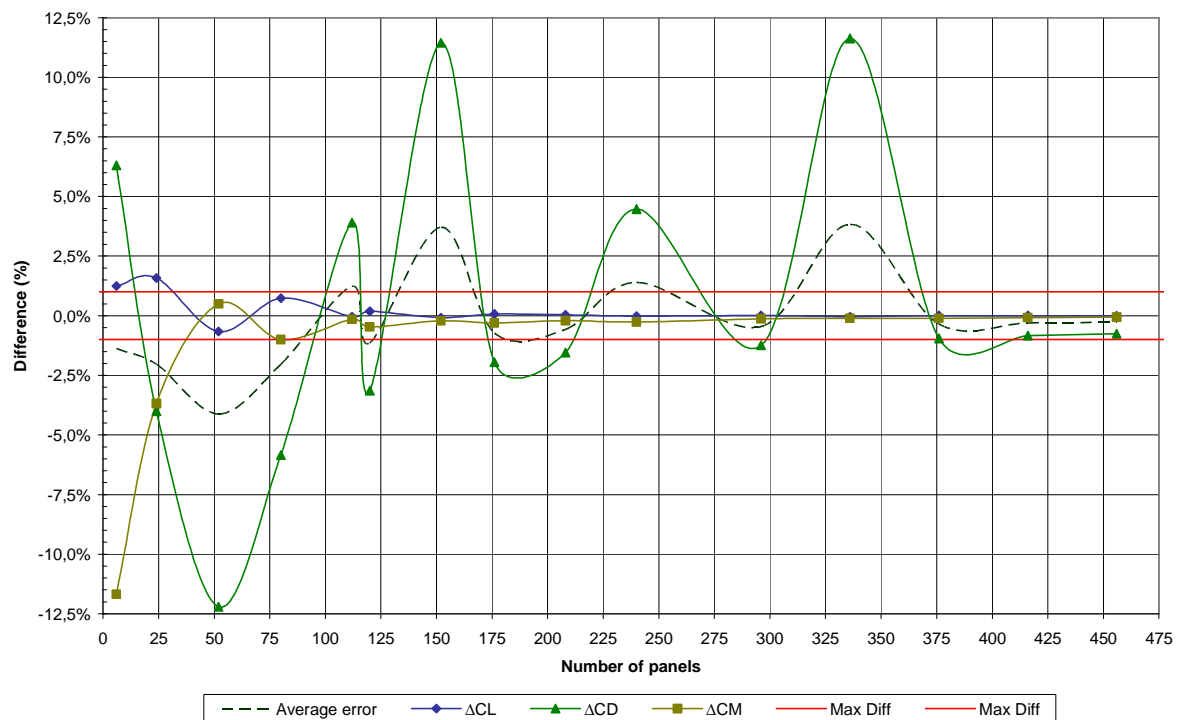


Figure 62. Grid convergence, Boeing 747-100

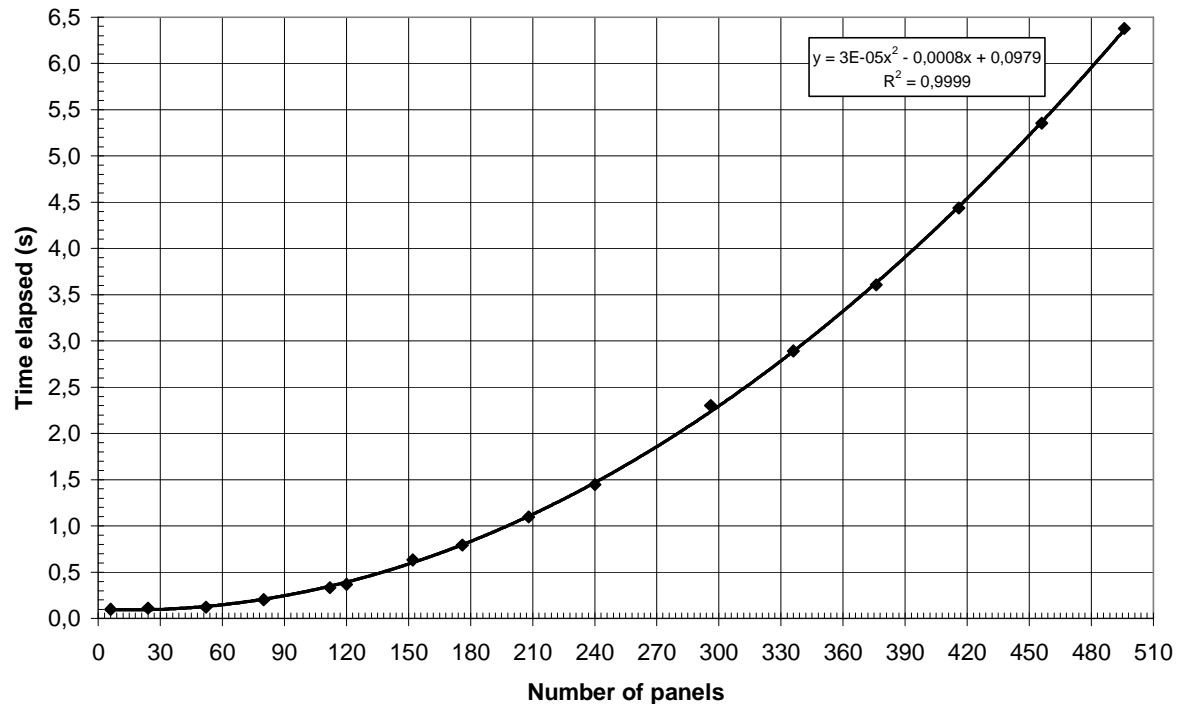


Figure 63. Time consumption, Boeing 747-100

The results for both aircraft and airfoils are discussed next.

A) Boeing 747-100

Analyzing the drag results, of the four methods the lowest error comes from Tornado with only 4.5% RMS, followed by PANAIR with a 1.5% greater difference, and the least accurate method is the Preliminary. This may be a result of the Oswald efficiency factor used, as well as the polar not having its minimum at the C_{D0} .

The C_{D0} value is best in Tornado. The value given by the Raymer calculations is 0.016 (as seen from the Preliminary result), which is not far from the actual 0.019. The combination of the wing drag calculated by Tornado and the Raymer drag for the rest of elements provided the closest result.

The lift slope is very similar in all methods except for the Preliminary, which has an extraordinarily high value. This may be due to the high Mach number, the large sweepback or the modeling of the airfoil. This method approximates every airfoil lift slope to two times pi, whatever airfoil it is. And that, as seen in this case, may not be a good value in every case.

The zero lift angle of attack is almost equal in the models. The Preliminary method has taken the Tornado value, as it will be in all examples. PANAIR has the most accurate result for this angle, but the difference is not significant enough to comment upon.

The RMS_{Lift} is smallest in PANAIR, but the other methods are very close (except for the Preliminary, which has an extremely large error).

The RMSs are only below the 5% limit in Tornado. All the others have values below 10%, which is outside the limits but excessively so, and may be accepted in the very first calculation.

Tornado's results are very close to the actual data but it has one problem, viz. that the error seems to increase with the increase in lift. In take-off and landing configurations, the error might be higher than desired. In any case, the difference at least shows that the drag is 10% above its actual value, which is better than having an approximation of 10% less when doing the sizing of the airplane.

PANAIR and AVL have very similar results in respect of both RMSs, which would lead to using AVL in this type of case if these two were the only options. The time to prepare and run the case in PANAIR totally discourages its usage.

B) Boeing 777-300

In this case, the drag has no linear term in the polar, which helps the Preliminary method to be more accurate. In fact, the drag calculation is second best in this model. Once again, Tornado gives the best results as regards the polar, although the RMS is quite high. The big differences come from the negative lift section, where the estimation is more than 15% lower than the actual value. All codes have errors above 10% for negative lifts, that is, for angles of attack under -3 degrees.

