Assessment of the aerodynamic characteristics of thick airfoils in high Reynolds and moderate Ma numbers using CFD modeling

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Abstract. The aerodynamic characteristics of thick airfoils in high Reynolds number is assessed using two different CFD RANS solvers: the compressible MaPFlow and the incompressible CRES-flowNS-2D both equipped with the k-ω SST turbulence model. Validation is carried out by comparing simulations against existing high Reynolds experimental data for the NACA 63-018 airfoil in the range of -10° to 20°. The use of two different solvers aims on one hand at increasing the credibility in the results and on the other at quantifying the compressibility effects. Convergence of steady simulations is achieved within a mean range of -10° to 14°, which refers to attached or light stall conditions. Over this range the simulations from the two codes are in good agreement. As stall gets deeper, steady convergence ceases and the simulations must switch to unsteady. Lift and drag oscillations are produced which increase in amplitude as the angle of attack increases. Finally in post stall, the average $C_L$ is found to decrease up to ~24° or 32° for the FFA or the NACA 63-018 airfoils respectively, and then recover to higher values indicating a change in the unsteady features of the flow.

1. Motivation and scope

One of the main objectives of the FP7 Innwind.EU Project is to design low solidity rotors for offshore applications that operate at relatively high tip speeds. High tip speed implies higher (than usual) Mach numbers so that compressibility effects need to be considered in the design of the outer blade region. At large sizes high tip speeds also result in very high Reynolds numbers (up to 12 million for the Innwind.EU 10 MW rotor) for which, airfoil behaviour has not been studied to sufficient extent. Finally, low solidity implies that thicker airfoils will be used, which sets the design further beyond current know-how. In support of this design activity, the aerodynamic behaviour of three FFA airfoils of different thickness is assessed using CFD modelling.

Two different URANS finite volume solvers are applied: the compressible MaPFlow and the incompressible CRES-flowNS-2D both equipped with the k-ω SST turbulence model. A wide range of angle of attacks (AOAs) from -32° to 32° is considered so as to cover both power production and extreme conditions. Depending on the AOA, the flow can exhibit inherent unsteadiness so the simulation set-up must be accordingly adapted. The turning point will depend on the airfoil shape, so at first an investigation is needed in order to determine the range of AOAs that allow steady
simulations. Next, the convergence rate to either a steady or a periodic state is examined. Validation is carried out in comparison to wind tunnel measurements for the NACA 63-018 airfoil [1]. The $C_L$-$C_D$ polar plots are produced for the FFA airfoils and the different trends in the linear and post-stall regions are discussed. Finally, the dependence on the Reynolds and Mach numbers is investigated for the FFA-W3-301 and the FFA-W3-241 airfoils respectively.

2. Methods and numerical specifications

2.1. Solvers
MaPFlow is a multi-block MPI enabled compressible solver equipped with preconditioning in regions of low Mach flow developed at NTUA [2]. The discretization scheme is cell centered and makes use of the Roe approximate Riemann solver for the convective fluxes. In space the scheme is 2$^{nd}$ order accurate defined for unstructured grids and applies the Venkatakrishnan's limiter. The time scheme is also 2$^{nd}$ order and implicit introducing dual time stepping for facilitating convergence. The solver is equipped with the Spalart-Allmaras (SA) and the $k$-$\omega$ SST eddy viscosity turbulence models.

CRESFlowNS-2D is an incompressible solver developed at CRES [3]. The code utilizes a restarting GMRES method for pressure correction. The $k$-$\omega$ SST model is used for turbulence closer. The code can be used for steady state calculations or transient calculations, where additional pseudo-time steps are introduced. A structured grid is used for the solution with various grid types (C-type, O-type) implemented.

2.2. Numerical Specifications
All simulations used the grids provided by DTU Wind in the context of InnWind project [4]. They are structured O-type grids with 513x257 cells. The distance of the first node from the surface of the airfoil corresponded to a $y^+$ of the order of $10^{-4}$. Also in all simulations the $k$-$\omega$ SST model was used assuming fully turbulent flow. Steady simulations were performed starting from the zero AOA and proceeded to higher (or lower angles) with a step of 2 degrees. Beyond a certain value of AOA, the simulations failed to converge to a steady solution indicating the onset of unsteadiness in the flow. So the simulations switched to unsteady simulations.

