Title: Evaluation of the performance of a Navier-Stokes and a viscous-inviscid interaction solver in trailing edge flap simulations.

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1. Introduction

Trailing edge (TE) flap is one of the most common flow control devices aiming at reducing the loads on the wind turbine blades. From the modelling point of view the dynamic character of flap introduces challenges, including unsteady flow phenomena and moving/deformable meshes. In order to evaluate the performance of its available computational tools NTUA simulated several static and dynamic TE flap cases, as well as combined TE flap-pitch cases, for which experimental data are available. A part of this work is related to the investigation of flow control on large wind turbine blades in the context of the AVATAR.EU FP7 Project.

2. Approach

The solvers used for the simulation of TE flap cases are the MaPFlow compressible Navier-Stokes solver [1] and the Foil viscous-inviscid interaction solver [2]. Both codes are capable of simulating fully turbulent and transitional flows. In MaPFlow the γ-Reθ transition model is implemented [3], whereas Foil employs the e^N transition model. Turbulence closure in MaPFlow is made using the k-ω SST turbulence model.

The work is divided in two parts. The first part refers to static TE flap cases for which steady state simulations are performed. In this part, the experimental data are taken from the measurements of the TL190-82 airfoil performed in the course of the European UPWIND project at the wind tunnel of the Institute of Aerodynamics and Gas Dynamics (IAG), University of Stuttgart. TL190-82 was specifically designed for load alleviation purposes by active trailing edge flaps. Static TE flap deflections in the range from -10 to 10 degree were examined in clean and tripped conditions at three different Reynolds numbers (Re = $1.5\cdot10^6$, $2.5\cdot10^6$, $3.3\cdot10^6$) [4]

The second part refers to dynamic TE flap cases combined with a harmonic motion of the airfoil (pitching), for which unsteady state simulations are performed. The experimental data are taken from measurements of NACA0012 carried out by Krzysiak and Narkiewicz in the trisonic N-3 wind tunnel located at the Institute of Aviation Warsaw, Poland [5]. The Reynolds number was fixed at $1.63\ 10^6$. A rigid trailing edge flap was implemented with a length 20% of the airfoil chord. The reduced frequency of the airfoil harmonic motion was k_A = 0.021, while the flap oscillation doubled this frequency, k_F = 0.042. The angle of attack and the flap deflection were governed by the equations

$$\alpha=\alpha_m+\Delta\alpha \ \sin(\pi k_A t) \ , \tag{1}$$

$$\beta=\beta_m+\Delta\beta \ \sin(2k_F t-\varphi) \tag{2}$$

where α_m and β_m are the mean values of the angle of attack and flap deflection, $\Delta\alpha$ and $\Delta\beta$ are the amplitudes of the airfoil and flap harmonic movement respectively and φ is the phase shift between the airfoil and the flap angle.

3. Main body of abstract

For the static TE articulated flap cases of the TL190-82 airfoil (FIGURE 1), MaPFlow uses an O-type mesh of 150000 cells generated by ICEM CFD. The non-dimensional distance of the first node from the wall is less or equal to 10^{-5}. Clean conditions are simulated with free transition modeling, whereas tripped conditions are simulated with fully turbulent and fixed transition modeling by MaPFlow and Foil respectively.

In FIGURE 2, the C_L polars predicted by the two solvers are compared with the available measurements for the flapping angles of -5° and +5°. In the linear region the two models well predict the lift, for both clean and tripped conditions. Differences appear at higher angles of attack (AOA) and they are more pronounced in the post-stall region. In general, stall is predicted at higher AOAs compared to the measurements. Tripping appears to have a drastic effect on the measurements by shifting stall to lower AOA. This effect is less pronounced in the predictions which present larger deviations from the measurements compared to clean conditions.

The comparison of the predicted C_D polars with the measurements is shown in FIGURE 3. In clean conditions, the fact that Foil better predicts drag than MaPFlow suggests that the e^N transition model identifies the transition locations more accurately than the γ-Reθ model. On the contrary, in tripped conditions, drag is better predicted by the MaPFlow solver as expected, since the fully turbulent simulation by the k-ω SST model is more accurate.

