SAND2014-20053C

Numerical Simulations of Subscale Wind Turbine Rotor Inboard Airfoils at Low Reynolds Number

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New blade designs are planned to support future research campaigns at the SWiFT facility in Lubbock, Texas. The sub-scale blades will reproduce specific aerodynamic characteristics of utility-scale rotors. Reynolds numbers for megawatt-, utility-scale rotors are generally above 2-8 million. The thickness of inboard airfoils for these large rotors are typically as high as 35-40%. The thickness and the proximity to three-dimensional flow of these airfoils present design and analysis challenges, even at the full scale, but more than a decade of experience with the airfoils in numerical simulation, in the wind tunnel, and in the field has generated confidence in their performance. When used on a sub-scale rotor, Reynolds number regimes are significantly lower for the inboard blade, ranging from 0.7 to 1 million. Performance of the thick airfoils in this regime is uncertain because of the lack of wind tunnel data and the inherent challenge associated with associated numerical simulations. This report documents efforts to determine the most capable analysis tools to support these simulations and to improve understanding of the aerodynamic properties of thick airfoils in this Reynolds number regime. Numerical results from various codes of four airfoils are verified against previously published wind tunnel results where data at those Reynolds numbers are available. Results are then computed for other Reynolds numbers of interest.

Nomenclature

α	=	angle of attack
C_D	=	drag coefficient
C_L	=	lift coefficient
C_M	=	pitching moment coefficient
C_P	=	pressure coefficient
c	=	chord
CFD	=	computational fluid dynamics
DOE	=	Department of Energy
DT	=	time step
Ma	=	Mach number
NRT	=	National Rotor Testbed
RANS	=	Reynolds Averaged Navier-Stokes
Re	=	Reynolds number based on chord length
SNL	=	Sandia National Laboratories
SWiFT	=	Scaled Wind Farm Technology

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I. Introduction

SANDIA National Laboratories (SNL) and The U.S. Department of Energy (DOE) are designing a modern, research-quality wind turbine rotor for use at the new Scaled Wind Farm Technology (SWiFT) site at Texas Tech University in Lubbock, Texas. Designated as the National Rotor Testbed (NRT)[1], the new rotor will be a public resource used to accelerate important rotor innovation and to conduct complex flow and turbine-to-turbine interaction research that will increase the efficiency of wind power plants and lower the cost of electricity. The blades are expected to provide a publicly available baseline blade design which will enable increased participation in future blade research as well as accelerated hardware manufacturing and testing for demonstration of innovation.

The SWiFT facility is unique in that it utilizes wind turbines that are large enough to represent the physics relevant to utility-scale machines, yet small enough to be extremely cost effective when compared to the megawatt scale counterparts. It features 1980s-era heavily modified[1] Vestas V27 225-kilowatt turbines with 27-meter (m) diameter rotors. Although the aerodynamic and structural technologies used in the original rotors of the V27 enabled a cutting-edge product in their own time, today's modern turbines (with capacity ratings of 1.5 to 3 megawatts and rotor diameters of 70 to 120 m) are able to take advantage of the fruits of an additional 20 plus years of wind turbine rotor technology research. Modern rotors are designed to a new level of optimal aerodynamic and structural efficiency, but they have their own challenges: acoustics, controls, sensing, aerodynamics, and structural dynamics. The goal of the NRT is to provide a greater understanding of these challenges as well as wind plant complex flow issues. It is envisioned that the NRT blades will be primarily used to study two phenomena in the near term: wake deficit recovery as a function of atmospheric conditions and turbine-turbine interaction effects due to wake impingement on a downstream rotor. Findings from turbine-turbine interaction research performed on these machines will be used to guide improvements in overall wind plant efficiency. The subscale nature of the NRT blades at SWiFT will enable high-fidelity measurements and sensing along with accurate simulation of the larger rotors, which is logistically simpler and more cost effective than relying on equivalent megawatt-scale test turbines. After the blades have been manufactured, they will replace the existing rotors on the DOE turbines at SWiFT.

Features of the new NRT blades do not represent the optimal design for a V27 size rotor, but instead are determined by aeroelastic scaling of relevant parameters and design drivers from a representative megawatt-scale rotor. It is important to note that, unlike many scaled tests, Reynolds number is not the parameter that will be kept constant for the rescaling of the NTR blades. Instead it is more relevant to match the circulation of the rotor. The lift curve slope and angle of attack margin are also important.

The thickness of inboard airfoils for these utility scale rotors is typically as high as 35-40%. The thickness and the proximity to three-dimensional flow of these airfoils present design and analysis challenges, even at the full scale. More than a decade of experience with the airfoils in numerical simulation, in the wind tunnel, and in the field has generated confidence in their performance. The DU-series of airfoils is in common use in commercial, utility-scale machines today. This paper looks at four in particular: DU 91-W2-250Mod, DU 97-W2-300Mod, DU 99-W3-350, and DU 99-W3-405. All of these except for the DU 99-W3-405 will be considered in the design of the NRT blades. These airfoils were designed specifically for application on the inboard region of wind turbine blades.

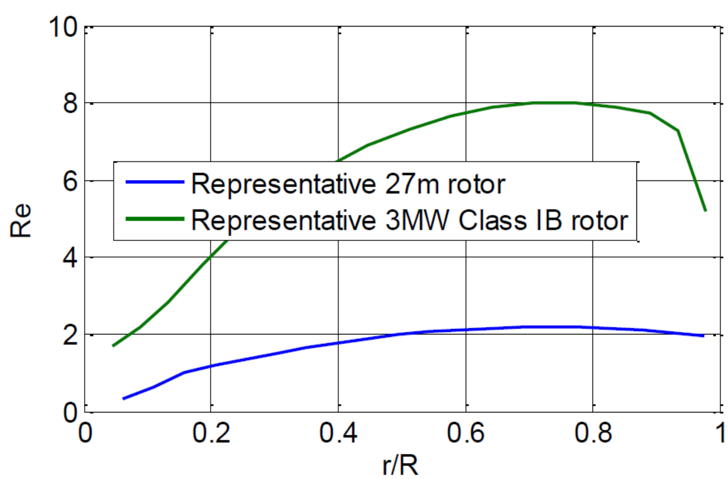

Figure 1. Approximate Reynolds numbers (in millions) along the rotor span for a 3 MW rotor compared to a 225 kW rotor.

Reynolds numbers for megawatt-, utility-scale rotors are generally above 1-2 million, maximum 6-8 million. The range in size of these utility-scale rotors is 80-120 m in diameter. When used on a sub-scale rotor, Reynolds number regimes are significantly lower for the inboard blade. Performance of the thick airfoils in this regime is uncertain because of the lack of wind tunnel data and the inherent challenge associated with associated numerical simulations. Figure 1 shows an example spanwise distribution of Reynolds numbers for a 3 MW rotor operating at rated wind speed compared to an example spanwise distribution of Reynolds numbers for a 27m, 225 kW rotor operating at rated wind speed.

There are several challenges to the design of the scaled blades. Because Reynolds numbers in the range of 500,000-1,000,000 are below the normal operating range of these DU airfoils, few wind tunnel tests and simulations have been done in this regime. At low Mach numbers simulations of the Navier-Stokes equations become more stiff. This requires greater time for convergence or scaling of the eigenvalues. The thick airfoils at higher angles of attack produce significant laminar separation bubbles on both the upper and lower surface[2]. This more detached flow also causes more eddies and time dependent flow features. In these cases, Unsteady Reynolds average Navier-Stokes (URANS) is more appropriate than Reynolds average Navier-Stokes (RANS).

For this paper a variety of simulation tools are explored in order to find the best method of producing accurate results, first in 2D and also looking ahead to the next step which will be 3D simulations. The simulation results will improve understanding of the aerodynamic properties of thick airfoils in this Reynolds number regime. The integrated boundary layer panel method code RFOIL as well as a Reynolds average Navier-Stokes computational fluid dynamics (CFD) code, Overflow, will be compared to experimental data for Reynolds numbers where data is available. The results for the lower Reynolds numbers of interest will be shown for all cases, even when wind tunnel data is not available.

II. Approach

While it is the goal of this project to use airfoils with reliable wind tunnel data whenever possible, it is probably that this might not always be the case. One example would be looking at transition airfoils along the blade between two known airfoils. In the absence of wind tunnel tests, capable analysis tools are needed to support simulations that enable improved understanding of the aerodynamic properties of thick airfoils in this Reynolds number regime.

Three thick airfoils designed at TU-Delft specifically for wind turbine blades will be used for the inboard section of the rotor: DU 91-W2-250Mod, DU 97-W-300Mod, and DU99-W3-350. These thick DU airfoils (25-35%) were not designed for low the Reynolds number operation (0.7-1.5M) that will be seen by the NRT scaled rotor, so testing in this regime has been limited. If used improperly, the inboard airfoils on the proposed design could harshly limit aerodynamic performance due to influence of Reynolds number on stall characteristics and maximum lift conditions ($C_{L,max}$). To better understand the effects of low Reynolds numbers without having to run more wind tunnel tests, CFD simulations will be run. With these results we can maximize our confidence in whatever inboard airfoils are chosen such that the performance of the NRT rotor is as predictable as possible. Most of the work has concentrated on DU 97-W-300Mod since there is more experimental data available in the literature for this airfoil. The DU 99-W3-405 airfoil was also modeled and results are shown here for completeness, although it is no longer being considered for use in the NRT blade. Table 1 lists the span location and Reynolds number range for each airfoil.

Table 1. Proposed airfoils for the new NRT blade.

NRT 13.5m			Reynolds number in millions	
Airfoil Thickness	Span Start	Span End	Re Low	Re High
35%	<18%	18%	--	~1.0
30%	18%	35%	0.7-1.0	1.2-1.75
25%	35%	55%	1.0	1.75-1.8
21%	55%	75%	1.0	1.6-1.75
18%	75%	99%	0.43-1.0	0.7-1.6

The codes RFOIL and Overflow were used to compute airfoil performance. Suitability of these codes was determined by first comparing their results against previously published wind tunnel data. Next, they are used to compute performance data for the lower Reynolds numbers of interest for the few cases where the wind tunnel data is not available. While RFOIL produces accurate results for lift and drag, it cannot be used for future 3D simulations. RANS results are compared with RFOIL at the lower Reynolds numbers which do not have experimental data as an extra check on the CFD values.

A. Naming Convention

There are four DU airfoils discussed in this paper with thicknesses of: 25, 30, 35, and 40%. This section explains the naming convention used for these airfoils in the rest of the paper. The naming conventions were requested by the designer of the original airfoils[3]. Table 2 lays out the naming convention used here compared with other published works[4-7] as well as which experimental data is available.