In order to accelerate convergence the CFL in MaPFlow is allowed to gradually increase from 1 to its final value within a certain number of iterations (or time steps). For the simulations of the FFA airfoils maximum CFL was set equal to 10, which was attained after 200 iterations. Higher maximum CFL values were tested but since they caused convergence difficulties at high AOAs, 10 was retained in all simulations for the sake of uniformity. The time step was set to 0.002 (dimensionless) and 10 dual steps per iteration were performed. In general, convergence was slow for all airfoils of the FFA family, especially as the AOA increased. For the simulations of the NACA 63-018 airfoil, a higher maximum CFL value of 30 was achieved for all angles of attack. The higher CFL value along with the smaller airfoil thickness led to a faster convergence as compared to the FFA airfoils.

Similarly, the simulations with CRESFlowNS-2D in steady flow mode beyond a certain angle of attack resulted in unnatural low-frequency variations in lift and drag. The time step was set to 0.001 (dimensionless). In general, convergence was slow for all airfoils of the FFA family, especially as the AOA increased.

3. Results
For the FFA airfoils, steady and unsteady state calculations were performed depending on the AOA according to Table 1. For the NACA 63-018 airfoils, convergence in steady mode was achieved for AOAs from -10° to 14°. Then up to 20° the simulations were switched to unsteady mode.

The onset of unsteadiness in the flow appeared at AOAs around 14°–16° (depending on the shape of the airfoil and the Reynolds number) and was combined with the formation of a von Karman street like wake (Figure 1). As the AOA increased, the intensity of the shed vortices also increased and the shaping of compact vortices was faster. The wave length increased resulting in a decreasing Strouhal number as shown in Table 2, where the amplitude and the Strouhal number of the converged
periodical $C_L$ variation, as predicted by the compressible code MaPFlow, are presented for the various AOs in the case of the FFA-W3-241 airfoil.

| Airfoil        | Ma  | Re     | Unsteady region     | Steady region     | Unsteady region     |
|----------------|-----|--------|---------------------|-------------------|---------------------|
| FFA-W3-241     | 0.26| $12 \cdot 10^6$ | AOA: (-32°)−(-16°) | AOA: (-12°)−(-16°) | AOA: 16°−28°       |
| FFA-W3-301     | 0.11| $3 \cdot 10^6$   | AOA: (-32°)−(-12°) | AOA: (-8°)−(-12°)  | AOA: 16°−32°       |
| FFA-360        | 0.09| $10 \cdot 10^6$  | AOA: (-32°)−(-12°) | AOA: (-8°)−(-12°)  | AOA: 16°−32°       |
| FFA-360-G      | 0.09| $10 \cdot 10^6$  | AOA: (-32°)−(-8°)  | AOA: (-8°)−(-14°)  | AOA: 16°−32°       |

Table 1: AOA range for steady and unsteady state simulations of the FFA airfoils.

| FFA-W3-241     | Re=$12 \cdot 10^6$ | Ma=0.26 | AOA | $\Delta C_L$ | St |
|----------------|-------------------|---------|-----|---------------|----|
|                |                   |         | -32°| 0.355         | 0.366 |
|                |                   |         | -28°| 0.295         | 0.549 |
|                |                   |         | -24°| 0.236         | 0.793 |
|                |                   |         | -20°| 0.083         | 1.099 |
|                |                   |         | -16°| 0.016         | 1.648 |
|                |                   |         | 20° | 0.035         | 1.16 |
|                |                   |         | 24° | 0.288         | 0.732 |
|                |                   |         | 28° | 0.342         | 0.488 |
|                |                   |         | 32° | 0.403         | 0.366 |

Table 2: Amplitudes and Strouhal numbers of the converged $C_L$ variation for the FFA-W3-241 airfoil. Unsteady calculations performed by MaPFlow.

Figure 1: Vorticity contours in the wake of the FFA-W3-241 airfoil at Re=$12 \cdot 10^6$. Left: AOA=16°. Right: AOA=24°. Predictions obtained with MaPFlow.

3.1. Convergence.
Simulations for FFA airfoils required at least 20000 iterations in order to achieve convergence of the steady state or a variation in mean $C_L$ less than 3%. On the contrary a significantly smaller number of time steps was sufficient in the NACA airfoil simulations. In Figure 2, the convergence history for both FFA and NACA airfoils at AOA=10° is depicted as predicted by MaPFlow. It seems that convergence is slower as the airfoil thickness increases. Therefore, the faster convergence in the NACA airfoil simulations can be attributed to its smaller thickness (18%) as well as to the higher CFL used in comparison to the FFA simulations. The convergence history of $C_L$ at AOA=20° is represented in Figure 3. For the FFA airfoils, as expected, the amplitude of the attained periodic state increased with airfoil thickness.
Figure 2: Convergence of $C_L$ for AOA=10°. Left: FFA airfoils. Right: NACA 63-018 airfoil. Predictions obtained with MaPFlow.