For the dynamic TE articulated flap cases of the NACA0012 airfoil, MaPFlow uses a C-type mesh of 88000 cells generated by ICEM CFD (FIGURE 4). MaPflow simulations are fully turbulent, whereas Foil considers fixed transition at 5% chord from the leading edge. The different test cases refer to different phase shifts between the airfoil pitching motion and the flap angle. FIGURE 5 shows the variation of the flap angle with the angle of attack for ϕ=148° and ϕ=206°. Measurements deviate from the nominal values provided by Equations (1),(2) possibly due to elastic deformations occurred during the experimental campaign or delay/errors in the response of the actuators controlling the motion of the airfoil and the flap. In order to fit the measured airfoil phase /flap relative motion, Nestor [6] suggested corrections to the phase shift from ϕ=148° to ϕ=135° and from ϕ=206° to ϕ=196°. The double frequency of the flap movement results in the appearance of two loops, one corresponding to a whole flap cycle when AOA is positive and another one corresponding to a whole flap cycle when AOA is negative.

In FIGURE 6 and FIGURE 7 the predicted lift and moment coefficients are compared with the measurements for ϕ=148° and ϕ=206° respectively. The overall shape of the loops is reproduced by both models, however, lift is generally overpredicted and moment is underpredicted. Larger differences are observed at the positive AOAs and are responsible for the overestimation in the slope of the double loop (C_L-AOA diagrams, FIGURE 6a and FIGURE 7a). A part of these differences can be attributed to the deviation of the measured flap angles from the theoretical values or to the 3D effects related to the experiment, such as the creation of stall cells along the blade model. For example, in FIGURE 5a, it can be observed that during the upstroke measured flap angles are lower than the nominal (positive AOA, negative flap), reducing the lift. A similar observation can be made in FIGURE 5b, where the measured values of the flap deflection are again more downwards that the theoretical used in the simulations, when the airfoil is in the downstroke phase (negative AOA, negative flap). Estimation of the 3D effect on the slope of the lift loops could be made by comparing predicted and measured lift polars at static TE flaps. However, no measurements have been reported for static TE flap.

It should be noted that Foil predictions are closer to the measurements compared to those of MaPFlow. One possible reason is that MaPFlow used fully turbulent simulation instead of fixed transition. On the other hand, there are no experimental data for drag, which is expected to be better predicted using the k-ω SST turbulence model implemented in MaPFlow.

In order to estimate the effect of the phase shift correction, as suggested by Nestor, to the predictions, a set of new simulations were performed by Foil. In FIGURE 8, the modified C_L, C_M loops for $\phi=196^o$ are compared with those of $\phi=206^o$ which is the corrected phase shift. Differences with measurements have been decreased suggesting that an even better correlation with the measured flap angle may result in a better and more fair comparison.

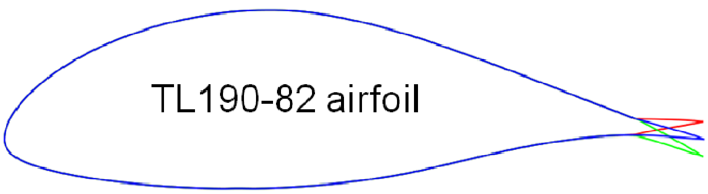
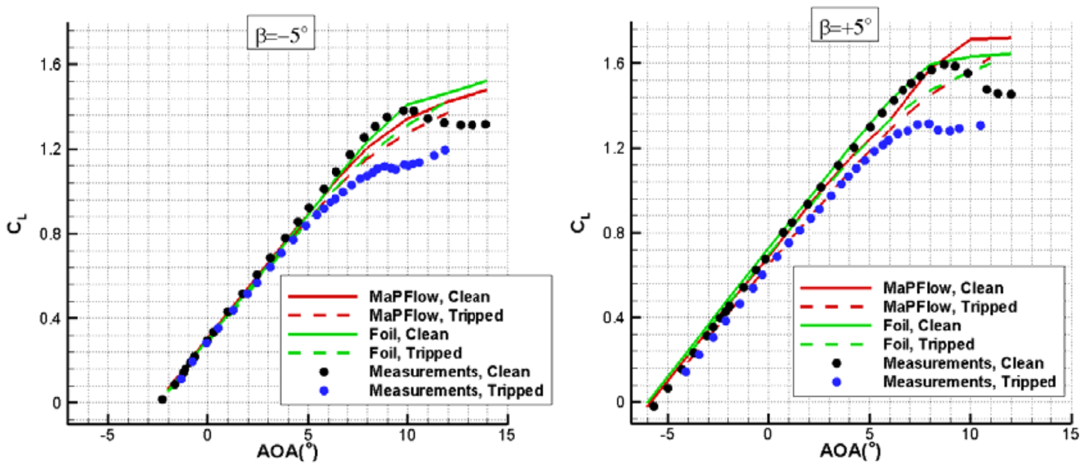
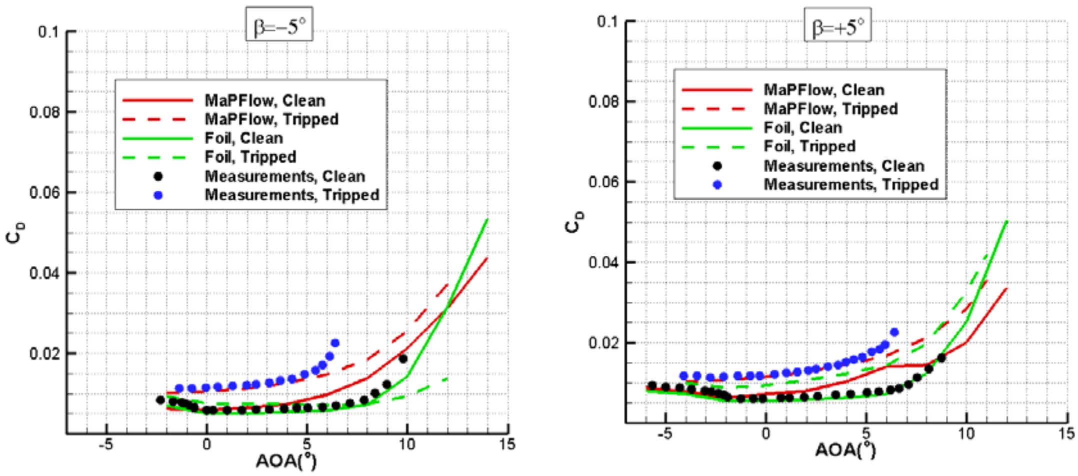