Table 2. DU Airfoil Map

Naming in This Report	DOWEC	Wind Tunnel Papers	Available Wind Tunnel Data (Re ×10^6)
DU 91-W2-250		DU 91-W2-250	0.7, 1, 1.5,2,3
DU 91-W2-250Mod	DU 91-W2-250.LM		7
DU 97-W-300		DU 97-W-300	0.7,1,2,2.5,3
DU 97-W2-300Mod	DU 97-W-300.LM	DU 97-W-300Mod	7
DU 99-W-350		DU 99-W-350	3
DU 99-W3-350	Adjusted DU 35		7
DU 00-W-401		DU 00-W-401	3
DU 99-W3-405	Adjusted DU4050		7

For the 25% thick airfoil, the DU 91-W2-250Mod airfoil was used. This is the same as the "DU 91-W2-250.lm" found in the file "DOWEC-NREL-5MW blade airfoil data-v2.xls" that was made available on the NREL forum site: https://wind.nrel.gov/forum/wind/viewtopic.php?f=2&t=440. The spreadsheet gives details of the airfoil used in the DOWEC offshore wind turbine research project [4] which was also the bases for the NREL 5MW offshore reference wind turbine design. The 'LM' versions were modified during the design of the blades for the DOWEC study to have thinner aft sections of the airfoils. There is also published wind tunnel data for the DU 91-W2-250 airfoil. The two airfoils are very similar, so the simulation results from the DU 91-W2-250Mod will also be compared to the DU 91-W2-250 wind tunnel data.

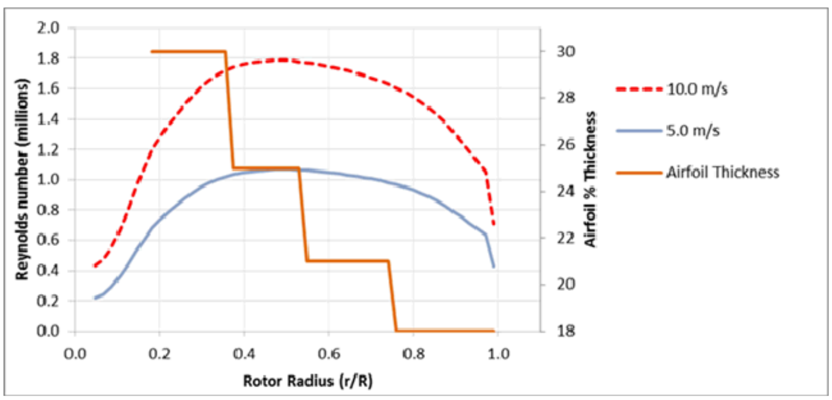

Figure 2. NRT 13.5m Reynolds number operating range and Airfoil Thickness for incoming wind velocities of 5 and 10 m/s.

For the 30% thick airfoil we will be using the DU 97-W-300Mod. This is the same airfoil as the "DU 97-W-300.lm" found in the DOWEC report[4]. The DU 97-W-300Mod was tested at multiple Reynolds numbers, between 1 million and 10 million, in the cryogenic wind tunnel of the DNW in Cologne, Germany[8]. This data has been published down to a Reynolds number of 2.9 million. For lower Reynolds numbers, the wind tunnel data for the DU 97-W-300 has been used for comparison. Again, the two airfoils are quite similar, so the simulation data from DU 97-W-300Mod will be compared to wind tunnel results from both.

For the 35% thick airfoil we will be using the DU 99-W3-350. This is the same as the "Adjusted DU 35" in the DOWEC report[4]. There is also published data for DU 00-W-350, however, the airfoils are different enough that the results from the simulations should not be cross compared. This airfoil might be used for span locations less than 18%.

For the 40% thick airfoil we will be using the DU 99-W3-405. This is the same as the "Adjusted DU4050" from the DOWEC report[4]. There is also published data for DU00-W-401, but again the airfoils are different enough to prevent simulation comparisons. It was decided to not use the DU 99-W3-405 airfoil on the new NRT blade after the investigation using RFOIL revealed its limited performance at low Reynolds numbers of the NRT usable range. It is still in this paper for completeness.

B. Published Wind Tunnel Data

There are published experimental data sets for the DU 97-W-300Mod at Re = 7 million[4] and for the DU 97-W-300 at Re = 1[6], 2[6, 7], 2.5[7], and 3 million[6, 7]. Re = 0.7 million data for DU 97-W-300 was also made available to us through personal correspondence with W.A. Timmer[3]. The DU 91-W2-250Mod has published data at Re = 7 million[4] and the DU 91-W2-250 has available data at Re = 1.5[7], 2[6], and 3[6, 7] million. Re = 0.7, and 1 million data for DU 91-W2-250 was also made available to us through personal correspondence with W.A. Timmer[3]. There is wind tunnel data for DU 99-W3-350 at Re = 7 million[4] and for DU00-W-350 at Re = 3 million[7]. There is wind tunnel data for the DU 99-W3-405 at Re = 7 million[4] and for DU00-W-401 at Re = 3 million[7].

The wind tunnel tests for these airfoils were run at two locations: the Low-speed Low-turbulence wind tunnel of the Faculty of Aerospace Engineering of Delft University and Laminar Wind Tunnel of the Institut für Aerodynamik und Gasdynmik der Universität Stuttgart. Both of these tunnels have a turbulence level that is less than 0.1%[6, 7]. RFOIL tends to match experimental results better in a low turbulence level wind tunnel like these better than in wind tunnels with a higher turbulence level[7].

These data are used to validate and compare the CFD codes at the Reynolds numbers where data is available. The tools which fit the data the best will be used to predict the forces on the airfoils at the lower Reynolds numbers of interest to the NRT where wind tunnel data is not available.

III. Analysis Tools

The simulations capabilities in this report were chosen for their potential applicability to this unique problem of thick airfoils combined with lower Reynolds number regime. The CFD code Overflow, which was developed by NASA, is compared with the panel code RFOIL to help determine which should be used in the full scale exploration of the SWiFT blade.

A. RFOIL

RFOIL[9] is a modification of the panel code XFOIL[10]. It is widely used for airfoil design, and has an incredibly quick turnaround time for producing output such as lift, drag, pitching moment, and pressure profiles. The modifications incorporate effects from rotating blades such as the Coriolis force and centrifugal force as well as cross flow velocity profiles. Despite these enhancements which do increase the accuracy for inboard airfoils, for our full blade design investigation we will most likely need to use a fully 3D CFD code in order to fully understand the important inboard 3D effects as well as any flow anomalies that occur when transitioning from one airfoil to the next along the span of the blade. RFOIL is still critical for providing validation of the CFD codes for scenarios that do not have wind tunnel data as well as providing transition locations on the airfoils that are needed for more accurate RANS calculations.

B. Overflow

The second set of software tested was the unsteady RANS flow solver Overflow[11-13]. The cases were run with a laminar flow in a specified region at the leading edge of the airfoil and then switched to fully turbulent using the Menter's SST *k-ω* turbulence model[14] at a specified location. The simulations were performed with second order time accuracy and dual time stepping. The force and moment coefficients were calculated using the FOMOCO utilities[15].

The meshes were created using Chimera Grid Tools[16-18]. They are all a C-grid which extends 30 chord lengths from the airfoil. For the DU 97-W-300Mod airfoil, there are 445,000 nodes with 637 around the airfoil, 96 in the wake, and 179

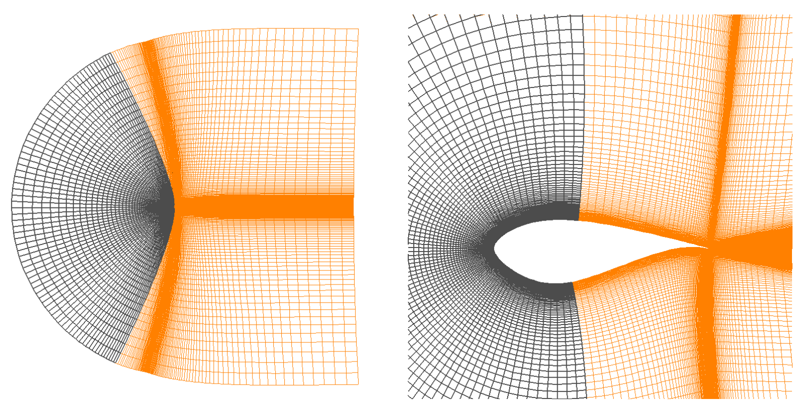

Figure 3. The Overflow grid for DU 97-W-300Mod created with Chimera Grid Tools. The gray region indicates where the production terms are turned off.

normal to the airfoil. The other airfoils have similar meshes. Overflow runs with 3 identical planes of the 2D grid. To trip the flow from laminar to turbulent, turbulence production terms in the gray region of Figure 3 are turned off so the transition to turbulence occurs where the turbulence terms are activated in the orange section. The trip locations are calculated with RFOIL.

IV. Simulation Results for 30% Thick Airfoil

The airfoils used for the simulations were: DU97-W-300Mod, DU 91-W2-250Mod, DU 99-W3-350, and DU 99-W3-405. These are the same airfoils used for the wind tunnel tests with Re = 7 × 10^6, but are different from the lower Reynolds number tests. The airfoils considered in the calculations are the ones which will be considered for the design of the new NRT blade. The following four sections will present the wind tunnel data and simulation results for each of the airfoils, starting with the DU97-W-300Mod here.

A. RFOIL

RFOIL[9] was used to produce results with various parameters that correspond with wind tunnel tests and other values of interest. The Mach number for the wind tunnel tests ranged from Ma = 0.05 to Ma = 0.213 (from reported velocities of 25 m/s to 75 m/s[6]). Assuming all else was held constant, this means that the Mach numbers are Ma = 0.05, 0.071, 0.1065, 0.142, 0.213 for Reynolds numbers of Re = 0.7, 1, 1.5, 2, and 3 million, respectively. Viscosity is on for all cases, and the turbulence amplification factor is set to an Ncrit = 9.0.

The pitching moment calculated by RFOIL for the DU97-W-300Mod is shown in Figure 4. The lift coefficient is plotted against both the drag coefficient and the angle of attack in Figure 5.

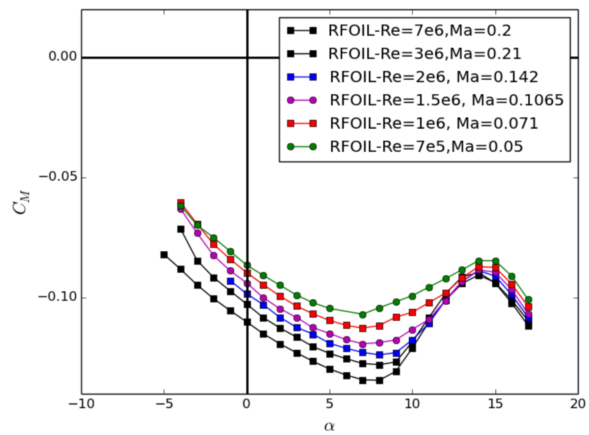

Figure 4. Pitching moment RFOIL results for DU 97-W-300Mod produced with Reynolds numbers ranging from 7 million to 0.7 million

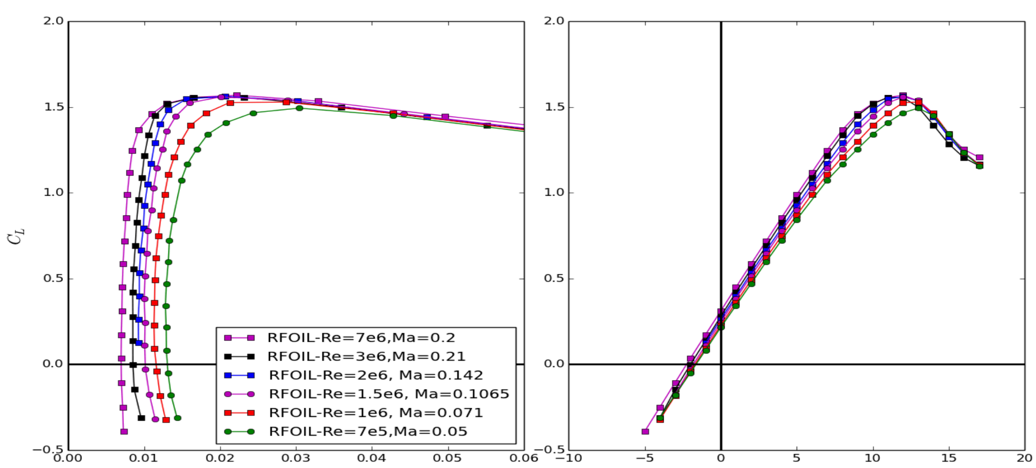

Figure 5. RFOIL results of lift versus drag and angle of attack for DU 97-W-300Mod produced with Reynolds numbers ranging from 0.7 million to 7 million

