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A Spreadsheet Tool for the AERODAS Model for Calculating Airfoil Pre-Stall and Post-Stall Lift and Drag Characteristics

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Abstract- In this study a spreadsheet tool with visual graphs is presented. The spreadsheet tool uses the AERODAS model developed by Spera (*NASA Technical Report, NASA/CR-2008-215434*) to predict airfoil pre-stall and post-stall characteristics that is needed as an input for a Blade Element Momentum theory simulation of a wind turbine blade. The spreadsheet tool uses simple up and down buttons to adjust some parameters needed for the AERODAS model with the help of visual graphs. With the presented spreadsheet tool predicting the airfoil polar characteristics in the pre-stall and post-stall regimes using AERODAS model becomes very easy and efficient. The spreadsheet tool is freely available for the scientific community to download. The usage and the efficiency of the presented spreadsheet tool is presented for various applications.

Keywords Pre-stall and post-stall lift and drag characteristics, airfoil polars at wide angle of attack range, AERODAS model

1. Introduction

In wind turbine blade design and analysis Blade Element Momentum theory (BEM) is used extensively. The Blade Element Momentum theory calculations require the lift and drag coefficients of the airfoil used in the wind turbine blade at a wide angle of attack range as an input since in wind turbine blades the airfoils operate in both the unstalled and stalled aerodynamic regimes. In the literature it is possible to find experimental airfoil polar data for some airfoil geometries however these data usually cover the angle of attack range until the stall angle (pre-stall). On the other hand, in the literature there are very few experimental airfoil polar (drag and lift) data with a wide angle of attack range that covers both the pre-stall and post-stall regimes (-180° to +180°) and however those are only for certain airfoils.

When the angle of attack is higher than the stall angle, airfoils behave like a flat plate. In the literature there are some extrapolation techniques that match the pre-stall lift and drag coefficients of the airfoils with the flat plate lift and drag coefficients after the stall (post-stall) in order to obtain the lift and drag coefficients for a wide angle of attack range to use in BEM simulations (Viterna and Janetzke [1], Montgomerie [2], Lindenburg [3], Tangler and Kocurek [4])

In a study, Spera [5] proposed a mathematical model, the AERODAS model, for calculating airfoil lift and drag characteristics in both the pre-stall and post-stall regimes as a function of the angle of attack for to use in torsionally-stiff wind turbine blade calculations. Spera [5] concluded that flat-plate behavior based predictions underestimate both lift and drag at large angles of attack. Therefore, in the AERODAS model at high angles of attack in the post-stall regime, the lift and drag behaviours are not assumed to be the same as the lift and drag behaviours of flat plates as it was done in other extrapolating models. Instead, empirical equations based on the measured behaviour of the airfoils themselves are derived. Since wind turbine airfoils have finite lengths, the AERODAS model equations contain explicit adjustments to take into account for the effects of aspect ratio of the wind turbine blade on lift and drag. Also, the airfoil thickness is added as another dependent variable in the model equations along with the aspect ratio and the angle of attack.

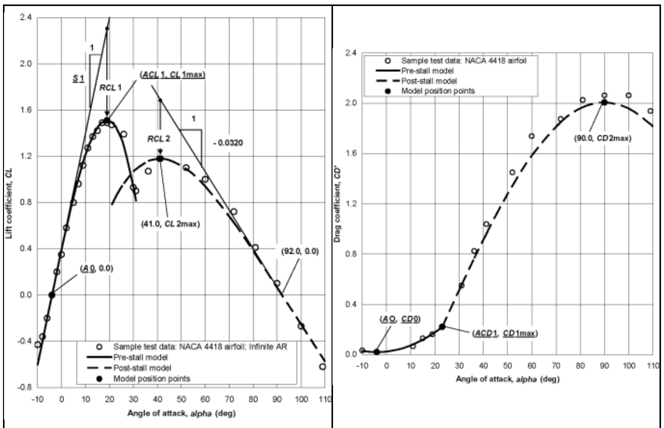
In the AERODAS model the lift and drag coefficients are modelled separately in the pre-stall and post-stall regimes. In the pre-stall regime, the basic model parameters are obtained by fitting simple curves to pre-stall wind tunnel test data. In the post-stall regime, the model includes the effects of airfoil thickness as well as the aspect ratio of the blade. In the AERODAS model, airfoil moment coefficients are not considered since for a wind turbine airfoil the torsional stiffness about its longitudinal axis is normally high.

As shown in Spera [5], the lift and drag coefficients calculated using the AERODAS model are in close agreement with reference test data for different airfoils and also the accuracy of the AERODAS model calculations is equal to or greater than other comparable extrapolating models available in the literature. Spera [5] also showed that the Blade Element Momentum (BEM) simulations of wind turbine power using the lift and drag coefficients calculated using the AERODAS model are in close agreement with available test data.

The AERODAS model provides a convenient method for calculating the lift and drag characteristics of wind turbine blade airfoils both in the pre-stall and post-stall regimes.

Even though the AERODAS model uses simple empirical equations, it requires some effort to obtain the parameters used in the model. The parameters cannot be obtained automatically for every different airfoil therefore the user must control and/or choose some parameters to construct the model equations.

Although the AERODAS model is a very powerful method to extrapolate the airfoil polar data to a wide angle of attack, it is not very easy to apply the model. In a wind turbine blade analysis sometimes many airfoils are considered and using the AERODAS model on many airfoils can be tedious. This constitute the main motivation of this study. In this study we have developed an Excel spreadsheet tool (freely available for the scientific community to download) to use the AERODAS model easily. In this developed spreadsheet tool, the user sets some parameters by just couple of clicks of the mouse while seeing the changes on visual charts. The developed spreadsheet tool does all the AERODAS model calculations automatically. We will present the usage of this spreadsheet tool by using both available experimental or computational pre-stall polar data for different airfoils.



a) Lift coefficient model **b)** Drag coefficient model

Fig.1. Configurations of the AERODAS model (source Spera [5])

2. AERODAS Model

The AERODAS model is developed by Spera [5] by modelling the trends of wide variety of airfoil test data by best fit using algebraic equations. Figure 1 illustrate the important parameters and slopes used in the AERODAS models for calculating airfoil lift and drag coefficients as functions of the angle of attack in both the pre-stall and post-stall regimes and also Table 1 lists the nomenclature used in the AERODAS model equations.