The C_{D0} value from Raymer is 0.011. This is slightly lower than the actual 0.013, which also influences the high RMS for drag. The C_{D0} in Tornado on the wing is roughly the same as in the Raymer version. Ultimately, the C_{D0} value is the same for all methods.

When analyzing the lift results, the Preliminary again has too high a value for the slope. AVL and PANAIR have almost the same slope as the Experimental value, which makes them have only 2% and 3% RMS respectively. The zero lift angle of attack is once again very similar, with a difference of only 0.3 degrees in the PANAIR solution, but the same angle for the other methods.

The analysis in this case leads to choosing AVL, but Tornado results are accurate enough. AVL has a lower error in both calculations, so it would be the best choice. The second best is Tornado. The problem with the solution in this case is that the error is substantial (outside the limits) for low angles of attack and for the drag this grows until very high lift configurations, near stall. If only drag is to be compared, the Preliminary would give a really good approximation and it would take the least time to achieve results if a zero lift drag had been calculated previously.

These two first cases are examples of the same type of airplane: high capacity, long-range aircraft. The results can therefore be used to analyze which software can be used to study one of the new aircraft of this type, such as the Boeing 787 or the A350. Both AVL and Tornado give good results in a relatively short time. PANAIR gives better results in these cases, but it should be used only if time is not important; nowadays the time spent on these calculations is to be kept as low as possible, though, and unless special software is available (PANIN, for instance) the time spent on the runs in PANAIR is going to be significantly higher than in any other code.

C) TF-8A research airplane

C.1) Mach 0.5

This case has really strange results. The errors in respect of drag are close to or above 10%, and in the lift case only Tornado is very close to the Experimental data.

As regards drag, Tornado has an approximate value of C_{D0} , which is nearer the actual solution. The Raymer calculation ($C_{D0}=0.028$) is above the real value. The wing calculation is better in Tornado, the AVL solution is too high, and PANAIR gives the same result as Raymer.

The lift slope is far from the actual data in most methods. AVL and Tornado have the best, but the α_{CL0} is better in the Tornado results, which makes it the best as regards lift, with a RMS close to the one achieved with the wing tunnel result approximation. Surprisingly, the Preliminary method has fairly good results compared with the other codes, even better than PANAIR as regards lift.

This difference in all methods may be caused by the addition of the area rule. As this aircraft is modified with its application, the results may differ significantly as regards both lift and drag.

If any method has to be used, the best would probably be Tornado, with the best results in respect of lift and the second best in respect of drag. If negative lift coefficients are not used, the Tornado values are the clearly the best. Once again, the Preliminary method could be a fast first test, giving average results.

C.2) Mach 0.8

The approximation with least RMS in respect of both lift and drag is Tornado.

The drag analysis shows that the K_2 value is too small in almost all methods, being less than a half of the Experimental approximation polar in two of the four codes. This means that in a high lift configuration (high lift being a C_L of 0.8) the drag estimation will be much lower, as can be seen from figures 29 and 45.

The Raymer zero lift drag is higher than the actual value. Once again, the Tornado approximation of the wing is better, as it also is with AVL and PANAIR in this case.

The lift slope calculations are quite close to the experimental data. Only the Preliminary method has a lower value, which makes it the worst approximation, even though it seems the most accurate on the actual error.

As stated above, the best method in this example is Tornado. But as seen in the previous calculations, at M0.5 for the same airplane the behavior is different, so this type of aircraft has to be treated with caution. The other codes have errors that may be too large to be acceptable.

D) Lockheed C-69 scaled research model

At low lift angles of attack, the errors in drag are not large but at middle and high lift the difference reaches values above 20%, which is very high. The fact is that even the approximation made using the Experimental data has a surprisingly high RMS. This can mean that this aircraft does not have a quadratic polar ($R^2=0.9836$), but a higher grade one. A fourth grade polar has an R^2 of 0.9995.

The zero lift drag, on the other hand, fits perfectly. Raymer's calculation gives a C_{D0} of 0.016 against the 0.015 of the experimental data.