B. Overflow

Overflow was first run for the DU97-W-300Mod airfoil using the fully turbulent Menter's SST *k-ω* turbulence model throughout the domain. However, this produced results which had consistently lower lift over the full range of angles of attack. Barone and Berg saw similar results with this airfoil[19] using the Spalart-Allmaras and *k-ω* turbulence models, and were able to match the experimental results only by tripping the flow from laminar to turbulent at the separation location predicted by XFOIL. When the boundary layer remains laminar near the leading edge, a large suction (negative C_P) peak develops that increases lift. Immediate development of a turbulent boundary layer, as seen in the Overflow results in Figure 7, will prevent this peak from developing and lift will be under-predicted. Overflow has the option of turning off the turbulence production terms in specified regions of the flow. This simulates the flow transitioning from laminar to turbulent flow at given location along the airfoil, allowing the flow to be "tripped" in the simulation. If this method is not used, the flow becomes turbulent sooner than is seen in the experimental results, and results in a lower value for the lift. Figure 6 shows Overflow results of the Mach number in the flow field for two different angles of attack.

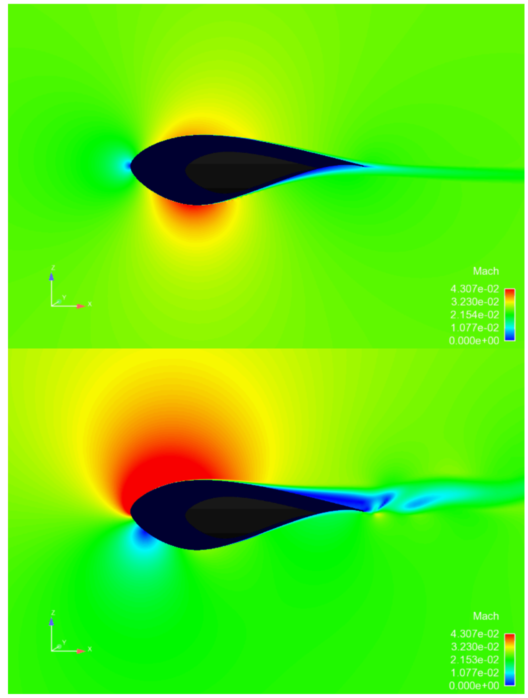

Figure 6. Mach number from Overflow for the DU 97-W-300Mod airfoil at Re = 0.7 million for α = -2° (top) and α = 16° (bottom).

As can be seen in Figure 7, the simulations where the boundary layer is tripped match well with the experimental data[6] up to stall, while the cases without the specified transition location under predicts the lift and over predicts the drag. RFOIL results both with and without zig-zag tape are also shown for comparison. The zig-zag tap would force the flow to trip farther forward, matching the case where the transition location is not specified in Overflow. The Overflow transition locations for both the upper and lower surface of the airfoil are taken from RFOIL runs with matching Reynolds number and angle of attack.

The Mach number was set to match the experimental setup ranging from Ma = 0.071 to Ma = 0.21 depending upon the Reynolds number. For the cases in which Re = 0.7 million, convergence was reached only when they were run in time accurate mode. This is indicated in figure legends as "OFTA". Figure 8 shows the pitching moment for the range of Reynolds numbers. Figure 9 presents the Overflow lift and drag results.

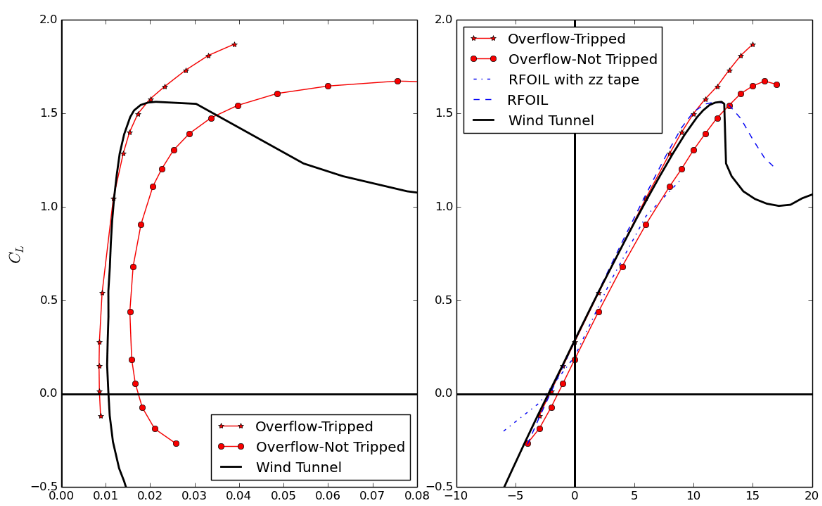

Figure 7. Overflow lift versus drag and angle of attck for Re = 3 million with tripped boundary layer (red stars) and the non-tripped data (red circles) and RFOIL results with and without zig-zag tape (blue), both using DU97-W-300Mod, compared to experimental (solid black) data using DU97-W-300.

C. Compiled Results

In order for a direct comparison, lift curves, drag polars, and pitching moments from all codes are plotted alongside the wind tunnel results. Experimental data at lower Reynold numbers are only available for the DU 97-W-300 instead of the DU 97-W-300Mod. However the two versions of the airfoil are similar enough that the simulation data of the DU 97-W-300Mod can be compared to the DU 97-W-300.

It has been found that RFOIL results consistently underpredict drag by 9% and that multiplying the drag results by a factor of 1.09 will improve the accuracy[5]. This is consistent with what was found in this

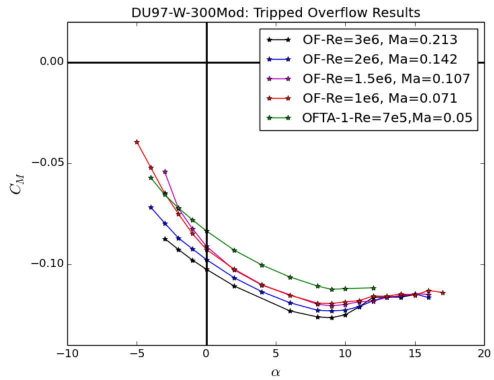

Figure 8. Overflow lift curves and drag polars for the DU 97-W-300Mod airfoil for Re = 3, 2, 1.5, 1 and 0.7 million. The Mach number is varied for each Reynolds number.

study as well. Figure 10 and Figure 12 compare both the corrected and uncorrected RFOIL drag values to the wind tunnel data as well as the Overflow results. For the higher Reynolds number (Re = 3×10^6) the Overflow drag values still match the experimental data better than RFOIL. However for the lower Reynolds number (Re = 1×10^6), the corrected RFOIL data are closer to the wind tunnel results.

The lift to drag ratio comparisons are shown in Figure 12 for DU97-W-300Mod at Re = 3×10^6 and = 1×10^6. For Re = 3×10^6, Overflow with specified transition locations match the wind tunnel[7] maximum C_L/C_D better than RFOIL. For Re = 1×10^6 the RFOIL results are more accurate.

Figure 11, Figure 13, Figure 14, and Figure 15 compare the Overflow and RFOIL data to the experimental data for Reynolds numbers of 0.7, 1, 2, 2.5, 3, and 7 million. For all Reynolds numbers, the results are fairly close, but the Overflow data does a slightly better job of matching the wind tunnel values, up until the angle of attach for which the airfoil reaches stall. The Overflow drag results match fairly well until the stall region, as well. The operating range for the inboard section of the NRT blade will mostly be below stall, so these discrepancies should have a negligible negative effect on design parameters. The RFOIL drag results seem to capture the drag values and shape of the curve quite well; however, for this airfoil Overflow does a better job at matching the experimental C_L/C_{Dmax}. The Overflow and RFOIL data for pitching moment at Re = 3×10^6 both match the experimental values well (Figure 15).

The comparison of simulation results to experimental data show that the most suitable analysis approach is to use a combination of RFOIL and Overflow. Overflow is needed because the results for C_L/C_{Dmax} agree well and it can also be used in the next steps that will use its 3D capabilities. There are also other useful features such as the Langtry-Menter γ-Re_θ transition model [20] that will be tested so that the transition location from RFOIL will not have to be "hard coded" in to the calculations. Because Overflow does a somewhat better at predicting C_L/C_{Dmax}, or at least not over predicting the value, it will be useful to use in conjuncture with RFOIL for blade plan form design. Since Overflow does not capture $C_{L,max}$ well, it will be better to rely on RFOIL for that value.

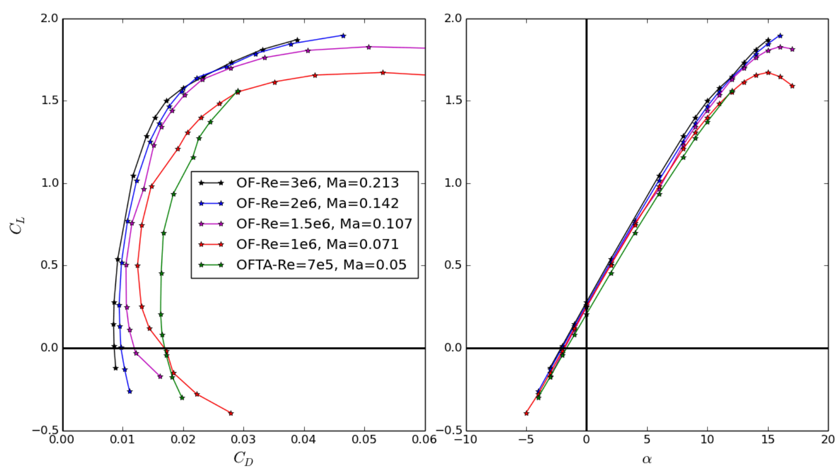

Figure 9. Lift data versus drag and angle of attack for the DU 97-W-300Mod airfoil using Overflow steady state and time accurate (OFTA) runs at Reynolds numbers ranging from 0.7 million to 3 million. All cases were tripped at the appropriate location for that Reynolds number and angle of attack and have Mach numbers that vary with the Reynolds numbers.