Figure 3: Convergence of $C_L$ for AOA=20°. Left: FFA airfoils. Right: NACA 63-018 airfoil. Predictions obtained with MaPFlow.

Figure 4: Convergence of $C_L$ for the FFA-360 airfoil, $Re=12\times10^6$, $Ma=0.09$. Left: AOA=0°. Right: AOA=16°. Comparison between predictions of compressible code MaPFlow and incompressible code CRES-flowNS.
Figure 5: Comparison of pressure coefficient plots between MaPFlow and CRES-flowNS-2D for the FFA-360 airfoil at AOA=16°, Re=10\times10^6, Ma=0.09. The higher pressure at the suction side predicted by CRES-flowNS-2D is the reason for the higher C_L value in Figure 4.

Figure 6: Unsteady calculation of the FFA-360 airfoil at AOA=32° for different time steps, Re=10\times10^6, Ma=0.09. Left: Time history of C_L. Right: Mean error of the u-momentum equation.

In Figure 4, the convergence histories of the two CFD solvers are compared. At AOA=0°, for which a steady state is obtained, both MaPFlow and CRES-flowNS-2D converge to the same C_L value. At AOA=16°, both solvers give a periodic response with the same Strouhal number. However, the mean value, as well as the amplitude, is different. Such differences are attributed to the presence of acoustic waves in compressible simulations that change the pressure level at the suction side as shown in Figure 5.

For the high AOAs (24°, 28°, 32°), the flow phenomena due to the deep stall are too complex. So, in order to obtain grid independent solutions, fine meshes and small time steps are required. A thorough parametric investigation of the numerical parameters is not the focus of the present work, so the same fine mesh with a minimum y⁺ of the order of 10^-4 is used in all simulations. However, it must be noted that a sufficiently small time step is required in order to ensure that the vortex shedding is properly captured. In Figure 6 the C_L time history and the corresponding error convergence are shown for two time steps in the case of the FFA-360 at AOA=32°. For dt=0.002, although a periodic state is obtained, the error in the u-momentum equation diverges. On the contrary when dt=0.001 is used, clear convergence is attained. The corresponding flows are compared in Figure 7. In the dt=0.002 simulation, the flow exhibits an unnatural vortex pairing at higher frequency while the trajectory of the
wake vortices follows a higher slope that that defined by the AOA. On the contrary the pattern in the
dt=0.001 case is reasonable, having the expected von Karman structure.

Figure 7: Vorticity contours of the flow around the FFA-360 airfoil for AOA=32°. Re=10−10⁶,
Ma=0.09. Left: Time step=0.002. Right: Time step=0.001. Predictions obtained with MaPFlow

3.2. \( C_L^L-C_D^L \) polars
The compressible MaPFlow was used for most of the subsequent computations for two reasons: First,
it is valid for the whole range of Mach number and second, it is faster due to the fact that implements
parallel processing. Validation of the MaPFlow predictions was performed using the existing
measurements for the NACA 63-018 airfoil [1]. Comparison of the mean \( \overline{C_L} \) polars for the various
Reynolds numbers is shown in Figure 8. A good agreement is observed in the linear region. In the
post-stall region predictions overestimate measurements, but the overall trend is reproduced. As Re
increases both measurements and simulations show that max\( \overline{C_L} \) convergences to a limiting upper
value. In the measurements, convergence to that limiting value is slower and so the largest difference
is seen in the smaller Re number of 3 \( 10^6 \). Also the angle of attack corresponding to max\( \overline{C_L} \) is higher in
the simulations indicating a delay is stall, which could be attributed to the turbulence modelling.
Furthermore, \( \overline{C_L} \) is found to decrease up to \( \approx 28^\circ \) and then recovers to higher values indicating a change
in the unsteady features of the flow. A similar lift recovery has been also reported for the NACA 63-215
and 4418 airfoils on the basis of wind tunnel tests [5]. Regarding drag, the difference in \( \overline{C_D} \)
between predictions and measurements at AOA=0 ° is 0.005 (Figure 9). Such a difference is justified
by the fact that the CFD predictions are fully turbulent. It should be mentioned that for Re=6 \( 10^6 \)
measurements with leading edge roughness are also available in [1]. In that case, the measured \( \overline{C_D} \) at
AOA=0 ° is in better agreement with the predicted value as shown in Figure 9 (left).
Figure 8: $C_L$ polar plots for the NACA 63-018 airfoil. Left: $Re=3,6,9\times10^6$. Right: $Re=15,20\times10^6$. Predictions obtained with MaPFloW