FIGURE 1: **Articulated TE flap for the TL190-82 airfoil**



(a) **(b)**

FIGURE 2: **C_L polars for TE static flap, TL190-82 airfoil, Re=2.5·10^6. (a) Flap=-5o, (b) Flap=+5o. Clean conditions correspond to free transition and tripped conditions correspond to fixed transition**



(a) (b)

FIGURE 3: C_D polars for TE static flap, TL190-82 airfoil, Re=2.5·106. (a) Flap=-5o, (b) Flap=+5o. Clean conditions correspond to free transition and tripped conditions correspond to fixed transition

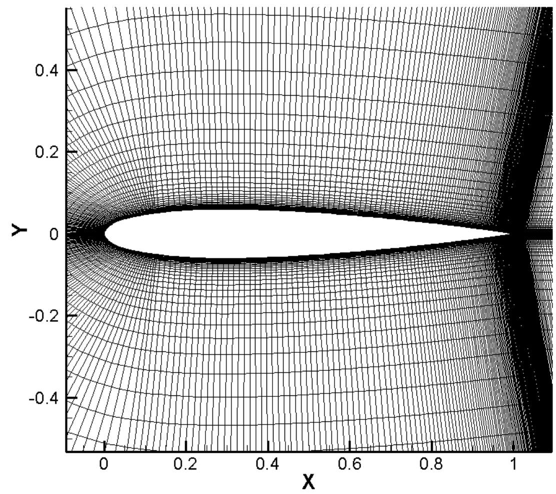
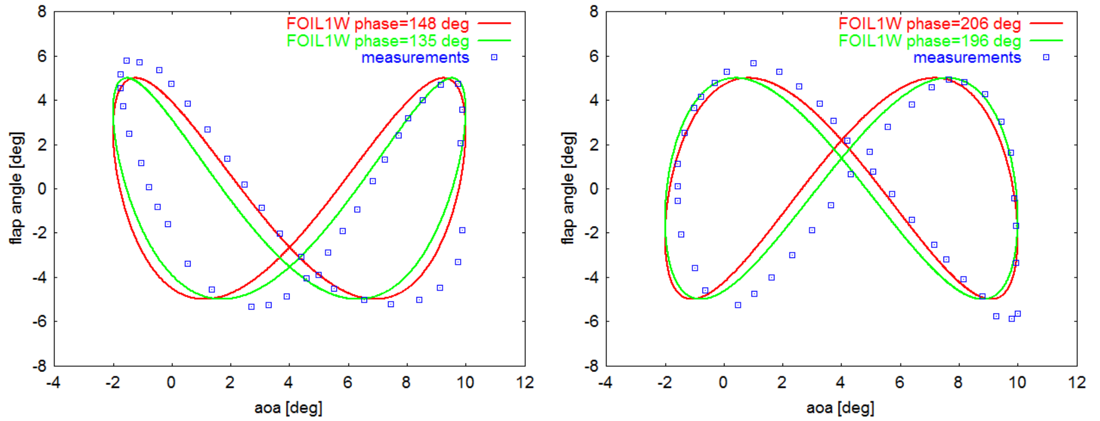
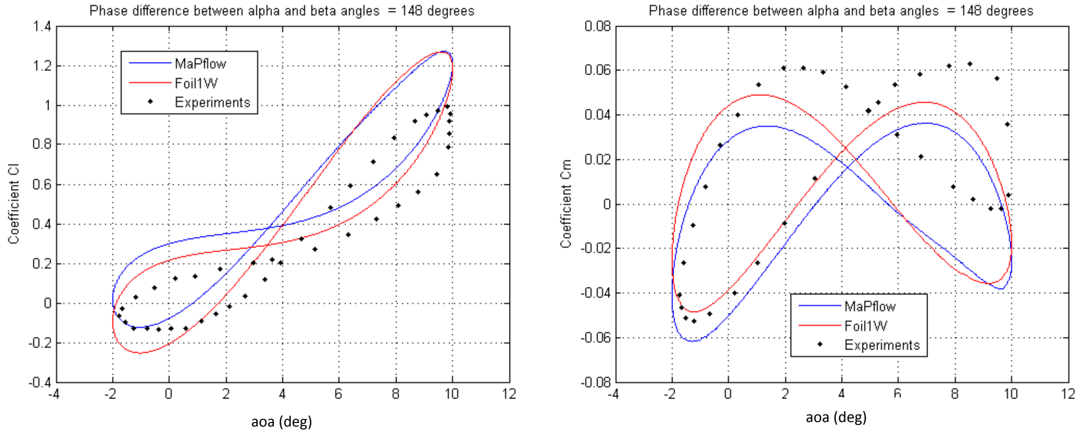