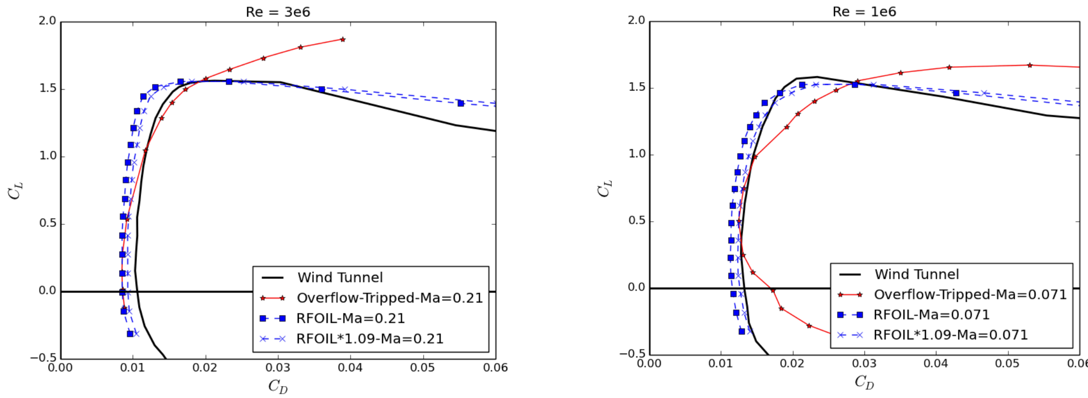

Figure 10. For Re = 3×10^6, RFOIL drag results with and without the correction factor of 1.09 and Overflow results with Ma = 0.21 are compared to wind tunnel values. Right: Comparison of drag results of DU 97-W-300Mod at Re = 1×10^6 from RFOIL, corrected RFOIL, and Overflow to wind tunnel results.

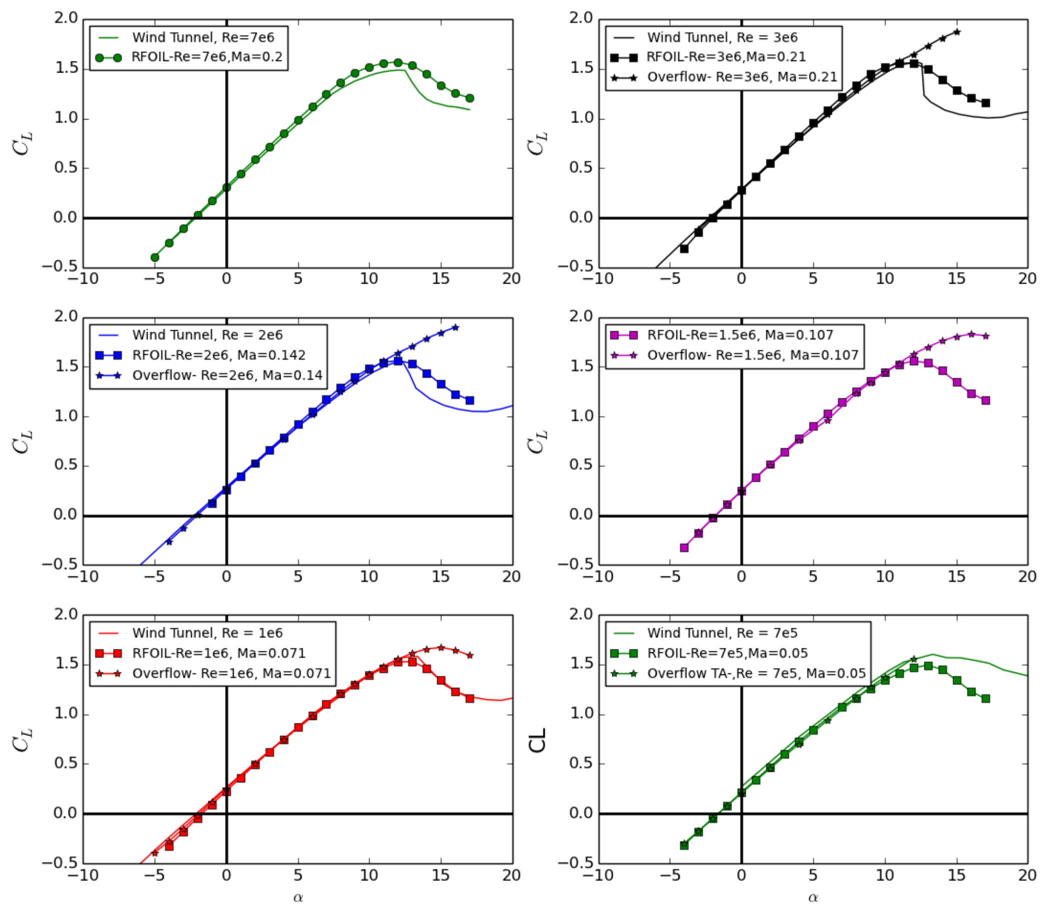

Figure 11. Comparison of the RFOIL and Overflow lift curves to the wind tunnel data for Re = 7 ×10^6, 3 ×10^6, 2 ×10^6, 1.5 ×10^6, 1 ×10^6, and 0.7 ×10^6 for the DU 97-W-300Mod airfoil.

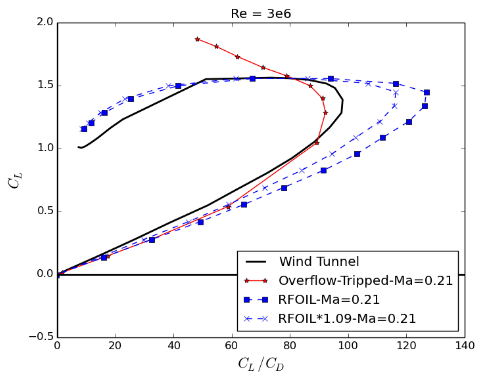

Figure 12. Left: Lift to drag ratio for DU 97-W-300Mod at Re = 3×10^6 for corrected and uncorrected RFOIL and tripped Overflow compared to DU97-W-300 wind tunnel data. Right: Comparison of lift to drag ratios for DU 97-W-300Mod at Re = 1×10^6 from RFOIL, corrected RFOIL, and Overflow to wind tunnel results.

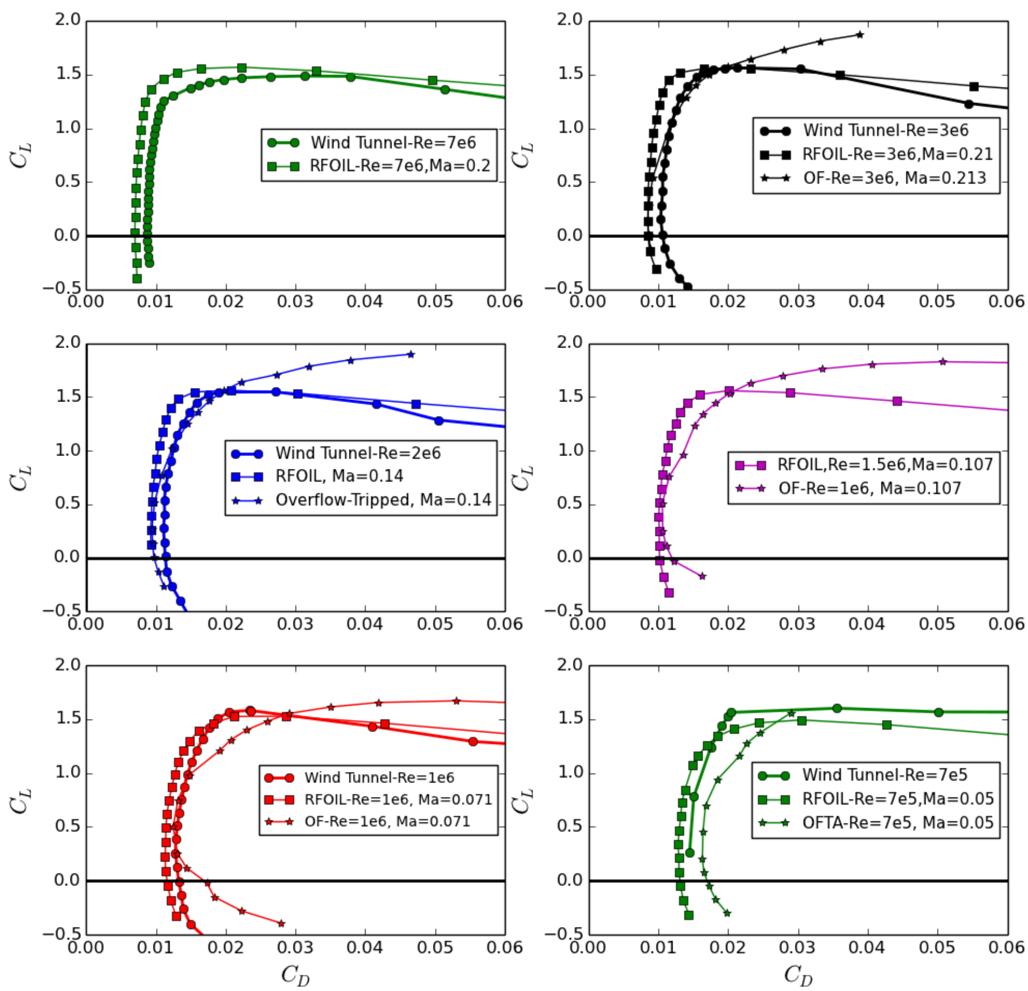

Figure 13. Comparison of the RFOIL and Overflow drag polars to the wind tunnel data for Re = 7 ×10^6, 3 ×10^6, 2 ×10^6, 1.5 ×10^6, 1 ×10^6, and 0.7 ×10^6 for the DU 97-W-300Mod airfoil.

