Study of the influence of oscillating trailing edge flaps on the AVATAR rotor using CFD simulations

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Abstract. In the present paper the effect of an oscillating trailing edge flap on the wind turbine blade loading and performance is investigated. Two CFD Unsteady Reynolds Averaged Navier-Stokes (URANS) solvers along with a simpler engineering Blade Element Momentum (BEM) model are used to simulate sinusoidal trailing edge flaps with a length of 10% chord and 10° maximum deflection, centered at 75% span and extending at 15% of the blade radius. The predictions reveal significant 3D effects on the hysteresis, as well as the location and magnitude of the maximum amplitude of loading. The increase of flapping frequency from 1P to 3P results in lower amplitude and larger hysteresis. A stronger influence of the flap is observed at the negative flap angles. The effect of increasing the flap length on the power and thrust of the turbine rotor is also investigated.

1. Introduction
Trailing edge flap is a flow control device that has been proposed to control loading on large wind turbine blades [1]. The effect of an oscillating flap on wind turbine rotors has been studied in the context of the AVATAR project using systematic 2D and 3D simulations. The predictions presented in deliverables D3.1 [2] and D3.2 [3] exhibited some large differences between the different codes regarding the increase of the sectional forces and the integrated power (up to 40%) and thrust (up to 12%). However, it should be noted that the complexity of the codes varied significantly from the simple engineering to the more advanced CFD solvers. The scope of the present work is to reduce the uncertainties stemmed from the previous simulations through a detailed comparison between the predictions of two CFD codes. Apart from providing reliable estimations of the effect of oscillating flap on the loading and power performance of the AVATAR blade, it is important to address the differences with simple engineering models. To this end, a simulation case is defined considering a stiff configuration of the AVATAR rotor at a uniform representative velocity. CFD simulations are performed using FLOWer and MaPFlow URANS compressible solvers that have been validated and used extensively in the aerodynamic simulation of wind turbine rotors. The engineering model employed is an integration of the 2D inviscid aerodynamic model FOILFS, which accounts for trailing edge active shape variations, into the BEM-based aerodynamic module of the aero-elastic tool hGAST.
2. CFD codes and computational setup

2.1. FLOWer

FLOWer [4] is a compressible URANS solver based on a finite-volume formulation for block-structured grids. To determine the convective fluxes a 2nd central discretisation with artificial damping is used, also called the Jameson-Schmidt-Turkel (JST) method. Time integration is accomplished using the semi-implicit Dual-Time-Stepping method. In the last years, FLOWer was continuously enhanced for wind turbine application at the Institute of Aerodynamics and Gas Dynamics, University of Stuttgart [5]. One of these enhancements is a functionality to realize trailing or leading edge flaps based on grid deformation [6], which is used in the present work.

Computational details. Four overset meshes are used in order to perform the simulation of one blade due to the 120° symmetry. The CH-type blade mesh consists of 14.1 million cells using 281 nodes chordwise and 201 nodes spanwise. A number of 35 nodes are distributed in the blade surface boundary layer using a geometrical progression of 1.14 growth rate with a first distance of $y^+=0.5$. Beyond that blocks attach with tanh-distribution towards the outer grid boundary. Spanwise refinements are introduced at the flap edges as described in [6]. The background mesh consists of 16.5 million cells. The spinner and nacelle mesh consist of 1.4 million and 1.3 million cells respectively (Figure 1). The upstream and downstream boundaries of the computational domain are positioned 13 rotor radii far from the blade surface, whereas the radial farfield boundary is positioned 7 rotor radii far from the blade surface. Advancing in time is realized employing 240 time steps per flapping period with 100 internal dual iterations which is oriented on previous investigations [6]. The Menter SST turbulence model is applied.

2.2. MaPFlow

MaPFlow [7] is a finite-volume multi-block MPI enabled compressible URANS solver equipped with low Mach preconditioning in regions of nearly incompressible flow. The discretization scheme is cell-centered and makes use of the Roe approximate Riemann solver for the convective fluxes. The scheme is 2nd order accurate in space on unstructured grids and applies the Venkatakrishnan’s limiter [8]. In time an implicit second order scheme is used introducing dual time stepping for facilitating convergence. The k-ω SST eddy viscosity model is used for turbulence closure.

Computational details. An O-type spherical mesh of 5.6 million cells is generated using the ANSYS ICEMCFD software. Due to the 120° symmetry, simulations of one blade using periodic conditions are performed. The farfield of the computational domain is extended 23 rotor radii far from the blade surface. Blade discretization is made using 185 nodes spanwise and 320 nodes chordwise. A number of 40 nodes are distributed in the blade surface boundary layer following a geometrical progress starting from $y^+=1$ for the first cell. A special refinement is made in the flap region, reaching a minimum grid spacing of 0.1m close to flap edges (Figure 2). A detail of a mesh slice showing the refinement along the span direction is shown in Figure 3. Advancing in time is realized employing 360 time steps per flapping period and 30 internal dual iterations.