Figure 9: $C_D$ polar plots for the NACA 63-018 airfoil. Left: $Re=3,6,9\times10^6$. Right: $Re=15,20\times10^6$. Predictions obtained with MaPFloW

Figure 10: $C_L$ - $C_D$ polar plots for the FFA airfoils. Comparison of airfoils with different thickness. Predictions obtained with MaPFloW
In Figure 10, the predicted $C_L$-$C_D$ polar plots for the different FFA airfoils are presented. As expected, stall appears at lower AOA as thickness increases. In addition, the increase in thickness results in lower $C_L$ and higher $C_D$ in the post-stall region. Attention should be paid to the effect of the Gurney flap (FFA-360-G airfoil) that gives a significant increase in the slope of $C_L$ over the linear range as well as higher max $C_L$. In the post-stall region, a recovery of lift is found similar to that already observed in the NACA airfoils. The turning point depends on the airfoil thickness. As thickness increases from 24% to 36%, this characteristic AOA is reduced from $28^\circ$ to $18^\circ$. Due to airfoil camber, the variation of $C_L$ is different at negative AOAs. For increasing thickness onset of separation appears earlier. The post stall (negative) slope after max $C_L$ is more or less the same indicating similar aerodynamic damping characteristics in case of vibrations. Slightly higher values are observed for the Gurney flap airfoil.

The dependence of $C_L$, $C_D$ predictions on the Reynolds number is shown in Figure 11 for the FFA-W3-301 airfoil. As expected, the increase of Reynolds number delays flow separation and leads to higher $C_L$ and lower $C_D$ values in the region of separated flow. Finally, the effect of Mach number was studied for the FFA-W3-241 and FFA-360 airfoils in the linear region of $C_L$, $C_D$. Figures 12, 13 show that by increasing the Mach number, lift increases and drag decreases. For the thicker airfoil FFA-360 the effect of Mach number appears stronger at high AOAs. The reason is the stronger effect of compressibility on the pressure at the suction side as depicted in the $C_p$ plots (Figure 14). The increase in lift with respect to Mach number is in accordance with Ackeret's linear theory for airfoils [6].

The comparison between the predictions of the MaPFlow and CRES-flowNS-2D codes is presented in Figure 15. MaPFlow simulations were also performed at Ma=0.09, so that comparison with the incompressible CRES-flowNS-2D be possible. A fairly good agreement is observed at the linear region for both FFA-W3-241 and FFA-360 airfoils. For the thicker FFA-360 airfoil MaPFlow predicts stall at a lower AOA as also mentioned above (see Figure 10). It is not clear if CRES-flowNS-2D presents the same trend since convergence was not possible in the $12^\circ$-$20^\circ$ range for FFA-W3-241. However, the predictions at $12^\circ$ and $20^\circ$ show that the comparison between the two codes is worse as we move away from the linear region. This is further supported by the comparison of the $C_p$ plots in Figure 16, which shows better agreement at $8^\circ$ than at $12^\circ$. In the same figure the difference in the predictions of MaPFlow for Ma=0.09 and Ma=0.26 also shows the effect of the compressibility. In order to explain the deviation of the predictions between the two codes at high AOAs the skin friction coefficient are plotted in Figure 17. CRES-flowNS-2D predicts a sudden peak in skin friction at the suction side close to the leading edge, which is not observed in the MaPFlow predictions. As a result the pressure at the suction side is reduced and produces a continuously lower lift as the AOA increases.

This peak in skin friction is not observed in CRES-flowNS-2D predictions for the 36% airfoil as shown in Figure 18 at AOA=10°. Therefore, the two codes predict similar pressure and lift coefficients, even in the post-stall region as shown in Figure 15. It seems that the skin friction predicted by the incompressible code is sensitive to surface curvature especially as the AOA increases. The difference in the behaviour of the two codes may be also related to the way velocity fluctuations are treated (in a compressible code velocity fluctuations are filtered through the density equation); however a clear explanation could not be found and further investigation is required.
Figure 11: $C_L$-$C_D$ polar plots at different Reynolds numbers for the FFA-W3-301 airfoil, $Ma=0.11$. Predictions obtained with MaPFlow.