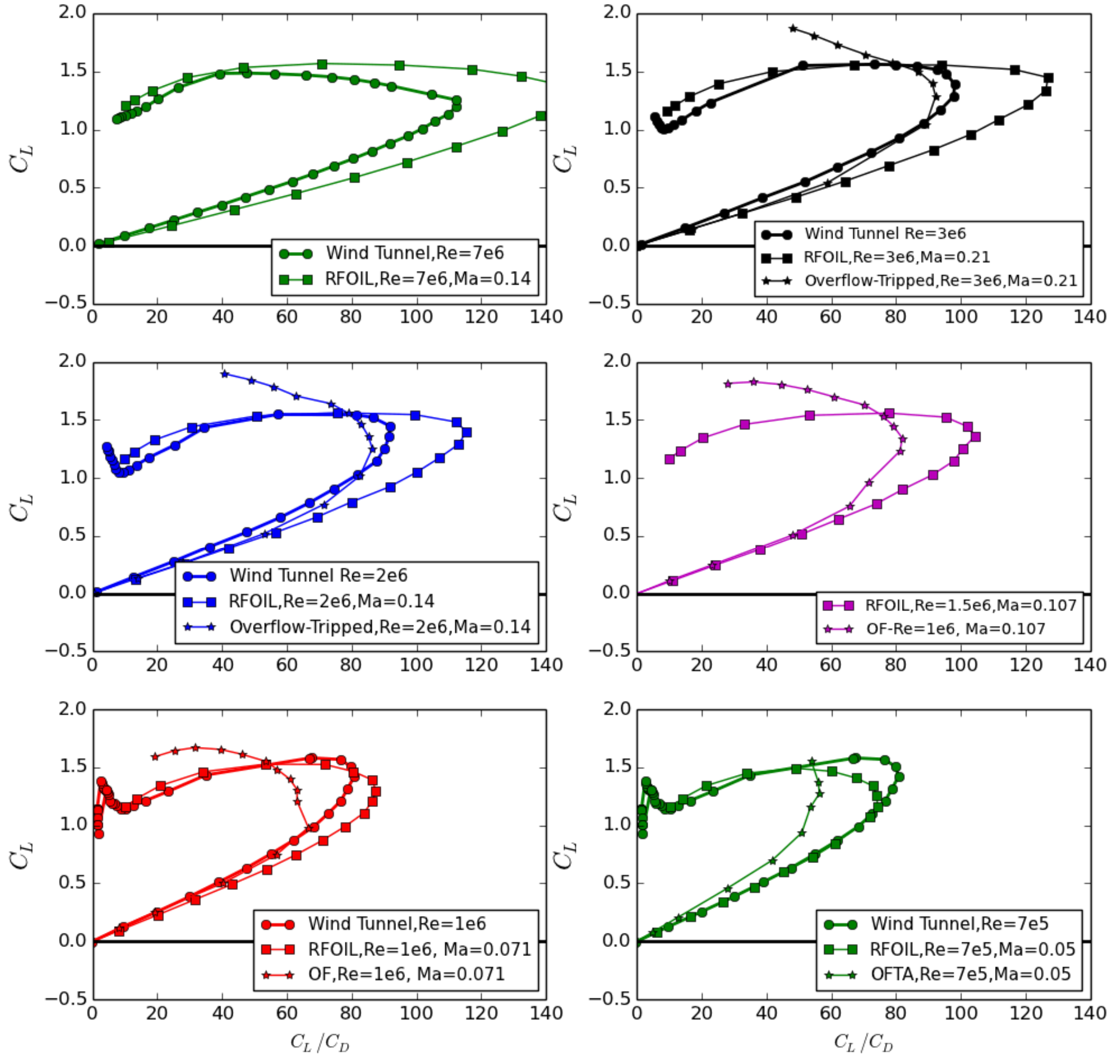

Figure 14. Comparison of the RFOIL and Overflow lift to drag ratios to the wind tunnel data for Re = 7 ×10^6, 3 ×10^6, 2 ×10^6, 1.5 ×10^6, 1 ×10^6, and 0.7 ×10^6 for the DU 97-W-300Mod airfoil.

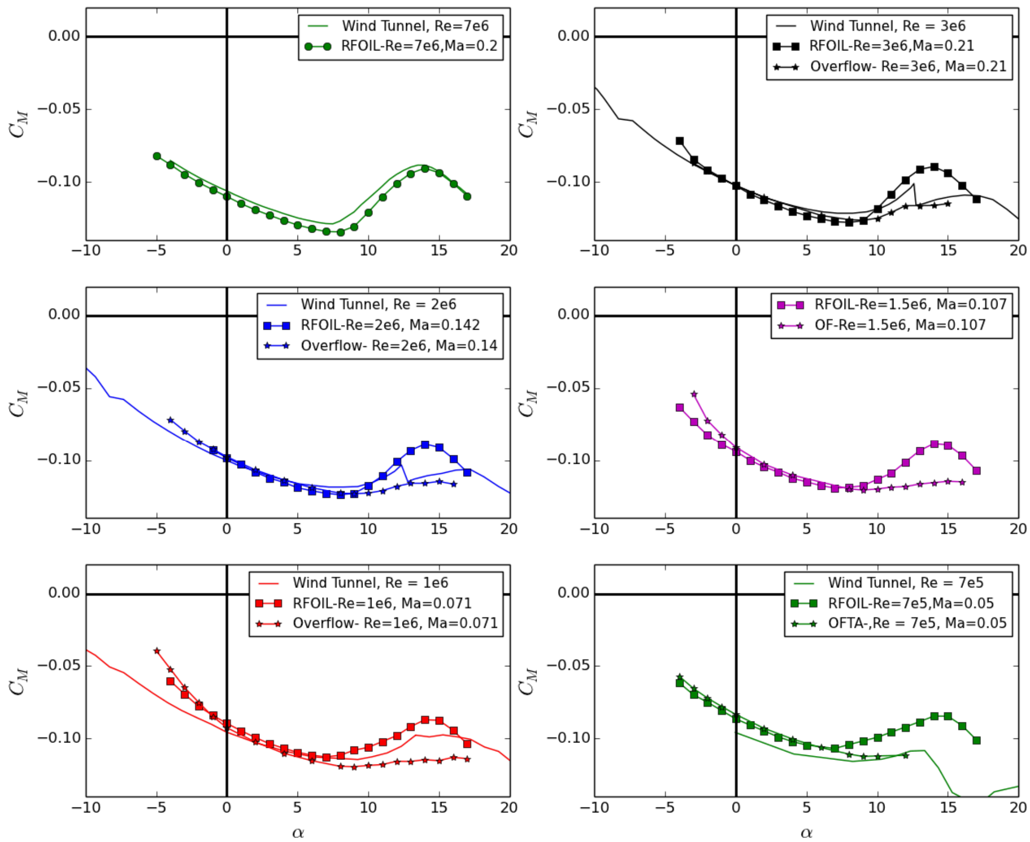

Figure 15. Comparison of Overflow and RFOIL pitching moment to experimental data for DU 97-W-300Mod.

V. Simulation Results for 25% Thick Airfoil

The 25% thick airfoil being considered for the NRT blade is the DU 91-W2-250Mod. This section presents the RFOIL and Overflow results for this airfoil. The Mach number is changed for each Reynolds number for the RFOIL and Overflow calculations.

A. RFOIL

The RFOIL calculations for the DU 91-W2-250Mod airfoil were run in a similar manner to what was done with the DU 97-W-300Mod airfoil. The default of Ncrit = 9 was used, viscosity was turned on, and the Mach number was adjusted for each Reynolds number and are the same as what is used in Section IV. Figure 16 shows the RFOIL pitching moment results, while Figure 17 shows the drag polars and the lift curves.

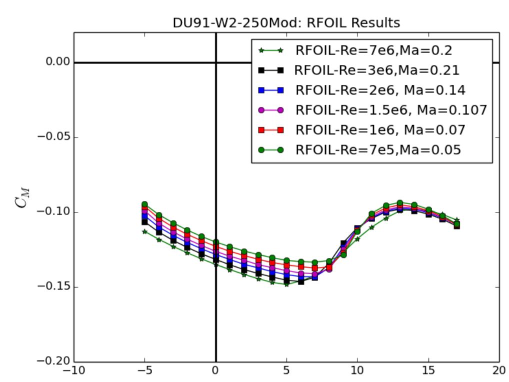

Figure 16. RFOIL DU 91-W2-250Mod pitching moment for a wide range of Reynolds numbers.

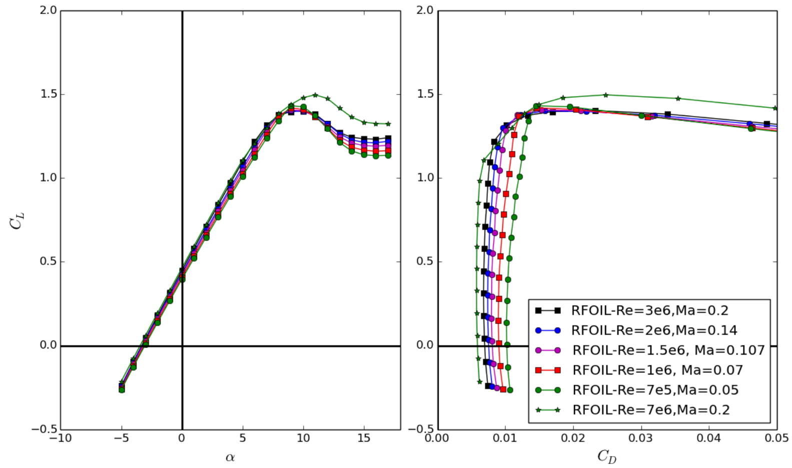

Figure 17. RFOIL DU 91-W2-250Mod lift versus drag and angle of attack for a wide range of Reynolds number values.

B. Overflow

The Overflow c-grid used for the DU 91-W2-250Mod airfoil is very similar to the DU 96-W-300Mod grid. It has 563 nodes around the airfoil and 96 nodes in the wake. There are 179 nodes perpendicular to the airfoil extending 30c away. Spacing near the wall has $y_+ \approx 1$. For the lower Reynolds numbers, Re = 1 and 0.7 million, the solution was not converging correctly so the “time accurate” mode with 12 Newton sub-iterations and a physical time step of DTPHYS = 0.001 was used. The simulations that are run using the time accurate mode are signified by “OFTA” in the figures. The iteration time step was also reduced to DT = 0.001. Figure 18 shows the pitching moment calculated with Overflow, and Figure 19 show the Overflow drag polars and lift curves.

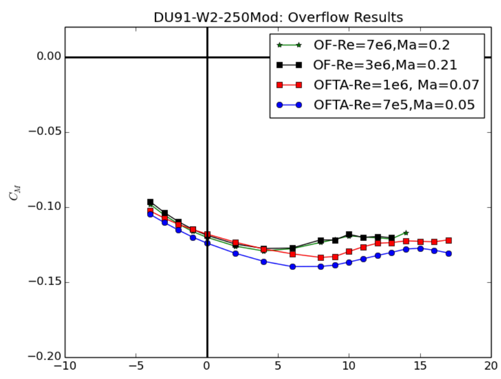

Figure 18. Overflow pitching moment for DU 91-W2-250Mod airfoil. “OFTA” indicates that the time accurate mode was used.

C. Compiled Results

This section shows the results from RFOIL and Overflow compared directly with the wind tunnel data where it is available. For this airfoil there are wind tunnel data available for Re = 7 million[4], million[6], million[6], 1.5 million[7], 1 million[3], and 7 million[3]. The lift curves are show in Figure 20.

As was done with the DU97-W-300Mod airfoil in Section IVC, the RFOIL drag correction factor of 1.09 is compared with RFOIL data without the correction in Figure 21 and Figure 22, Overflow data, and wind tunnel data for both Re = 3×10^6 and 1×10^6. For this thinner airfoil, the correction factor does a much better job at bringing the RFOIL data into alignment with the experiment. For both Reynolds numbers, the corrected results match the wind tunnel data better than both the non-corrected RFOIL and the Overflow data.

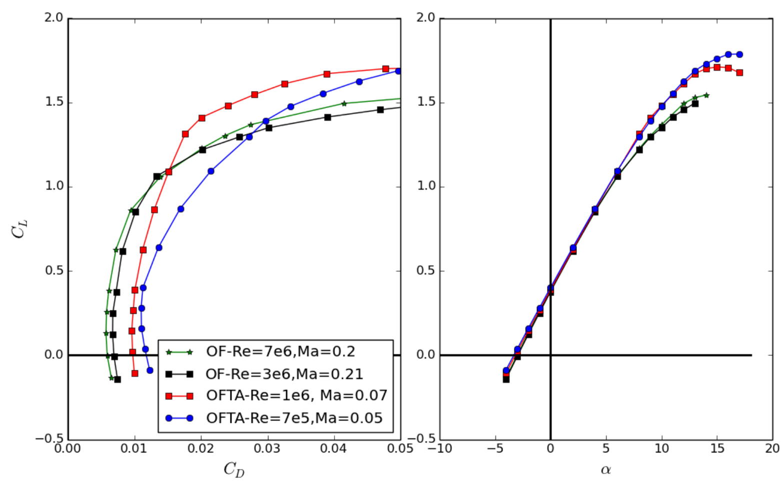

Figure 19. Overflow drag and lift curve data for DU 91-W2-250Mod airfoil at Re ranging from 0.7 to 7 million. “OFTA” indicates that the time accurate mode was used.