Table 1. Nomenclature used in the AERODAS model

$CL1$	lift coefficient in the pre-stall regime
$CL2$	lift coefficient in the post-stall regime
$CD1$	drag coefficient in the pre-stall regime
$CD2$	drag coefficient in the post-stall regime
α	angle of attack
$A0$	angle of attack at which $CL1 = 0$
$ACL1$	angle of attack at maximum pre-stall lift
$CL1max$	maximum pre-stall lift coefficient
$S1$	slope of linear segment of pre-stall lift curve
$CD0$	minimum drag coefficient at $\alpha = A0$
$ACD1$	angle of attack at maximum pre-stall drag
$CD1max$	maximum pre-stall drag coefficient
$RCL1$	reduction from extension of linear segment of lift curve to $CL1max$
$N1$	exponent defining shape of lift curve at $CL1max$
$RCL2$	reduction from extension of linear segment of lift curve to $CL2max$
$N2$	exponent defining shape of lift curve at $CL2max$

In the AERODAS model, the lift coefficient in the pre-stall regime is defined as the following equation

$$CL1 = S1 \times (\alpha - A0) - RCL1\left(\frac{\alpha - A0}{ACL1 - A0}\right)^{N1}$$

where $RCL1$ and $N1$ is defined as

$$RCL1 = S1 \times (ACL1 - A0) - CL1max$$

$$N1 = 1 + CL1max/RCL1$$

Also, the drag coefficient in the pre-stall regime is defined as the following

$$CD1 = CD0 + (CD1max - CD0)\left(\frac{\alpha - A0}{ACD1 - A0}\right)^{M}$$

In the post-stall regime, the lift coefficient is defined as the following

$$CL2 = -0.032(\alpha - 92.0) - RCL2\left(\frac{92.0 - \alpha}{51.0}\right)^{N2}$$

where $RCL2$ and $N2$

$$RCL2 = 1.632 - CL2max$$

$$N2 = 1 + CL2max/RCL2$$

Similarly, in the post-stall regime the drag coefficient is defined as

$$CD2 = CD1max + (CD2max - CD1max) \times \sin\left(\frac{\alpha - ACD1}{90.0 - ACD1} \times 90\right)$$

As mentioned earlier in AERODAS model $CL2max$ and $CD2max$ are considered to be a function of the airfoil thickness (t/c) and the aspect ratio of the blade (AR). Also again as mentioned earlier, in AERODAS model the lift and drag coefficients are considered to change with the finite ratio and therefore are adjusted by the finite aspect ratio. The parameters that are adjusted by the finite aspect ratio are the following

$$ACL1 = ACL1' + 18.2\ CL1max' \times AR^{-0.90}$$

$$ACD1 = ACD1' + 18.2CL1max' \times AR^{-0.90}$$

$$CL1max = CL1max'\left\{0.67 + 0.33\exp\left[-(4.0/AR)^2\right]\right\}$$

$$CD1max = CD1max' + 0.280CL1max'^2 \times AR^{-0.90}$$

$$S1 = \frac{S1'}{1 + 18.2\, S1' \times AR^{-0.90}}$$

where the primed values are the infinite aspect ratio values.

We will not go into the details of the AERODAS model, the reader is referred to Spera [5] for further details.

3. AERODAS.xls Spreadsheet Tool

We have developed the AERODAS.xls spreadsheet for the students to use the AERODAS model developed by Spera[5] easily in their wind turbine blade design projects in the Wind Engineering course at Bahcesehir University, in Istanbul, Turkey. Students and researchers who wish to use the AERODAS model in their studies can obtain the AERODAS.xls spreadsheet tool from [6] where the spreadsheet is available for download freely. Below we will demonstrate the usage of the spreadsheet tool.

The spreadsheet has 3 sheets; “data”, “calculations” and “table_input”. The “data” sheet is used to enter the polar data coming from experiments or simulations and it has all the tools for the user to control and set the parameters used in the AERODAS model. All the calculations for the model equations are done in the “calculations” sheet. If a researcher tabulates his/her AERODAS parameters in a publishment, the user can use “table_input” sheet to reconstruct that published polar data. When the “table_input” sheet is used all the data in the “data” sheet and all the calculations in the “calculations” sheet is bypassed and the model equations are calculated according to the parameters entered in the “table_input” sheet.

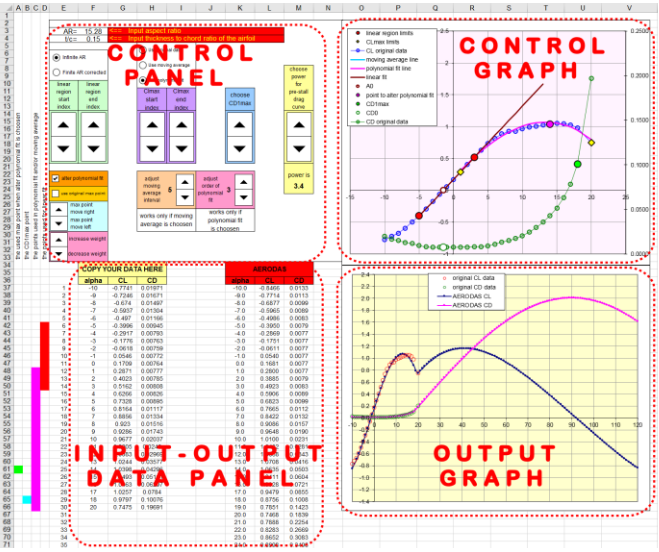


Fig.2. Input/Output panels and graphs in the AERODAS.xls spreadsheet tool

The spreadsheet uses some macros for calculations therefore the macros should be allowed by the user. For most applications the user deals only with “data” sheet. This sheet has four panels (parts); the input-output data panel is where the user enters the data and the calculated output data is located; the output graph is the graph where the input and output data is shown; the control panel is the panel where the user adjusts and set some parameters; the control graph is the graph that helps the user to set the parameters as shown in Figure 2. All the graphs and output data changes dynamically as the user changes any parameter.

To start using the spreadsheet tool, the user needs to have the pre-stall regime lift and drag coefficient of the considered airfoil, which will be the input of the AERODAS model. For this the user can either go through the many experimental studies in the literature that publish polar data or use a simulation software such as XFOIL and obtain polar data for a chosen airfoil. Since the AERODAS model assumes that the rotor is torsionally-stiff, the model does not need the moment coefficient as an input, it only needs the lift and drag coefficients. The user enters the lift and drag coefficients at corresponding angles of attack as an input for calculations in three columns. The user also enters the thickness to chord ratio of the considered airfoil and also the aspect ratio of the considered wind turbine blade. Since usually the published experimental polar data and also the simulation polar solutions are for infinite aspect ratio, the user should always start the analysis by selecting infinite aspect ratio (“Infinite AR”). After obtaining the AERODAS parameters the user might obtain the results for the finite aspect ratio based on the entered wind turbine aspect ratio by selecting the “Finite AR corrected” at the final. These are the only initial inputs the user enters for an analysis as shown in Figure 3.