The lift slope has a very close value among the methods and with the Experimental. AVL and PANAIR, with their larger results, have the two highest RMS errors.

The zero lift angle of attack is the same for Experimental, Tornado and PANAIR, and slightly higher for AVL. But this 0.3 degree difference in the position of the curve makes the method give the worst results for lift. Surprisingly, the Preliminary method is second best here, only beaten by Tornado. PANAIR, with the greater slope, is behind the Preliminary calculations.

Summing up the facts from the results, the best method for this aircraft is PANAIR, even though the RMS for lift is higher than the others. The second grade polynomial approach seems not to work for this aircraft, while lift is well modeled.

E) Boeing Stratocruiser

E.1) Conventional Configuration

Looking at the RMS, the drag data is very close. The maximum error is around 10%, but most are under 5%, which is an impressive result. The Preliminary method has the worst data for drag, but the error seems to come from the C_{D0} : the Raymer calculation is above the actual result on 4 drag counts, while the other methods gave the same value as the Experimental approximation. If the zero lift drag had been the same as in the other methods, the RMS would have been reduced to 5%, that is, in the same values as the other methods.

The lift slope has similar results. The Preliminary calculation is once again the least accurate, and the RMS is therefore above 15%. Both PANAIR and Tornado have the same slope, and the closest to the Experimental value. But the difference in the zero lift angle of attack makes Tornado have the second highest RMS value, while PANAIR has a nicer 2% error. If only positive angles of attack were investigated, the actual error is low in all of the codes except for the Preliminary method.

The analysis of the results shows that the best code in this case may be PANAIR, with AVL a close second. If the drag results are more important, AVL would be the best method to use. And the fact that the simulation time is an extra point in its favor means that it is better to use AVL if a faster calculation is to be made.

E.2) Bomber Aircraft

In this example, the preliminary method has the smallest RMS values for drag, and is not bad as regards lift.

The K_2 coefficient is too low in all methods although, as can be seen from figure 49, until around a C_L of 0.5, the difference in the results in all methods is no greater than 5%. That is, if the lift coefficient is below the set value, any method will give acceptable results.

The Raymer zero lift drag calculation has very good results. Actually, the Tornado wing drag is one count above the actual value, as is the PANAIR calculation.

The lift slope is surprisingly very different in all four methods. Only the AVL approximation is above the Experimental value and the others are much lower. Even with this, the RMS is reduced by the fact that the zero lift angle of attack is larger (absolute value) in the other methods.

The best method would be AVL or the Preliminary. In the case of lift, the errors come at small angles of attack, and in drag just the opposite. But the two methods are complementary: the lift problem is better solved in AVL for low angles and the drag is better in the Preliminary. If a fast solution is required, the Preliminary should be the method to use, but the user has to interpret the solution with caution.

F) Aero Commander 680 Super

In this airplane, the drag estimation is quite bad in most of the methods (errors above 10% in almost all lift values), but very good as regards lift (errors below 5% at most angles of attack).

There is no big differences on the K_2 coefficient on any of the approximations. The problem seems to be in the linear term, where the closest value to the Experimental data has the lowest RMS and the furthest has the greatest.

The C_{D0} is very accurate; the wing value seems to be correct for the methods which calculate it too.

The $C_{L\alpha}$ shows similar values in all methods. The preliminary approach is below and the others above, but never far from the Experimental results.

The zero lift angles are close in all calculations. This, added to the slope issue, causes the RMS_{Lift} to be very low in the methods.

For a civil propeller aircraft, like the one analyzed here, the best software would be PANAIR if all coefficients are to be estimated. If only the lift data is important, any other code could be considered, and would give fairly accurate results in a much shorter time. The position and interference of the nacelles and propellers on the wing are a problem which is difficult to solve in Tornado or AVL, and this may be the source of the substantial RMS_{Drag} on them, although the lift results do not seem to be affected by incorrect modeling of these areas.

G) NACA 2412

The results regarding this airfoil are an example of why the user should use the simulations with caution.