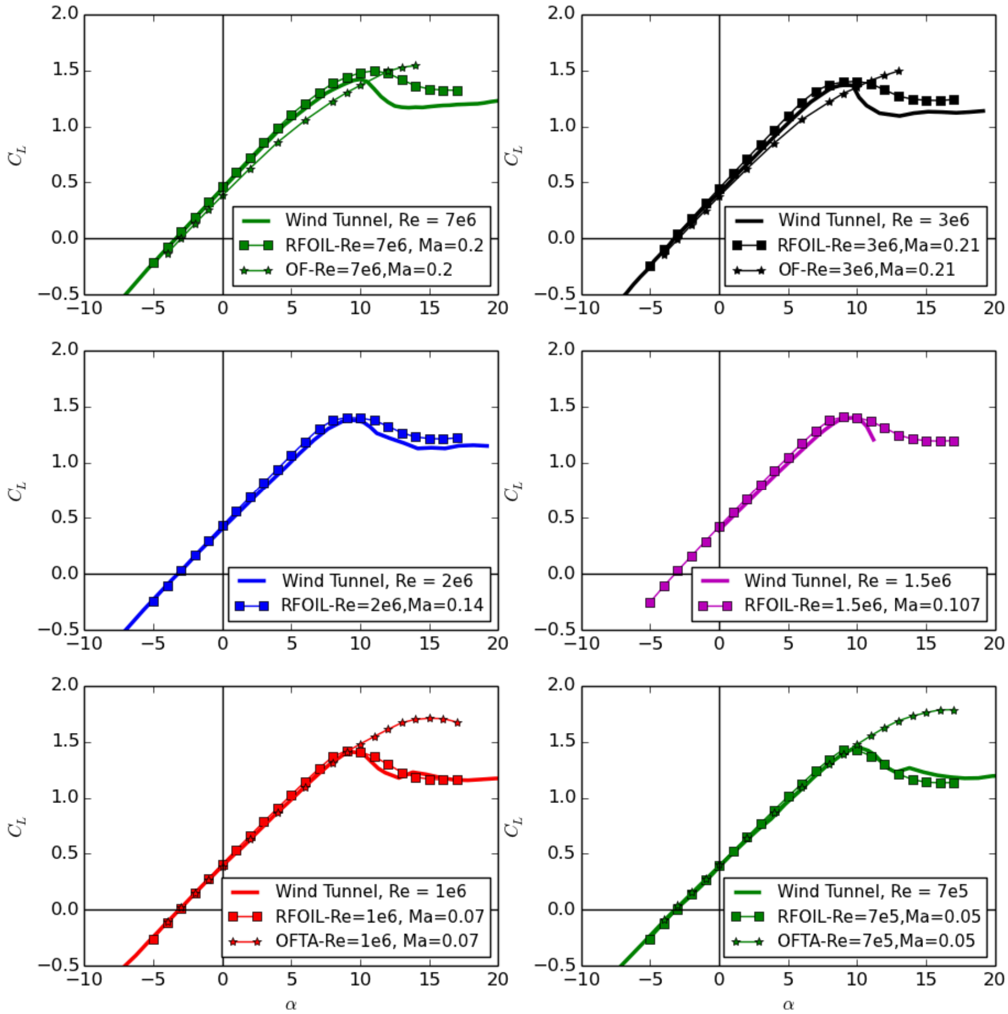

Figure 20. Comparison of RFOIL and Overflow lift curves to the wind tunnel data for the DU 91-W2-250Mod airfoil. "OFTA" indicates that the time accurate mode was used for the Overflow runs.

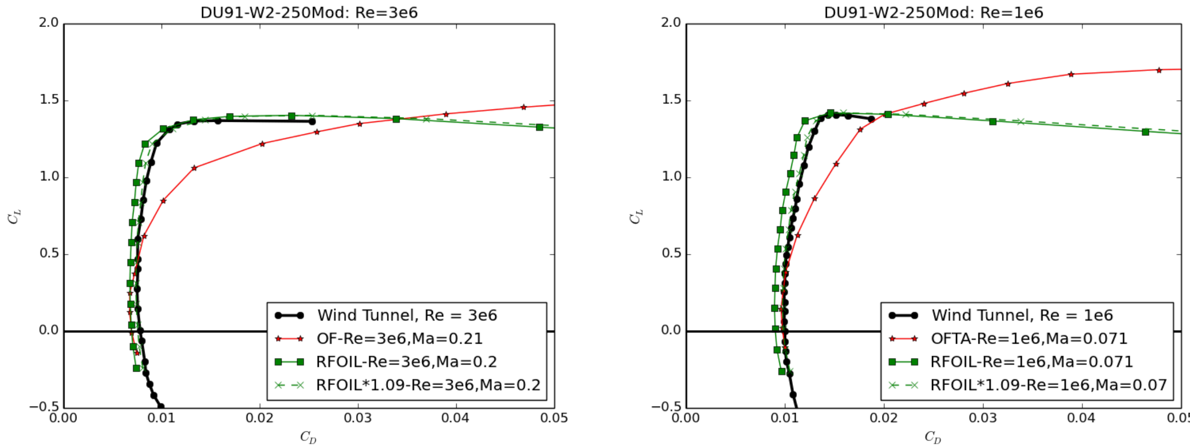

Figure 21. Left: For Re = 3×10⁶, RFOIL drag results with and without the correction factor of 1.09, and Overflow results are compared to wind tunnel data. Right: the same for Re = 1×10⁶. "OFTA" indicates that the time accurate mode was used in Overflow.

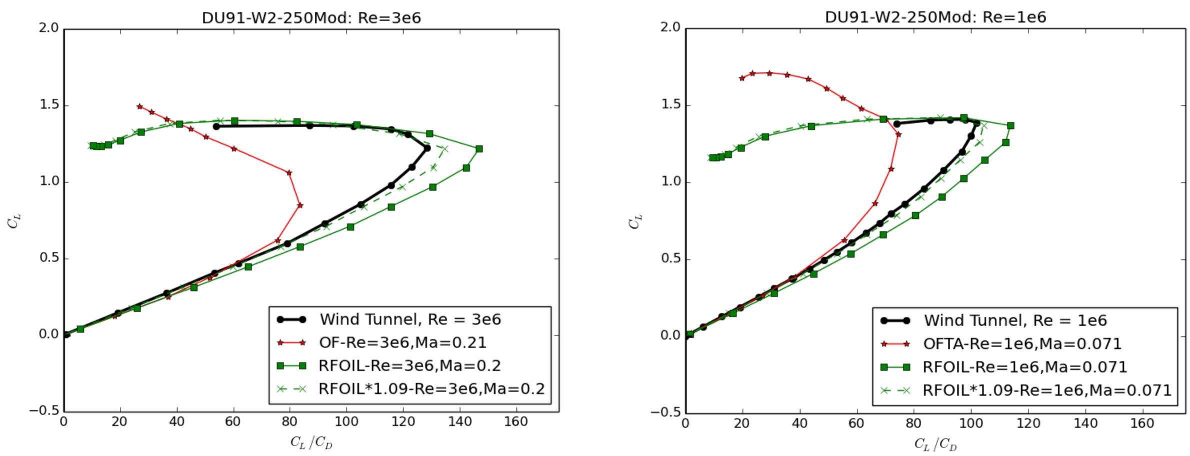

Figure 22. Left: For Re = 3×10⁶, RFOIL lift to drag results with and without the correction factor of 1.09, and Overflow results are compared to wind tunnel data. Right: the same for Re = 1×10⁶. "OFTA" indicates that the time accurate mode was used in Overflow.

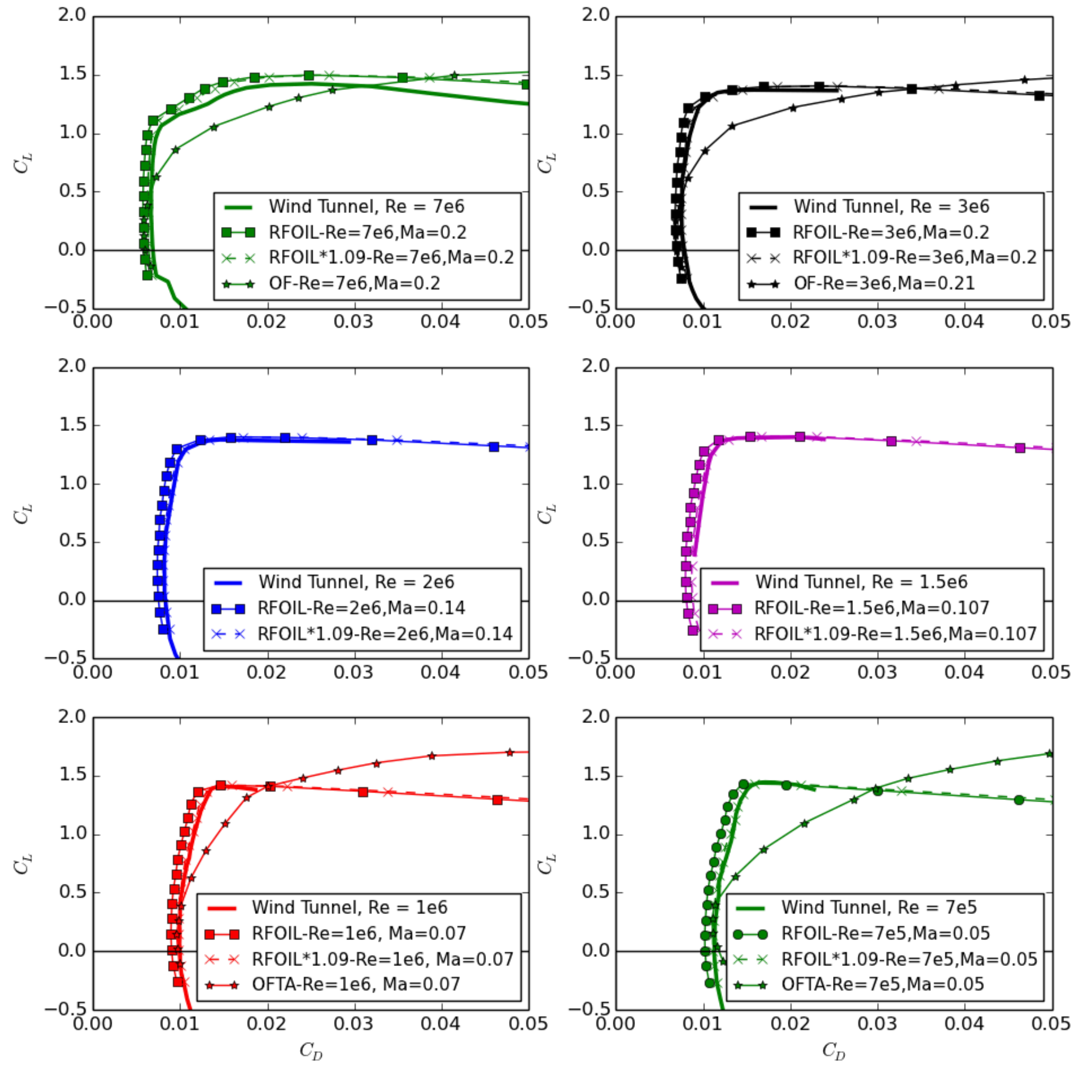

Figure 23. Comparison of RFOIL and Overflow drag polar data to the wind tunnel data for the DU 91-W2-250Mod airfoil. RFOIL results both with and without the 1.09 correction factor are shown. "OFTA" indicates that the time accurate mode was used for Overflow.