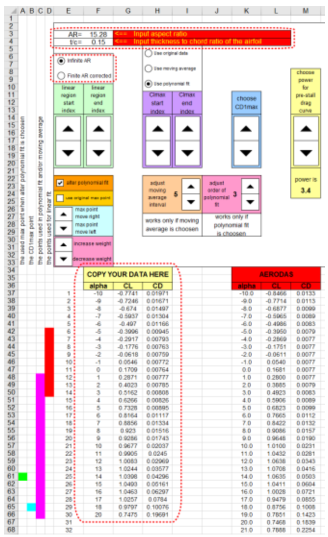


Fig.3. The inputs needed to start the calculations in the AERODAS.xls spreadsheet tool

3.1. Lift Coefficient Calculations

In the pre-stall region calculations, the AERODAS model needs the parameter S1 which is basically the linear slope of the lift coefficient in the pre-stall ramp as shown in Figure 1-a. In AERODAS.xls linear regression is used in order to calculate S1. For this the user is required to choose the region of the data points used in the linear regression. The user uses up/down arrows to set the first and also the last data points of the chosen region. The user can see the input lift data in the control graph next to the control panel. The user can also see the chosen first and last data point and the corresponding fitted linear line as well in this figure dynamically. The chosen data points for the linear regression by the user is highlighted as red in a column next to the input data as shown in Figure 4.

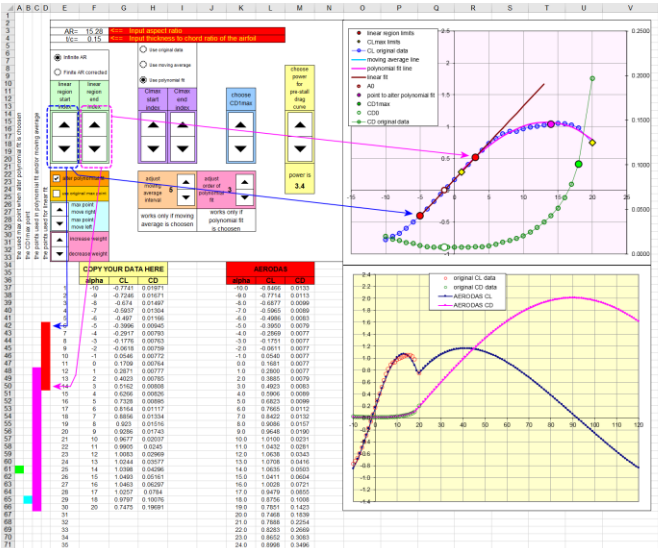


Fig.4. Setting the linear slope of the lift coefficient in the AERODAS.xls spreadsheet tool

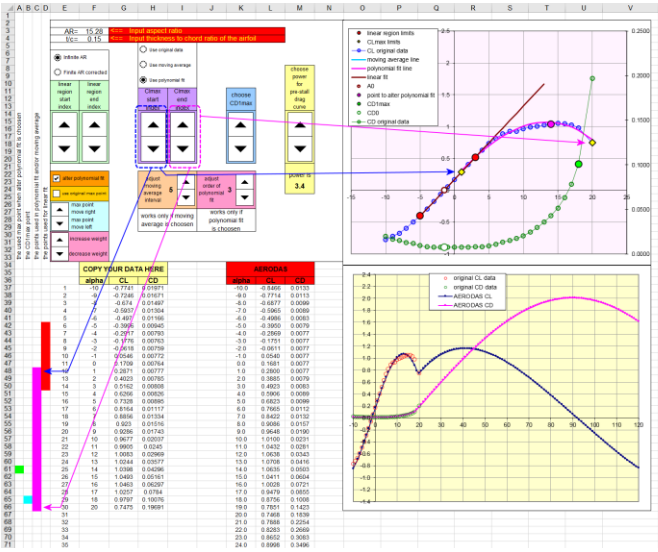


Fig.5. Setting the peak value of the lift coefficient in the AERODAS.xls spreadsheet tool

In the pre-stall region calculations, the AERODAS model needs the parameter RCL1 which is basically the vertical distance between the peak CL point (*i.e.* largest value of the lift coefficient) and the linear slope line as shown in Figure 1-a. Therefore, in order to calculate RCL1, the peak value of the lift coefficient is required. According to our experiences with XFOIL, depending on the chosen airfoil and the Reynolds number, sometimes the XFOIL calculated lift coefficient is very smooth with a very clear definite peak however sometimes the lift coefficient may have several humps or zigzag type behaviour near the peak which eventually make it difficult to select the peak value. In the AERODAS.xls, the user has 3 options for selecting the peak value. If the user chooses "Use original data" option, the spreadsheet uses the original data as is and obtain the peak value from the original input data and then calculates the RCL1 accordingly. However, if the input lift data has humps or zigzag type behaviour near the peak the user has 2 other options. One option is that the user might smooth the lift data using a moving average. If the user chooses the "Use moving average" option, then the user must set the region of data points in which the moving average is applied and also set the interval of the moving average. The peak value is obtained from the smoothed data. The other option is to fit a curve to the lift data near the peak using a nonlinear polynomial regression and then obtain the peak value from this fit. If the user chooses the "Use polynomial fit" option then the user must set the region of data points in which the nonlinear polynomial regression is applied and also set the degree of the nonlinear polynomial regression. The user uses up/down arrows to set the first and also the last data points of the chosen region where the moving average or the nonlinear polynomial regression is applied and also to adjust the moving average interval or to set the degree of the nonlinear polynomial regression. Again, as similar the user can see the chosen first and last data points in the control graph and also the chosen data points in this region is highlighted as pink in a column next to the input data as shown in Figure 5. In order for the user to see the vertical distance between the linear slope line and the peak value of the lift coefficient, the tip of the linear slope line always ends over the peak maximum lift value.

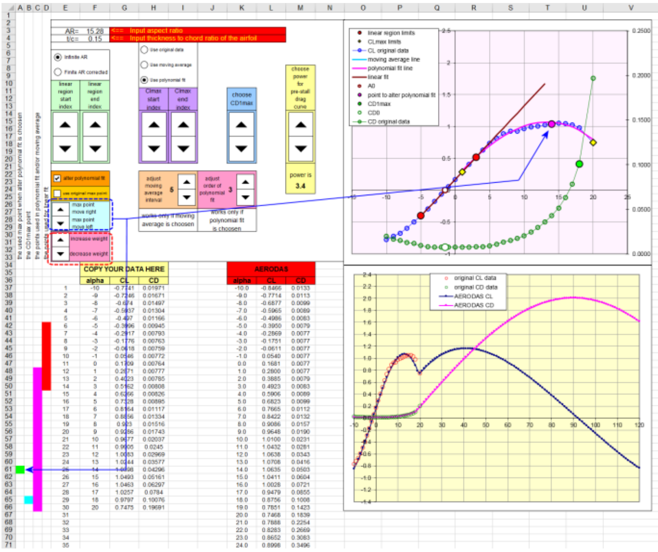


Fig.6. Altering the polynomial fit in the AERODAS.xls spreadsheet tool

The "Use polynomial fit" option offers a very effective way to obtain the peak lift value for most airfoils. Even though this option is very efficient, from our experience, we think that for some airfoils sometimes it should be better if the user is able to alter the nonlinear polynomial regression curve according to the user's choices. For this reason, in the AERODAS.xls the user can choose "alter polynomial fit" option to alter the automatically drawn nonlinear polynomial regression curve. This option is available only if "Use polynomial fit" is chosen. The way this altering option works is that the user can choose a point in the chosen data region and change the weight of this point in the calculation of the nonlinear regression. By doing this, it is possible to alter the fitted curve very smoothly. The user can choose any point to increase the weight or else use the max point of the original input data and increase its weight. If "alter polynomial fit" is chosen, the user can see the chosen point in the control graph and also the chosen point is highlighted as green in a separate column next to the input data as shown in Figure 6.