FIGURE 4: Computational mesh around the NACA0012 airfoil



(a) (b)

FIGURE 5: Theoretical and measured variation of the flap angle with the angle of attack for (a) $\phi=148^{o}$ and (b) $\phi=206^{o}$. Nestor [6] suggested phase corrections from 148^{o} to 135^{o} and from 206^{o} to 196^{o} in order to fit the measured airfoil / flap relative motion



(a) (b)

FIGURE 6: **Comparison of predicted C_L, C_M coefficients with measurements. Phase shift is 135°**

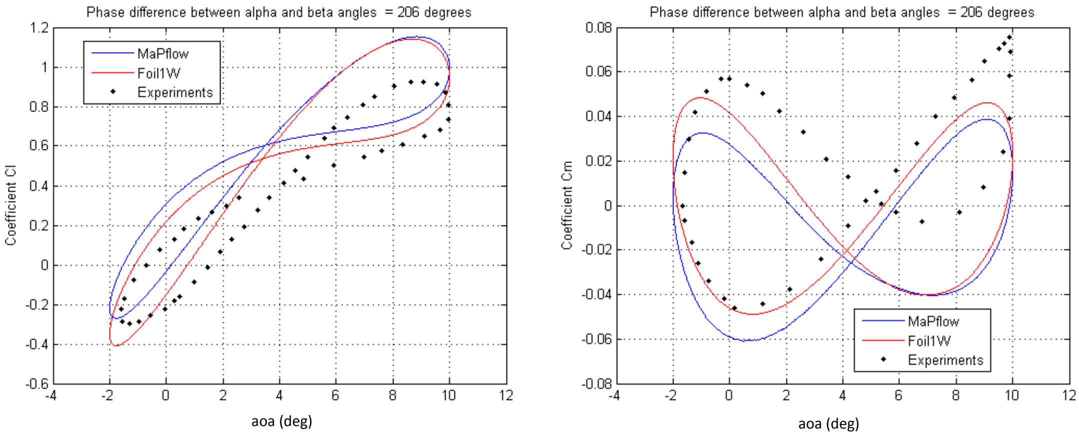


FIGURE 7: **Comparison of predicted C_L, C_M coefficients with measurements. Phase shift is 206°**