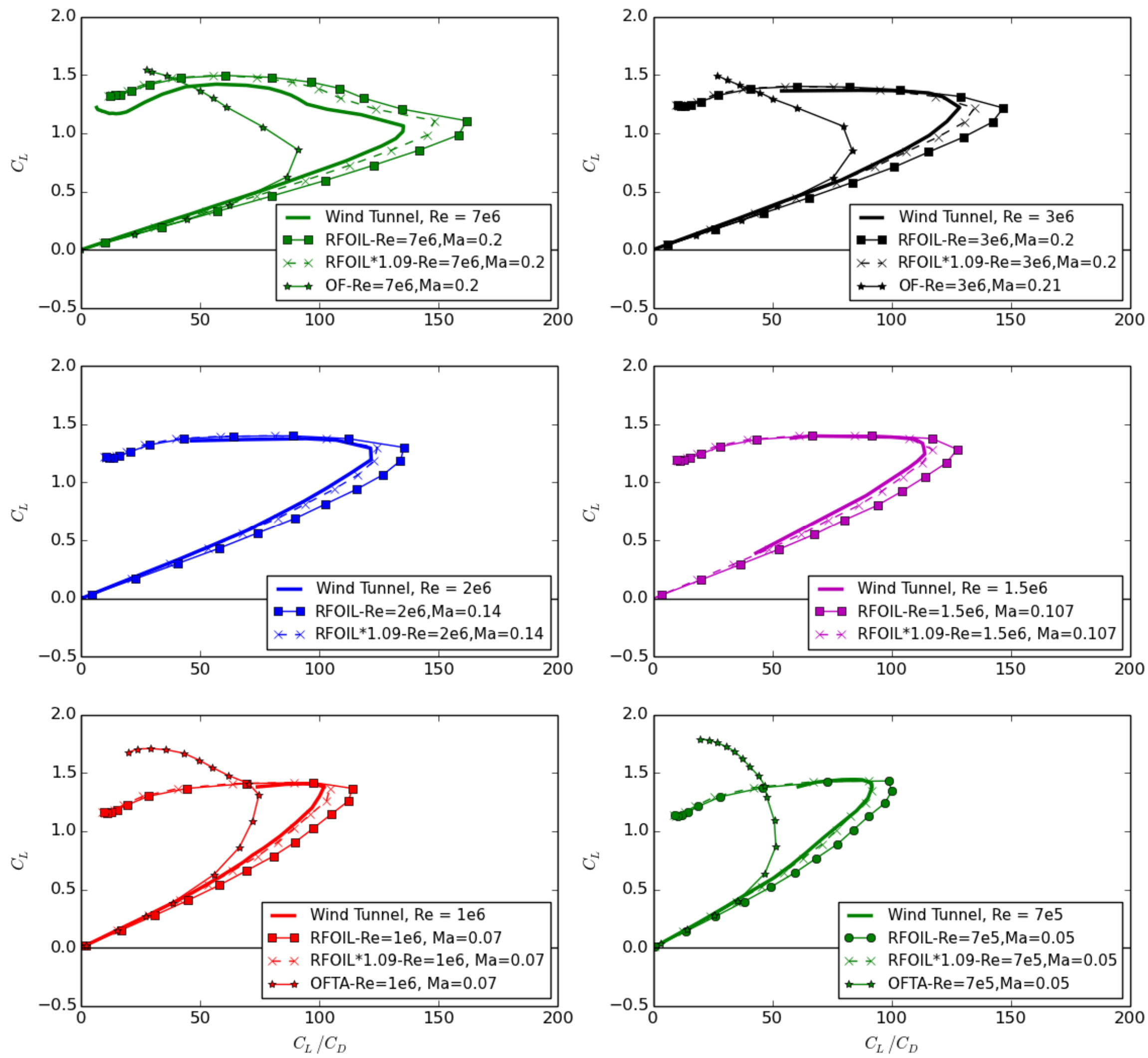

Figure 24. Comparison of RFOIL and Overflow lift to drag ratio to the wind tunnel data for the DU 91-W2-250Mod airfoil. RFOIL results both with and without the 1.09 correction factor are shown. "OFTA" indicates that the time accurate mode was used for Overflow.

For this airfoil, RFOIL does a very good job fitting the wind tunnel data. It matches several key features of the various plots even better than Overflow. The match between the RFOIL drag results with the correction factor and the experimental data is even better than for the DU97-W-300Mod. Like with the DU97-W-300Mod airfoil, RFOIL captures the $C_{L,max}$ of the lift curve more closely (Figure 20). The upper left corner of the "drag bucket" in Figure 21 and Figure 23 is matched very well by RFOIL with the correction factor, but is under predicted by Overflow. This can be seen again in Figure 24 which shows the lift to drag ratio. RFOIL slightly over predicts the $C_l/C_{D,max}$, while Overflow is under predicting it. Thus making, the Overflow results are more conservative, even if they are farther off. Figure 25 shows that both match the pitching moment results fairly well, with RFOIL capturing the shape slightly more accurately.

VI. Simulation Results for 35% Thick Airfoil

For the 35% thick airfoil there is data at Re = 7 × 10^6 for the DU 99-W3-350 airfoil and at Re = 3 × 10^6 for the DU 99-W-350 airfoil. As seen in Figure 26 these two versions of this airfoil are sufficiently different that the simulations of one should not be compared to the wind tunnel experiments of the other. The NRT airfoil would use the DU 99-W3-350[6, 7] version so the Overflow and RFOIL simulations are run with this airfoil.

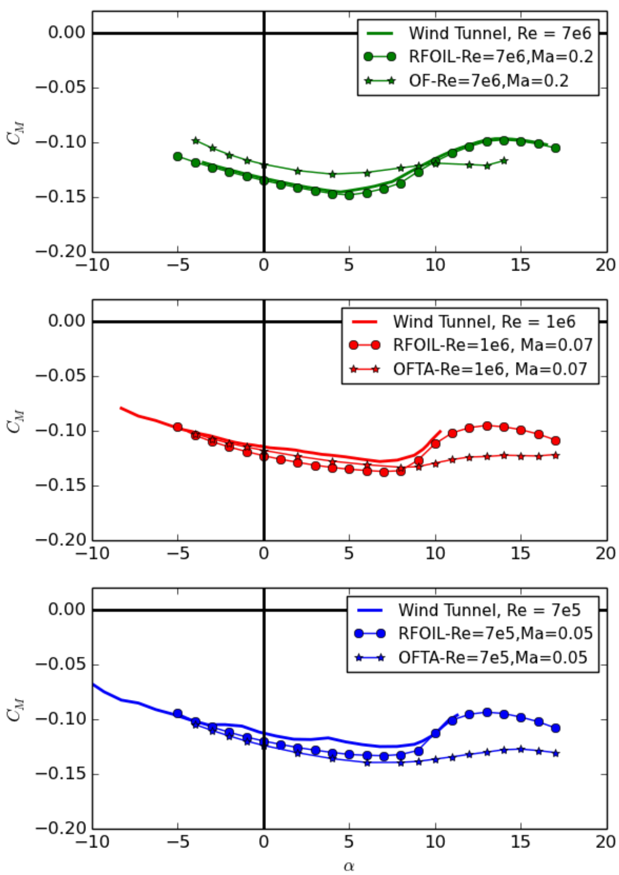

Figure 25. Comparison of RFOIL and Overflow pitching moment to the wind tunnel data for the DU 91-W2-250Mod airfoil. "OFTA" indicates that the time accurate mode was used.

A. RFOIL

Figure 26 shows the comparison of the RFOIL simulations to the wind tunnel data, and Figure 27 shows the RFOIL results for Re = 7 million to 0.7 million.

B. Overflow

Overflow calculations were made using the DU 99-W3-350 airfoil for Re = 7 and 1 million (Figure 28). These were both run in the time accurate mode, since it was expected that this thicker airfoil would have more trouble converging in the steady state mode due to shedding eddies. The mesh is a c-grid which has 560 nodes around the airfoil and 96 nodes in the wake. There are 204 nodes perpendicular to the airfoil extending 30c away. The spacing near the wall is such that $y_+ \approx 1$.

C. Compiled Results

The RFOIL and Overflow results are compared to the wind tunnel data for DU 99-W3-350 at Re = 7 × 10^6, and to each other at Re = 1 × 10^6 in Figure 29. The RFOIL data seems to match the wind tunnel data better for this airfoil than for the thinner ones, although the lift values are slightly higher than they should be.

VII. Simulation Results for 40% Thick Airfoil

Originally, a 40% thick airfoil was going to be used in the new NRT blade design. After this study had been started, it was decided to not use it due to its limited performance at lower Reynolds numbers. The data created before that point is presented here for completeness. Two 40% thick airfoils were considered. The DU 99-W3-405 has available lift and drag wind tunnel data at Re = 7 × 10^6 and the DU 00-W-401 has lift data at Re = 3 × 10^6. RFOIL results for the former are compared to the wind tunnel data in Figure 30, and Figure 31 shows the RFOIL lift versus drag and angle of attack for Re = 0.7 million to Re = 7 million.

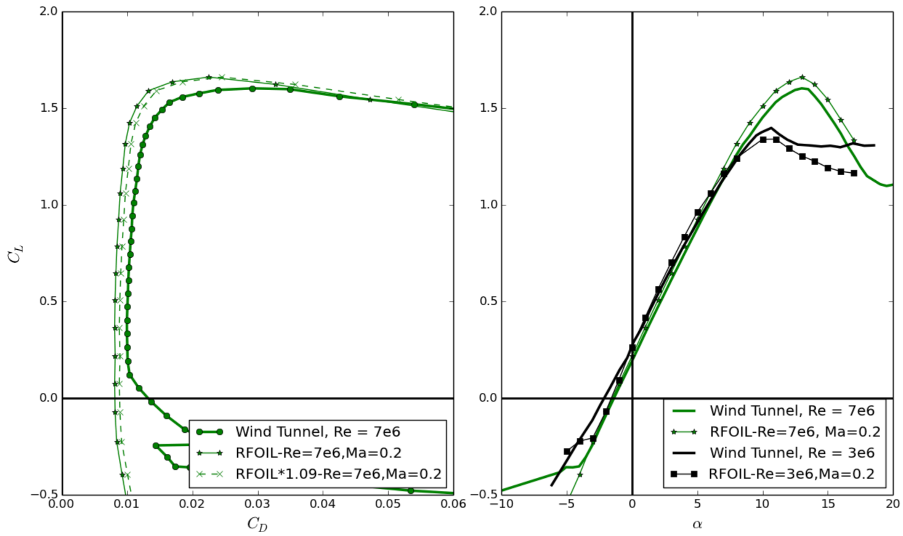

Figure 26. RFOIL lift versus drag and angle of attack comparisoned to wind tunnel results for the the DU 99-W3-350 at Re = 7×10^6 and just the lift curve for the Adjusted DU99-W3-350lm airfoil at Re = 3×10^6.