3.2. Drag Coefficient Calculations

For the drag coefficient calculations, the AERODAS model needs CD1max and ACD1 values as shown in Figure 1-b. ACD1 and CD1max defines the point that separates the pre-stall region and the post-stall region for the drag coefficient. ACD1 is the angle of attack and CD1max is the drag coefficient at this angle. The user can choose this dividing data point of the pre-stall and post-stall regions by using the up/down arrows. The chosen point can be seen in the control graph and also the chosen data point is highlighted as cyan in a column next to the input data as shown in Figure 7.

The last step in AERODAS model drag calculations is to set the exponent for the pre-stall drag curve. Using the up/down arrows the user adjusts the exponent (M). As the exponent increases the curve gets more flat and this mainly affects the curve near the chosen CD1max point in the pre-stall region as shown in Figure 7. By comparing with the input drag data in the output graph, the user sets the exponent value that fits best to the input drag data.

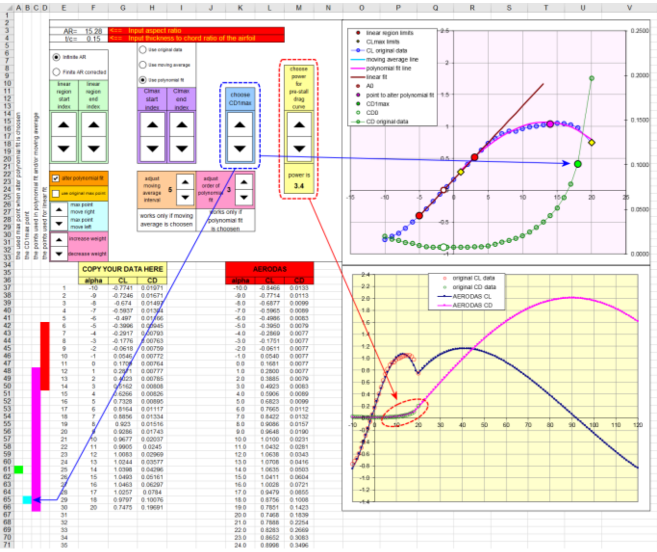


Fig.7. Setting drag coefficient parameters in the AERODAS.xls spreadsheet tool

The options in the AERODAS.xls spreadsheet tool described above helps the user to set the parameters needed in the AERODAS model. After setting these parameters, the calculated AERODAS model lift and drag coefficients are given in the output panel with 1-degree interval in the angle of attack. The graph of these calculated lift and drag coefficients are given in the output graph as well. As mentioned earlier the user must always start the analysis for an infinite aspect ratio. After obtaining the AERODAS lift and drag curves for an infinite aspect ratio the user might choose the "Finite AR corrected" option and the spreadsheet tool will modify the lift and drag coefficient calculations of the AERODAS model according to the input aspect ratio value.

4. Demonstration of AERODAS.xls Spreadsheet Tool

In order to obtain the polar coefficients of a chosen airfoil for a wide range of angle of attack using the AERODAS model, the user needs the lift and drag coefficients of the chosen airfoil in the pre-stall regime. In the literature it is possible to find many experimental studies that publish the lift and drag coefficient until the stall angle for different airfoils. One option is that, for the chosen airfoil if there are any available published experimental data, the user can use these data. Another option is that the user can use a simulation software in order to calculate the pre-stall lift and drag coefficient of the chosen airfoil. We will demonstrate both options in order to show the usage and efficiency of the AERODAS.xls spreadsheet tool.

4.1. Using a Simulation Software

Among the available simulation softwares that can calculate the pre-stall lift and drag coefficient for a chosen airfoil, most probably XFOIL is the most popular and extensively used simulation software.

XFOIL [7] is developed by Prof. Mark Drela from Massachusetts Institute of Technology in 1986 [8]. XFOIL uses high order inviscid linear-vorticity panel method to calculate airfoil polars. XFOIL is an excellent airfoil design and analysis tool. The accuracy of XFOIL is demonstrated in many studies in the literature [9,10,11]. The output of XFOIL is a text file in which the angle of attack and the corresponding lift and drag coefficients are tabulated.

In an experimental study Bloy and Roberts [12] performed wind tunnel tests and measured the lift and drag coefficients of the NACA 63-215 airfoil in the range from -20° to 200° angle of attack. In their experiment the Reynolds number was 0.55×10^6. The NACA 63-215 airfoil geometry is shown in Figure 8.

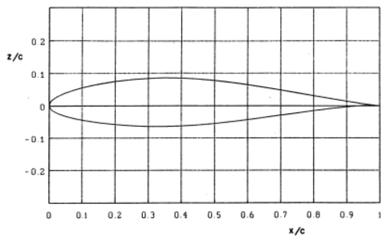


Fig.8. NACA 63-215 airfoil shape (Source: Bloy and Roberts [12])

The wind tunnel measured lift and drag coefficients of Bloy and Roberts [12] are given in Figures 9 and 10. We note that Figures 8, 9 and 10 are taken from Bloy and Roberts [12].

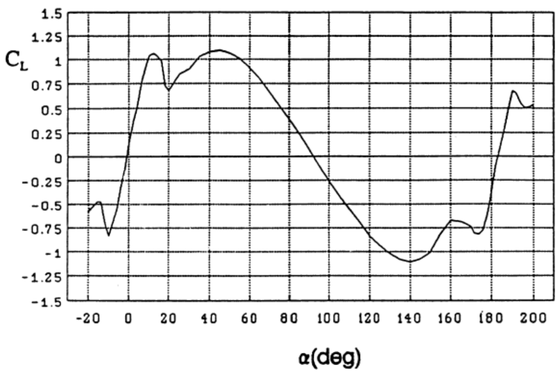


Fig.9. The lift coefficient of NACA 63-215 airfoil versus the angle of attack (Source: Bloy and Roberts [12])

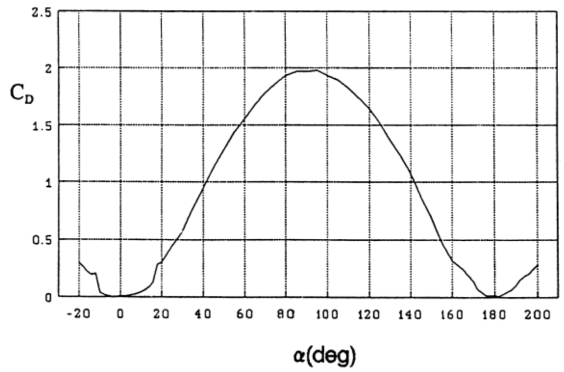


Fig.10. Drag coefficient of NACA 63-215 airfoil versus the angle of attack (Source Bloy and Roberts [12])

For the NACA 63-215 airfoil, first we use XFOIL program and obtain the pre-stall lift and drag coefficients. Then we use the developed AERODAS.xls spreadsheet tool and calculate the lift and drag coefficients for a wide angle of attack range. We, then compare this AERODAS model lift and drag coefficients with the experimental results of Bloy and Roberts [12].