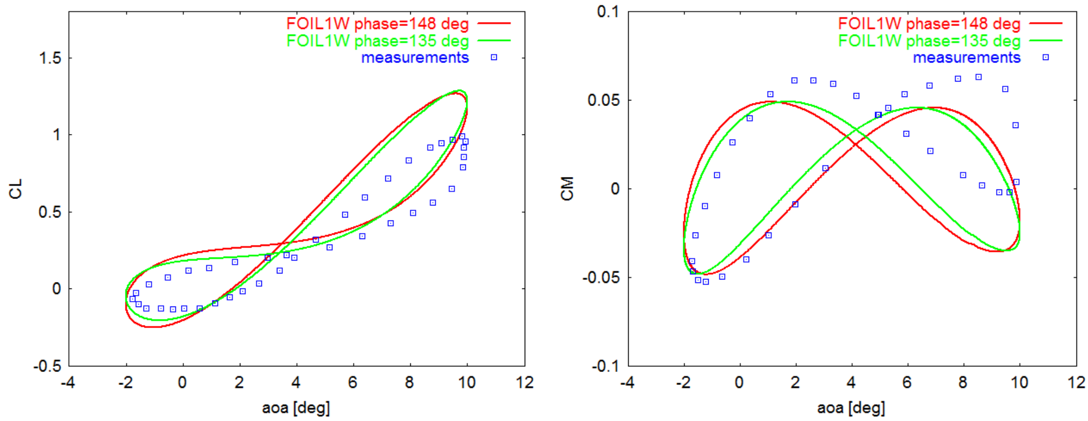


FIGURE 8: **Modification in C_L, C_M coefficients predicted by Foil when the phase shift is corrected from 148° to 135°**

4. Conclusion

Several static and dynamic TE articulated flap cases were simulated by two solvers, the MaPFlow CFD solver using the k-ω SST turbulence model, and the viscous-inviscid interaction Foil model using the e^N transition model. Regarding the static TE cases, numerical models give acceptable C_L errors in the linear region. In free transition cases, the e^N transition model showed a better behavior than the γ-Reθ transition model, probably because it predicts the transition locations more accurately. The location of the $C_{L,\ max}$ was not well reproduced by the numerical models. Therefore, in the post-stall region the predicted errors were almost doubled compared to those found in the linear region. In the tripped condition cases, drag is better predicted by fully turbulent simulations using the k-ω SST model.

Regarding the dynamic TE flap cases (along with a harmonic movement of the airfoil), the measured flap angle deviates from the one obtained from the theoretical relationships to be used as input to the simulations. This is a first reason for the differences between predictions and measurements of the lift and momentum coefficients. Although the correction suggested by Nestor partly improved the correlation with the experimental data, an even more accurate representation of the input flap angle must be sought. Another reason maybe the 3D effects, such as the creation of stall cells along the blade model. Nevertheless, the comparison between predictions and measurements is encouraging because the shape of the lift and momentum variations is well reproduced and the mean level is predicted satisfactorily in many cases.

5. Learning objectives

Developing and simulating flow control devices such as trailing edge flap to reduce the loads on wind turbine blades. Simulation of static and dynamic trailing edge flap using advanced computational tools. Evaluation of the computational performance using available experimental data.

6. References

[1] Papadakis G. and Voutsinas S.G., 2014, “In view of accelerating CFD simulations through coupling with vortex particle approximations” in: *The Science of Making Torque from Wind Journal of Physics: Conference Series*, IOP Publishing Copenhagen pp. 012126

[2] Riziotis V.A. and Voutsinas S.G., 2008, “Dynamic stall modelling on airfoils based on strong viscous–inviscid interaction coupling”, *International Journal for Numerical Methods in Fluids* 56 2 185-208.

[3] Niels N. Sorensen, 2009, “3D CFD computations of transitional flows using DES and a correlation based transition model”, Risø-R-1692(EN) report.

[4] Lutz T. and Wolf A., 2010, “Aerodynamic and acoustic design of wind turbine airfoils with trailing-edge flap” in Proceedings of DEWEK 2010, DEWI, Germany.

[5] Krzysiak, A. and Narkiewicz, N. Aerodynamic loads on airfoil with trailingedge flap pitching with different frequencies. *Journal of aircraft*, 43:407-418, 2006

[6] Nestor Ramos Garcia, “Unsteady Viscous-Inviscid Interaction Technique for Wind Turbine Airfoils”, PhD Thesis, DTU Department of Mechanical Engineering, April 2011.