The lift slope is quite good, as it can be extracted from table 9. The CFX value is a little low, though. This can come from the setup of the problem, by having an insufficiently high wingspan, or the inlet and outlet not being at the necessary minimum distance, among other possible causes. Tornado is the second best model as regards lift, with an aspect ratio of 100, while PANAIR and AVL have problems in this section, with 9 and 12% RMS.

The pitching moment is accurate, inside the valid limits and even below 4%. There is a small wave in the AVL results that should not be there, as the moment is supposed to be constant. But the rest of the methods do not seem to have that variation.

The main problem seems to come from the negative angles of attack in respect of lift. This makes it difficult to decide which is the best method. But as Tornado could run the whole problem without any complements, as is the case with the Preliminary method, and as it does not calculate the pitching moment, the best code to use in this case is Tornado.

H) NACA 0012

This example has better results for all the methods.

The lift slope is very similar in all the methods. Tornado has the highest slope and RMS, and as with the drag calculations, the Preliminary method is best, due to the high aspect ratio and the actual slope being closer to the ideal 2π approximation.

The zero lift angle of attack is accurate for all the methods, as would be expected from a symmetric airfoil. The actual error is lower than 5% on all points, which is better than might be expected with this kind of model.

The pitching moment is 0 for all analyzed angles of attack (which are low angles so that the methods can model the situation correctly). The Tornado results are perfect, but not the others. The moments are in the order of 10^{-4} , which is quite acceptable for the error, as the C_M for the NACA2412 was in the order of 10^{-2} . The difference possibly arises out of the size of the model, as the aspect ratio may not be sufficient, or may be an approximation error. Either way, the results seem to be valid if interpreted with caution.

From this analysis, it is clear that the Preliminary calculations are best for lift, as the geometry is not the most adequate for the other codes. But as the pitching moment is not calculated in this method, the results are not complete and the analysis would therefore also be incomplete. This is not acceptable, so the best results in all areas come from AVL and Tornado. Tornado has greater errors as regards lift, but AVL has problems with the pitching moment. That is a big point for Tornado, as errors in respect of pitch moments would mean deflection of stabilizing surfaces to compensate for a moment that does not actually exist.

In an airfoil test, it was observed that the codes which produced the best results for regular aircraft have problems with the results. This may not seem important as airfoils are easily tested in wind tunnels and have already been extensively analyzed, but it may be something to take into account if the airplane has a very high aspect ratio (above 15). As an example, the aircraft in the Solar Impulse project (which intends to fly a solar-powered airplane non-stop around the world) has an aspect ratio of 20, and most of these airplanes have an extremely high aspect ratio, so using this type of software may not be 100% advisable for them. Gliders are another example of when not to use the validated codes, as is also the case with newly developed airfoils.

For elliptical wing aircraft (like the C-69 or the Boeing Stratocruiser) a great many partitions (4 is the minimum acceptable) are needed to model the wings in Tornado and AVL. This increases the input and processing time, but the results would be improved to much more acceptable values than those already achieved.

To sum up the results for all validation cases, it can be concluded that there is no ideal code that can solve all desired cases in a reasonable time, but they complement each other. From the analysis of the results, the ideal code for the different cases will vary. The quality of the results may also depend on the Mach number used, which can in fact play an important role in some airplanes. The software that is most likely to be used, if only one code is to be run, is Tornado. The results must be analyzed carefully to check that they are inside the expected field, to avoid unexpected problems arising.

The methods have different user-friendliness, which may need to be taken into account. For instance, Tornado and AVL usually give similar results in most of the cases but for AVL to work properly, input documents with the airfoil coordinates are needed and have to be provided by the user, while Tornado can use any of the ones in its database, including all NACA 4- and 5-series airfoils. The interface is very user-friendly and the user is guided through the setup process. Neither AVL nor PANAIR can do this. The data has to be prepared totally by the user and put into a special input file for each case. The Preliminary method does not need anything but the aspect ratio, the Oswald efficiency factor (which can be approximated or calculated) and the sweepback at the leading edge.

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