The coordinates of NACA 63-215 airfoil is available freely in airfoil databases or publishments in the literature [13]. Using XFOIL, we have obtained the lift and drag coefficients of NACA 63-215 airfoil at the same Reynolds number (0.55×10^6) with that of Bloy and Roberts [12]. The output data file of XFOIL software is given in Table [2].

Table 2. XFOIL output for NACA 63-215 airfoil
(Nomenclature is given at the bottom of the table)

XFOIL Version 6.99

Calculated polar for: NACA 63-215

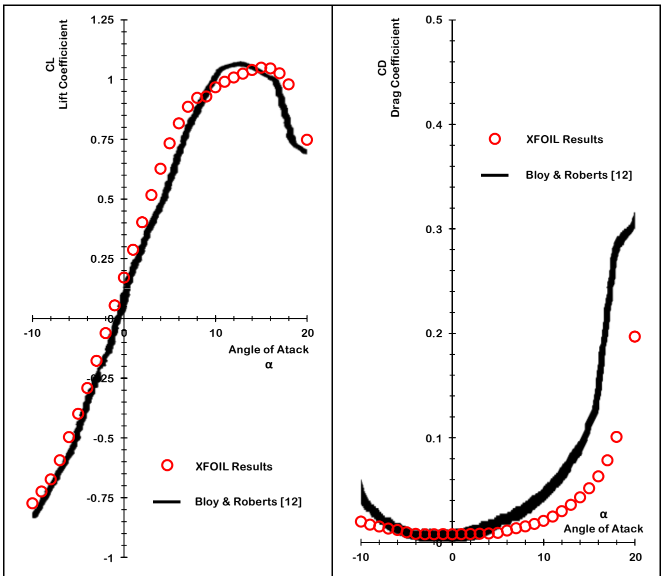
1 1 Reynolds number fixed Mach number fixed

xtrf = 1.000 (top) 1.000 (bottom)
Mach = 0.000 Re = 0.550 e 6 Ncrit = 9.000

alpha	CL	CD	CDp	CM	Top_Xtr	Bot_Xtr
-10.000	-0.7738	0.01971	0.01428	-0.0555	0.9849	0.0201
-9.000	-0.7245	0.01671	0.01089	-0.0495	0.9025	0.0219
-8.000	-0.6740	0.01498	0.00877	-0.0403	0.8522	0.0248
-7.000	-0.5937	0.01304	0.00653	-0.0362	0.8244	0.0389
-6.000	-0.4970	0.01166	0.00500	-0.0345	0.7928	0.0645
-5.000	-0.3996	0.00945	0.00351	-0.0340	0.7644	0.2306
-4.000	-0.2917	0.00793	0.00270	-0.0348	0.7403	0.4506
-3.000	-0.1776	0.00763	0.00243	-0.0355	0.7108	0.5234
-2.000	-0.0618	0.00759	0.00248	-0.0364	0.6887	0.5792
-1.000	0.0546	0.00772	0.00243	-0.0374	0.6613	0.6010
0.000	0.1709	0.00764	0.00248	-0.0386	0.6409	0.6344
1.000	0.2871	0.00777	0.00250	-0.0396	0.6148	0.6536
2.000	0.4023	0.00785	0.00272	-0.0406	0.5919	0.6848
3.000	0.5162	0.00808	0.00281	-0.0412	0.5490	0.7055
4.000	0.6266	0.00826	0.00300	-0.0411	0.4878	0.7388
5.000	0.7328	0.00895	0.00348	-0.0407	0.4026	0.7651
6.000	0.8164	0.01116	0.00503	-0.0371	0.2055	0.7941
7.000	0.8856	0.01334	0.00675	-0.0310	0.0829	0.8321
8.000	0.9231	0.01516	0.00852	-0.0189	0.0375	0.8779
9.000	0.9287	0.01742	0.01116	-0.0028	0.0217	1.0000
10.000	0.9676	0.02038	0.01424	0.0043	0.0181	1.0000
11.000	0.9906	0.02449	0.01855	0.0119	0.0163	1.0000
12.000	1.0083	0.02969	0.02401	0.0182	0.0153	1.0000
13.000	1.0244	0.03576	0.03036	0.0228	0.0147	1.0000
14.000	1.0398	0.04296	0.03799	0.0259	0.0145	1.0000
15.000	1.0493	0.05161	0.04700	0.0269	0.0140	1.0000
16.000	1.0463	0.06298	0.05879	0.0255	0.0135	1.0000
17.000	1.0258	0.07839	0.07467	0.0203	0.0132	1.0000
18.000	0.9797	0.10077	0.09760	0.0090	0.0130	1.0000
20.000	0.7479	0.19678	0.19446	-0.0413	0.0135	1.0000

Nomenclature:
CL:lift coefficient, CD:drag coefficient, CDp:pressure drag coefficient, CM:momentum coefficient, Re:Reynolds number, Mach:Mach number, Ncrit:transition criterion, xtrf:effective transition location, Top_Xtr:top forced transition location, Bot_Xtr:bottom forced transition location, alpha:angle of attack

Figure 11 shows the pre-stall lift and drag results of XFOIL as functions of the angle of attack for NACA 63-215 airfoil. In this figure we also include the results of Bloy and Roberts [12]. In Figure 11-a one can notice that the XFOIL simulation results deviate from the experimental results within an error. There is deviation in the location of the maximum lift coefficient around at the peak. The experimental lift data has a peak value at around 12° angle of attack however the XFOIL simulation data has a linear flat behaviour around this angle with having a peak at around 17° angle of attack. While majority of the airfoils have a continuous smooth peak, for NACA 63-215 airfoil the XFOIL gives the lift coefficient with almost a linear flat behaviour at the region where the experimental data have a peak. For this kind of results the "alter polynomial fit" option described above becomes very handy and let the user locate the peak lift value easily in the AERODAS.xls spreadsheet tool. In Figure 11-b one can also notice that there is deviation in the drag coefficients also between the XFOIL predictions and the experimental results of Bloy and Roberts [12]. Nevertheless, the AERODAS model does not use the original input lift and drag data in the output data directly. It only uses the input data to obtain the parameters used in the model equations. The output data is calculated using the model equations afterwards.