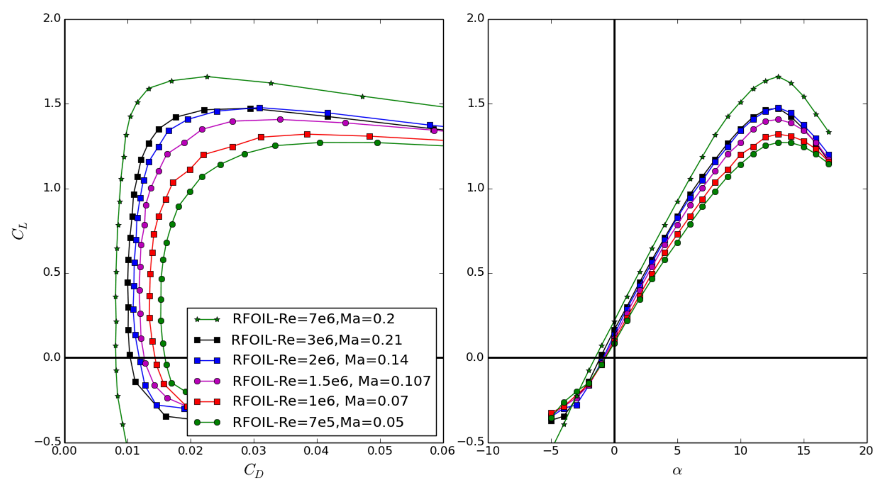

Figure 27. RFOIL DU 99-W3-350 lift versus drag and angle of attack for a wide range of Reynolds number values.

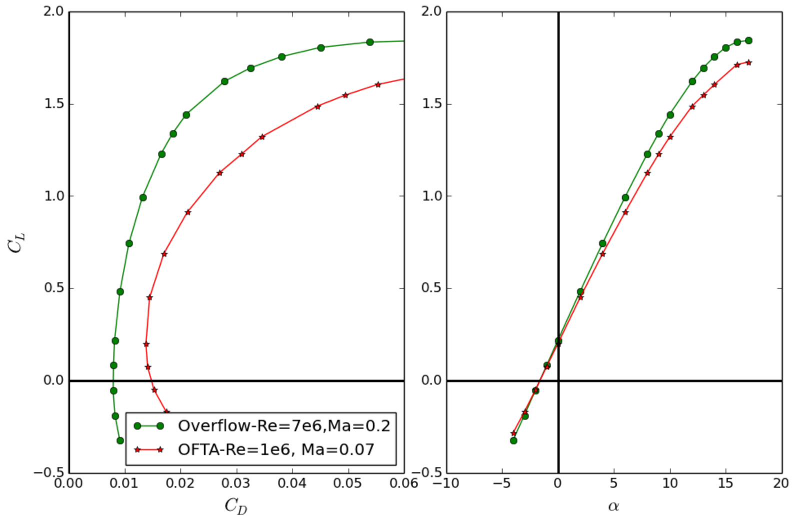

Figure 29. Overflow results for lift versus drag and angle of attack curves for the DU 99-W3-350 airfoil at Re = 7 and 1 million. Both cases are run in the time accurate mode.

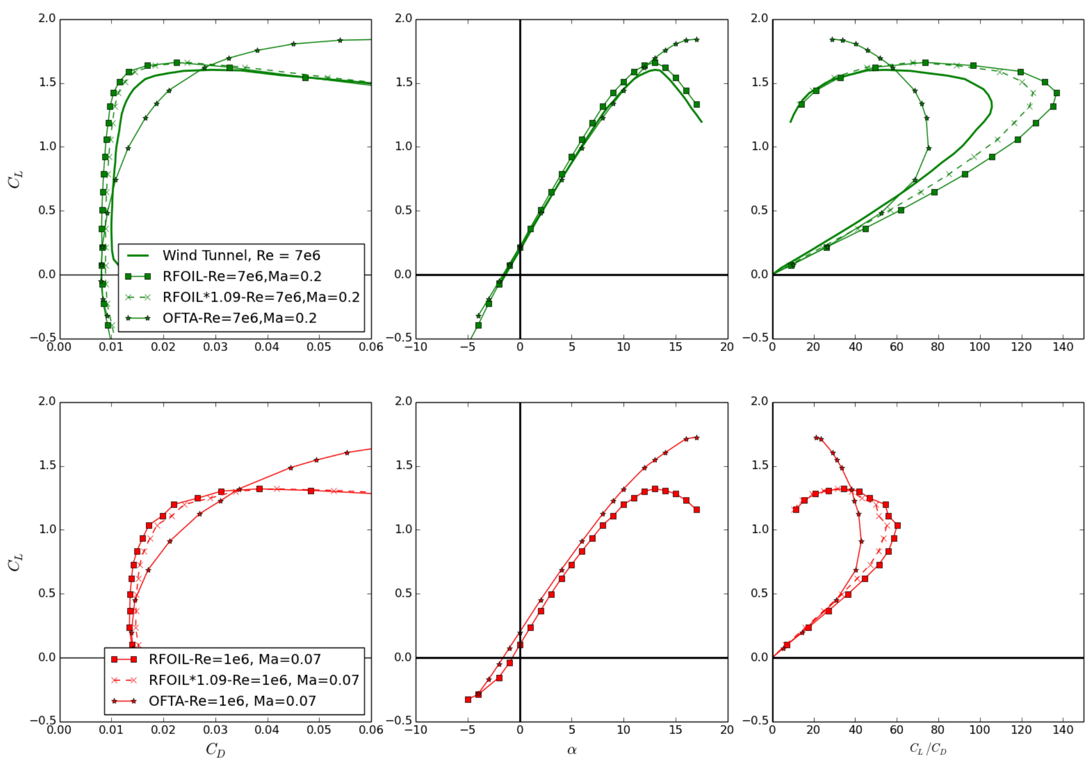

Figure 28. Comparison for the DU 99-W3-350 airfoil of RFOIL and Overflow lift versus drag, angle of attack, and the lift to drag ratio to the wind tunnel data at Re = 7 × 10^6 for the top row and Re = 1 × 10^6 on the bottom row.

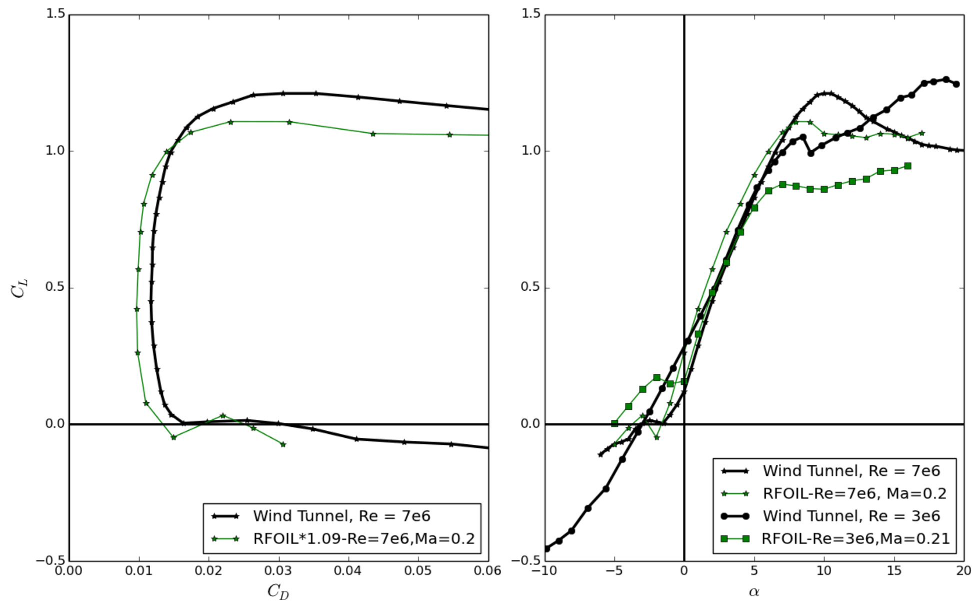

Figure 31. RFOIL data for DU 99-W3-405 compared with wind tunnel data at Re = 7 × 10^6 of the same airfoil and lift curve data at Re = 3 × 10^6 for DU 00-W-401.

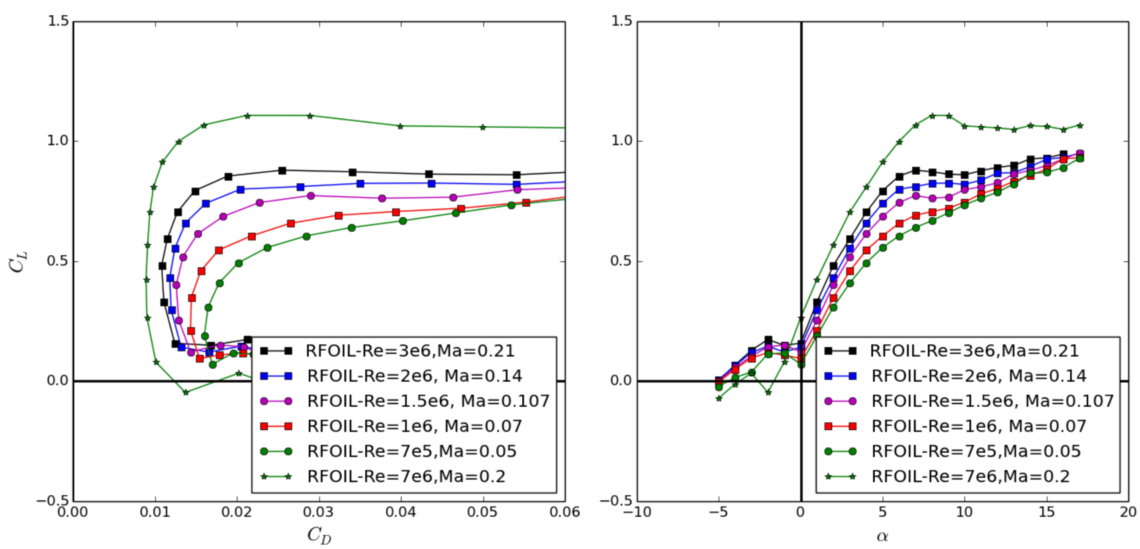

Figure 30. RFOIL DU 99-W3-405 lift versus drag and angle of attack for a wide range of Reynolds number values.

VIII. Conclusions

There are several take away points from this study. RFOIL has once again proven to be a very useful tool which gives accurate **results** and can be used for comparison to other codes for scenarios where experimental data are not available. Overflow, while it does miss the value of $C_{L,max,}$ is fairly accurate otherwise and does have the option of expanding to 3D analysis. If that is needed it will be worthwhile to either explore methods that will increase the accuracy at $C_{L,max}$ or making sure that the angles of attack are within the range where Overflow works well.

Overflow has been used extensively and successfully for CFD studies of airfoils (see work by van Dam, Chow, Blaylock, Baker, Sclanfani), including thick airfoils. Thick airfoils, especially at lower Reynolds numbers, can be tricky to simulate, but Overflow has several features that can be applied to help get an accurate model. These include transition models, Detached Eddy Simulation, and soiled leading edge functions. It also has 3D capabilities that can be used in the next step of blade design. While Overflow does a poor job at capturing correct stall lift and drag values, the operating range for the inboard section of the NRT blade will be mainly below stall. Overflow does an accurate job of predicting the forces on the blade in the angle of attacks of interest.

Simulations of thick airfoils at low Reynolds numbers are much more finicky than thin airfoils at high Reynolds numbers. Attention must be paid to convergence of these airfoils.

Acknowledgments

Thanks to Matt Barone for consultations and making the data he has available to us and special thanks to Nando Timmer for helpful correspondence and access to the wind tunnel data files.

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