Figure 12: $C_L$-$C_D$ plots in the linear region at different Mach numbers for the FFA-W3-241 airfoil. Predictions obtained with MaPFlow.

Figure 13: $C_L$-$C_D$ plots in the linear region at different Mach numbers for the FFA-360 airfoil. Predictions obtained with MaPFlow.
Figure 14: $C_p$ plots at different Mach numbers, AOA=10°, for the FFA-W3-241 and the FFA-360 airfoils. Predictions obtained with MaPFlow

Figure 15: $C_l$ - $C_D$ polar plots for the FFA airfoils. Comparison between predictions of compressible code MaPFlow and incompressible code CRES-flowNS-2D.

Figure 16: Comparison of pressure coefficient plots between MaPFlow and CRES-flowNS-2D for the FFA-W3-241 airfoil, Re=12\times10^6. Left: AOA=8°. Right: AOA=12°
In order to assess the aerodynamic performance of thick airfoils at high Reynolds numbers and increased Ma numbers, CFD simulations were performed on three FFA airfoils in a wide range of AOAs. First, a numerical investigation was performed focusing on: the distinction between steady and unsteady calculations; the convergence; and the choice of the proper time step. Steady state simulations were found adequate for a range of AOAs approximately between -8° and 14°. For higher AOAs, steady state simulations failed to give a converged mean value of $C_L$, $C_D$, indicating the onset of unsteady flow phenomena. Unsteady calculations converged to a periodic variation of $C_L$, $C_D$, which is driven by the frequency of vortex shedding. A number of 20000 time steps proved to be sufficient for most of the simulated cases. For AOAs higher than 24° it was observed that a sufficiently small time step must be used, otherwise the wake structure may be lost leading to non-physical simulated flows.

After tuning the numerical parameters, CFD predictions were validated against the wind tunnel measurements of the NACA 63018 airfoil in a wide range of Reynolds number from $3 \times 10^6$ to $20 \times 10^6$. Good agreement was obtained for $C_L$ in the linear region, whereas onset of stall was predicted at...
higher AOAs and resulted in a lift overestimation in the post-stall region. The overall trend of the $C_L$ curve was well predicted. Regarding drag, CFD predictions exhibited a shift at zero AOA justified by the fact that calculations were fully turbulent. A similar shift was presented in the measurements when surface roughness was added at the leading edge.

Next, the effects of thickness, Reynolds and Mach numbers on the aerodynamic characteristics of the FFA airfoils were investigated. A higher thickness reduced the lift and increased the drag at "high" AOAs; namely outside the linear region. For the studied FFA airfoils, the linear region lied approximately between -5° and 10°. In the post-stall region there was a certain value of the AOA, dependent on the airfoil thickness, at which the $C_L$-AOA curve changed trend, denoting a change in the unsteady features of the flow. The same trend has been observed in the wind tunnel measurements of the NACA 63-215 and 4418 airfoils. Changing the Reynolds number from $3 \times 10^6$ to $10 \times 10^6$ gave a considerable increase in the maximum $C_L$ (16%), but the increase over the linear region was much smaller (3-5%). A similar effect in the linear region was caused by the increase of the Mach number from 0.11 to 0.31.

Finally, a comparison was made between the predictions of the compressible and the incompressible CFD solvers. The two codes showed good agreement in the linear region for both 24% and 36% airfoils. As the AOA increased, the incompressible code predicted a lower pressure at the suction side of the 24% airfoil resulting in a lower lift This is attributed to the prediction of a peak in the skin friction close to the leading edge. Such a peak is not present in the 36% airfoil predictions and the agreement between the two codes becomes better even in the post-stall region. Further investigation is required in order to better understand whether the airfoil thickness has a physical or numerical effect on the prediction of the skin friction.

In conclusion, CFD predictions are capable of predicting the basic flow features around thick airfoils at high Reynolds numbers. However, the occurrence of strong unsteady phenomena at high AOAs demands unsteady calculations with small time steps leading to a significant increase of the computational cost. As thickness increases, unsteady vorticity structures become more complex and appear at lower AOAs. Therefore, a proper tuning of the numerical parameters is necessary in order to achieve a fast convergence without losing the complex unsteady flow features.

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