a) Lift coefficient **b)** Drag coefficient

Fig.11. Comparison of NACA 63-215 airfoil XFOIL results with the results of Bloy and Roberts [12]

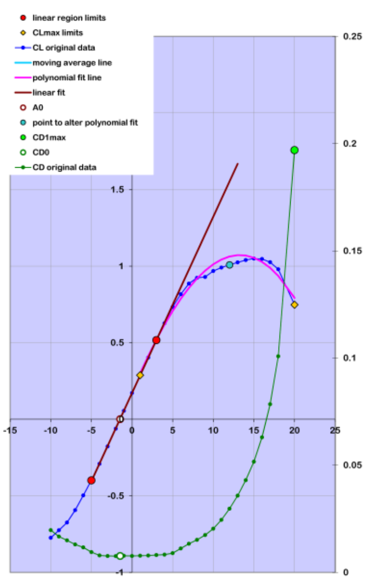


Fig.12. The "Control Graph" panel in AERODAS.xls spreadsheet tool for NACA 63-215 airfoil calculations

Using the "alter polynomial fit" option in the AERODAS.xls spreadsheet tool, we have smoothened the linear flat region for the considered NACA 63-215 airfoil as shown in Figure 12 and one can notice that there is a smooth transition from the linear ramp (shown with brown line) to a smooth curve (shown with pink line) in the lift coefficient.

The calculated AERODAS model parameters for NACA 63-215 airfoil is given in Table 3. Figures 13 and 14 show the output lift and drag coefficients of the AERODAS model for NACA 83-215 together with the experimental results of Bloy and Roberts [12]. As it is seen in Figures 13 and 14, the predictions of the AERODAS model is quite impressive and the agreement is very good with the experimental results.

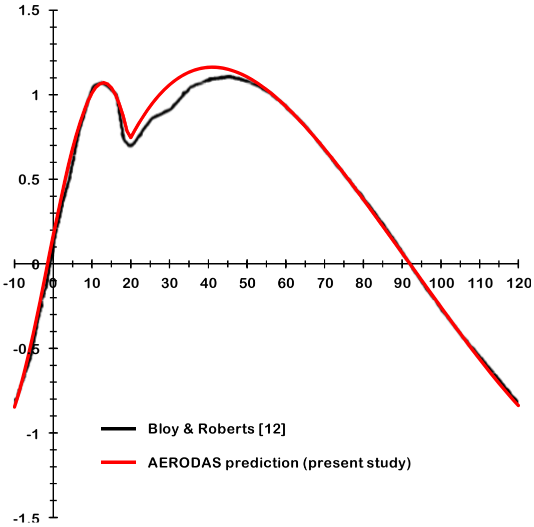


Fig.13. Lift coefficients comparison of NACA 63-215 airfoil

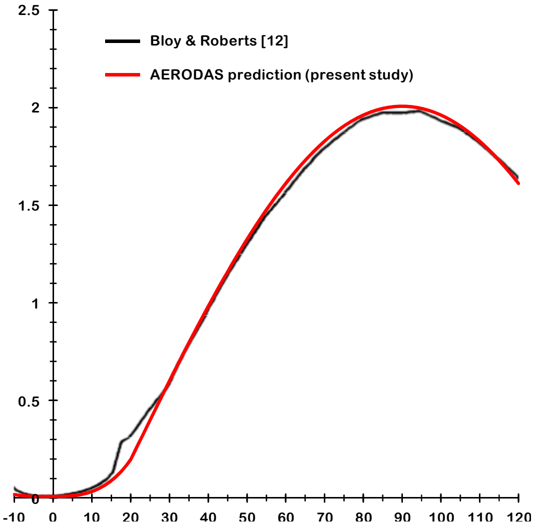


Fig.14. Drag coefficients comparison of NACA 63-215 airfoil

4.2. Using Published Experimental Data

In the literature it is possible to find many experimental aerodynamic data for a wide variety of airfoils. In most of these studies the polars are presented in graph figures. With the help of a digitizer software, one can easily obtain numerical data from these graph figures.

Table 3. AERODAS model parameters for NACA 63-215 airfoil
(Nomenclature is given Table 1)

AERODAS LIFT AND DRAG MODEL	
AR =	infinite
t/c =	0.15
Pre-stall Parameters	
CL1max =	1.0716
ACL1 =	13
S1 =	0.1151
A0 =	-1.4691
RCL1 =	0.5941
CD1max =	0.1969
ACD1 =	20
N1 =	2.8035
CD0 =	0.0077
M =	3.2
Post-stall Parameters	
CL2max =	1.1632
RCL2 =	0.4688
CD2max =	2.0072
N2 =	3.4814

In an experimental study, Satran and Snyder [14] performed wind tunnel measurements on GA(W)-2 airfoil and obtained the lift and drag coefficients from 0 to 360 degrees angles of attack. The GA(W)-2 airfoil geometry is shown in Figure 15.

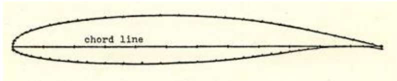


Fig.15. GA(W)-2 airfoil shape
(Source: Satran and Snyder [14])

The wind tunnel measured results of Satran and Snyder [14] for lift and drag coefficient is given in Figure 16 and 17. Figures 15, 16 and 17 are taken from Satran and Snyder [14].

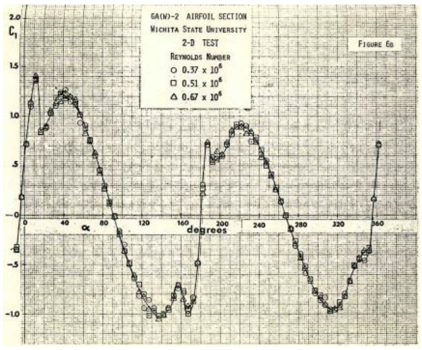


Fig.16. Lift coefficients of GA(W)-2 airfoil versus the angle of attack (Source: Satran and Snyder [14])

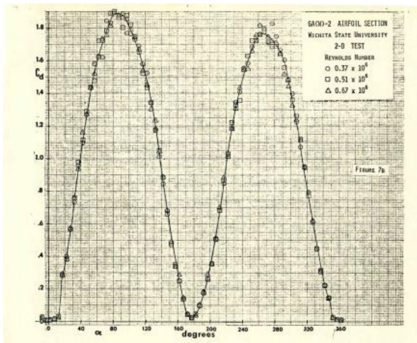
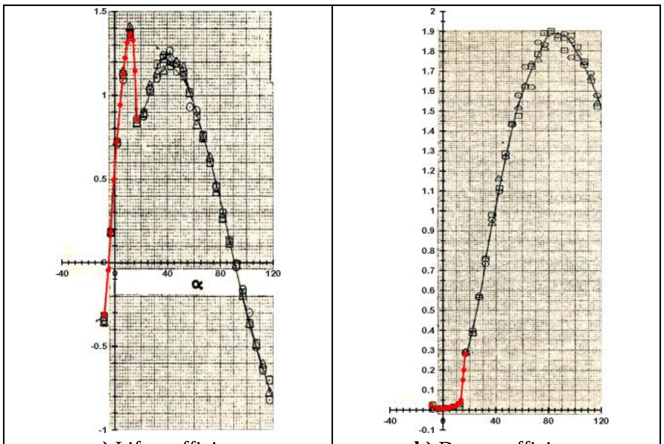


Fig.17. Drag coefficients of GA(W)-2 airfoil versus the angle of attack (Source: Satran and Snyder [14])

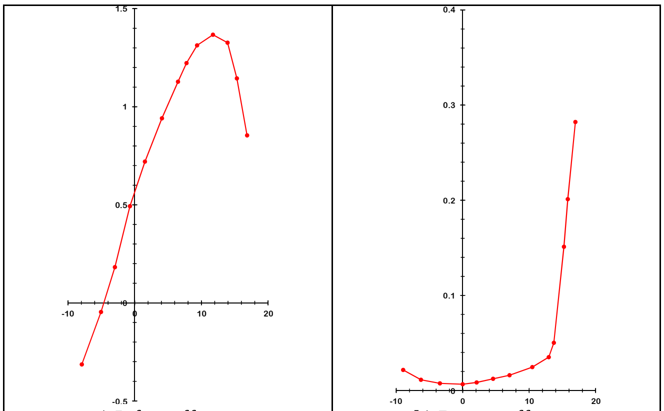
Satran and Snyder [14] did not provide any tabulated numerical results. In order to read numerical values from their [14] lift and drag coefficient graphs given in Figure 16 and 17, we used a freeware digitizer software (Engauge Digitizer

[15]). We note that we choose this airfoil as an example because the results of Satran and Snyder [14] includes both the pre-stall and post-stall regimes. We use only the pre-stall lift and drag data digitized from the figures of Satran and Snyder [14] in order to set the AERODAS model parameters. We, then, calculate the AERODAS model lift and drag coefficients for a wide angle of attack range. We use the post-stall lift and drag coefficients measured by Satran and Snyder [14] to compare the lift and drag predictions of the AERODAS model. Figure 18 shows the digitized points from the figures of Satran and Snyder [14]. Figure 19 shows the same digitized points alone in a different scale. In the AERODAS.xls spreadsheet tool we used the data shown in Figure 19 as an input for the calculations.



a) Lift coefficient **b)** Drag coefficient

Fig.18. Digitizing the results of Satran and Snyder [14]



a) Lift coefficient **b)** Drag coefficient

Fig.19. The lift and drag coefficients used in AERODAS calculations

As seen in Figure 19-a the lift coefficient of GA(W)-2 airfoil has a smooth curvature around the peak value and there is a clear definite peak value. For this reason, for this airfoil we used the "Use original data" option in the AERODAS.xls spreadsheet tool and Figure 20 shows the graph panel for the GA(W)-2 airfoil calculations.

Our calculated AERODAS model parameters for the GA(W)-2 airfoil is given in Table 4. Figure 21 shows the lift and drag coefficient predictions of the AERODAS model for GA(W)-2 airfoil together with the digitized experimental results of Satran and Snyder [14]. As seen in Figure 21, except the predictions of drag coefficient in a small region around 90° angle of attack only, the agreement is very good with the experimental results. Again, the prediction of the AERODAS model is again quite impressive

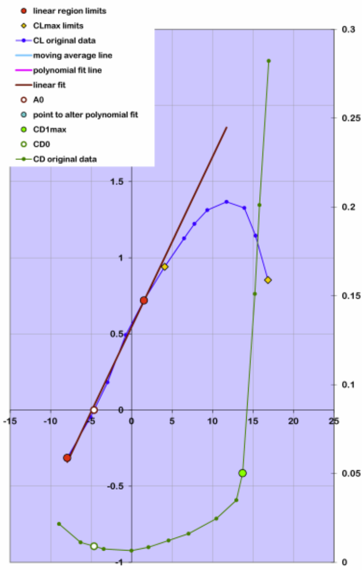
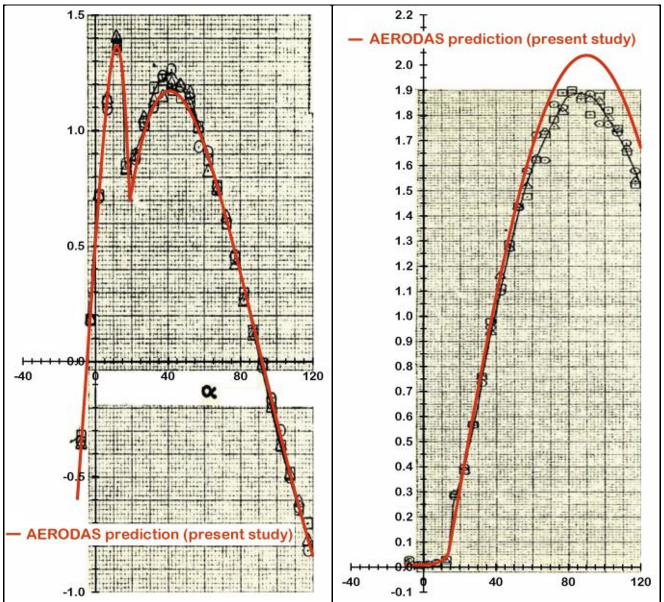


Fig.20. The "Control Graph" panel in AERODAS.xls spreadsheet tool for GA(W)-2 airfoil calculations



a) Lift coefficient **b)** Drag coefficient

Fig.21. Comparison of GA(W)-2 airfoil polars

Table 4. AERODAS model parameters for GA(W)-2 airfoil
(Nomenclature is given in Table 1)

AERODAS LIFT AND DRAG MODEL	
AR =	infinite
t/c =	0.15
Pre-stall Parameters	
CL1max =	1.0716
ACL1 =	13
S1 =	0.1151
A0 =	-1.4691
RCL1 =	0.5941
CD1max =	0.1969
ACD1 =	20
N1 =	2.8035
CD0 =	0.0077
M =	3.2
Post-stall Parameters	
CL2max =	1.1632
RCL2 =	0.4688
CD2max =	2.0072
N2 =	3.4814

4.2. Tabulate Pre-Stall and Post-Stall Characteristics

Since the AERODAS model uses empirical equations for calculating the lift and drag coefficients, if one tabulates his/her AERODAS model parameters it would be possible for another one to reconstruct the same lift and drag coefficients. This can help researchers to validate their results. The parameters listed in Table 3 and 4 is enough for someone to reconstruct the AERODAS lift and drag coefficients we present in Figures 13, 14 and 21. Tabulating the AERODAS pre-stall and post-stall parameters is easier than tabulating the whole lift and drag data. AERODAS model offers a convenient way to share the polar results. As to give an example, Spera [5] tabulated the AERODAS parameters he used for NREL SERI S809 airfoil in his simulations of UAE Phase VI blade, as given in Table 5.

Table 5. AERODAS model parameters for NREL SERI S809 airfoil (from Spera [5])

(Nomenclature is given in Table 1)

AERODAS LIFT AND DRAG MODEL			
PARAMETERS FOR NREL SERI S809 AIRFOILS			
Constants for All Airfoils			
ACL2		41.0	
ACL3		92.0	
S2		-0.0320	
ACD2		90.0	
Constants for Specific Airfoil			
Name		S809 Smooth	
AR		10,000	
t/c		21.0	
A0		-1.0	
ACL1'		14.0	
ACD1'		20.1	
S1'		0.155	
CL1max'		1.07	
CD0		0.007	
CD1max'		0.2	
M		3.0	
F1		1.138	
G1		1.922	
Lift/Drag Model Parameters			
	Reference	Test Data	Blade
AR	10,000.00	10,000.00	15.28
1/AR	0.0001	0.0001	0.0654
S1	0.155	0.155	0.125
ACL1	14.0	14.0	15.7
ACD1	20.1	20.1	21.8
CL1max	1.07	1.07	1.047
RCL1	1.254	1.254	1.033
N1	1.85	1.85	2.01
CD1max	0.2	0.2	0.226
CL2max	1.138	1.138	1.036
RCL2	0.494	0.494	0.596
N2	3.3	3.3	2.74
CD2max	1.921	1.921	1.624

The AERODAS.xls spreadsheet tool has "table_input" sheet as shown in Figure 22 in order for easy reconstructing of the lift and drag coefficients using shared AERODAS model parameters. One can use this sheet and reconstruct the lift and drag coefficients used in another study easily.

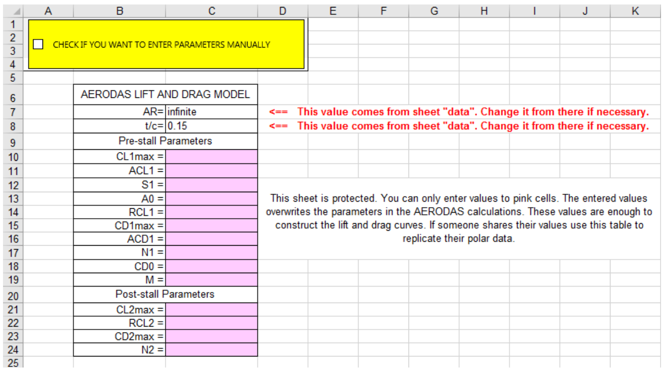


Fig.22. Table input of AERODAS parameters

As an example, using the "table_input" sheet we have reconstructed the NREL SERI S809 airfoil polars used in Spera [5] using his published AERODAS parameters given in Table 5. In Figure 23, coloured circle symbols show the present reconstructed lift and drag coefficients and the black lines show the same used in Spera [5]. Since the same parameters and same equations are used for the lift and drag coefficients, both the present results and the results of Spera [5] are identical as seen in Figure 23. The AERODAS.xls spreadsheet tool with the "table_input" sheet helps researchers to share their lift and drag coefficients easily. In Blade Element Momentum simulations, the polars are used as an input and therefore for this reason the Blade Element Momentum simulation results are very sensitive to the used input polars. In two different studies, even though the same Blade Element Momentum simulation is used, if the polar inputs belonging to a particular airfoil are slightly different in both studies, the simulation results may be very different from each other. This makes the verification process, which is essential for a simulation study, difficult. With the help of AERODAS spreadsheet tool, researchers can share their polars and different studies may use identical inputs which makes the verification of simulation results available and easy.

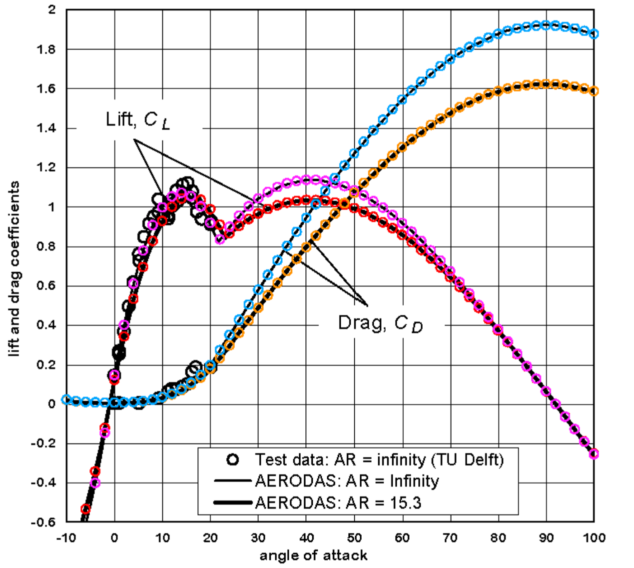


Fig.23. Reconstructed NREL SERI S809 airfoil polars using the AERODAS model parameters published by Spera [5]

In web page of National Renewable Energy Laboratory (NREL) there exist a freeware excel tool (Airfoilprep.xls) for extrapolating the lift and drag coefficients [16]. This tool uses the Viterna method [1] to extrapolate the lift and drag coefficients to full 360-degree. In this tool it is possible to change the maximum drag coefficient according to the aspect ratio of the blade as an option, however the thickness of the chosen airfoil do not have any effect in the calculations. The major difference of AERODAS.xls developed in this study that uses the AERODAS model [5] from Airfoilprep.xls developed in NREL [16] that uses the Viterna method [1] is that the AERODAS model contains explicit adjustments for the effect of aspect ratio on both lift and drag coefficients and also the thickness of the chosen airfoil appears as a variable in the model equations and affects the solution.

5. Conclusions

Wind turbine design and/or analysis projects that includes the Blade Element Momentum simulations are very effective for students to learn aerodynamics, how to design and/or analyse a wind turbine in wind energy related courses. In such a project there are some steps for the students to follow. In some steps the student should do a literature survey or run simulations using a BEM code (preferably written by themselves) depending on the content of the project. For all of the steps that the student should follow there is either a freeware simulation code or there is enough literature for the students to follow without any difficulty. However, depending on the airfoil to be used in the wind turbine rotor chosen by the student, for obtaining the lift and drag coefficients for a wide angle of attack range which are one of the main inputs of a BEM simulation there are not many freeware options to use. The AERODAS model developed by Spera [5] is a very powerful model for predicting the polar coefficients for airfoils. Without having a visual tool, the AERODAS model is not easy to apply since it requires many efforts to use the model. The AERODAS.xls spreadsheet tool developed in this study makes the use of the AERODAS model very easy and effectively as demonstrated. The AERODAS.xls spreadsheet tool developed in this study is freely available for download for students and researchers.

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