2.3. hGAST

The engineering model is an integration of the inviscid aerodynamic model FOILFS into the BEM code hGAST [9], capable of providing unsteady, sectional aerodynamic characteristics of the blade sections installed with shape morphing actuators. FOILFS accounts for the unsteady aerodynamics associated with the TE active shape variations. It is based on linear aerodynamic theory and simulates unsteady aerodynamics due to arbitrary camber line variations of a 2D airfoil. In order to take into account dynamic stall conditions, FOILFS is enhanced with ONERA model. The required input are the steady-state lift, drag, and moment characteristics for the various airfoil deflected shapes, which in the present analysis have been simulated using the 2D version of the MaPFlow code for fully turbulent flow conditions.
Computational details. The polars of the aerodynamic loads are derived through 2D simulations of the MaPFlow CFD code for the various flap angles between -10° and +10° with a step of 2.5°. All simulations correspond to fully turbulent flow at $Re=17\cdot10^6$ and $Ma=0.23$. In order to cover all possible AoAs, polars are derived for a range of -14° to 16° with a step of 2°. In few cases, the combination of the large AoAs with the flap angles results in unsteadiness of the flow; unsteady-state simulations are adopted in those cases. The numerical mesh consists of approximately 100000 cells.

**Figure 1**: FLOWer simulation setup

**Figure 2**: Detail of the blade surface close to the flap region used in MaPFlow simulations

3. Results

3.1. Definition of the simulation case

In order to evaluate the influence of the oscillating flap in the loading and power performance of the turbine rotor, the stiff choice for a velocity of 9m/s is considered. Since the rated power corresponds to a 10m/s velocity, the 9m/s is chosen as a representative operational condition. The corresponding settings for the rotational velocity and the pitch angle are 8.49 rpm and -2° respectively. For the flap configuration, a curvilinear flap shape with a length of 10% chord and a maximum flap deflection of ±10° are selected. All codes use the same relationship for the deformation of the mean line of the blade sections in the flapping region, as defined in [2]. They also consider a linear interpolation of the
discretized blade surface along the spanwise direction at the flap edges. The discontinuity of the geometry in that region has been approximated as a solid membrane which does not allow the fluid flowing through it. The flap is centered at 75% blade span and is extended over 15% of the blade length. Flapping frequencies of 1P and 3P are considered. Both CFD simulations assume fully turbulent flow.

**Figure 3**: Detail of a mesh slice close to the flap region used in MaPFlow simulations

### 3.2. Neutral simulation without flap

The predictions of the two codes are first compared for the neutral position, which is actually a steady state simulation without flap. Although a grid independency study has been already performed in the context of the re-evaluation of the AVATAR rotor [10], such a comparison is suggested due to the fact that flap simulations require locally refined meshes. Moreover, in the context of the re-evaluation, MaPFlow simulations were performed using DTU meshes. In Figures 4, the predicted thrust and driving sectional forces are compared and found to be in good agreement. The predicted integrated thrust and power are given below (Table 1) and present relative differences about 2.4% and 1.4% respectively.

|                | MaPFlow | FLOWer | Difference |
|----------------|---------|--------|------------|
| **Thrust (kN/m)** | 1231    | 1261   | 2.35%      |
| **Power(kW)**     | 6487    | 6367   | 1.37%      |

**Table 1**: Neutral simulation (no flap) - Comparison between MaPFlow and FLOWer predictions for the integrated thrust and power

### 3.3. Oscillating flap simulations – Comparison between codes

The predicted radial distributions of loads are compared in Figure 5, Figure 6 (1P case) and Figure 7, Figure 8 (3P case). In all figures results corresponding to four different flap deflections are presented; the two maximum flap deflections ±10° and the two neutral positions (zero flap deflection). Zero up stands for the neutral position when the blade is moving from the positive flap angles to the negative ones (upwards), and zero down stands for the neutral position when the blade is moving in the opposite direction. The differences between the two neutral positions denote the flow hysteresis. Both CFD codes predict the same variation pattern in the flap region, including the sharp jumps of the
driving force at the flap edges due to the fact that they use a refined grid in that region. Regarding thrust, the agreement in the 1P case is very good, whereas in the 3P case there is a small difference in the maximum amplitude at the positive flap angle. This is also depicted in the corresponding loop gradient (Figure 7b) indicating that the effective angles of attack (AoA) are not the same at all instants. Regarding driving force, there is a good agreement in terms of maximum amplitudes and loop gradients in the 1P case (Figure 6). Small differences in level can be justified by the pre-existing differences in the neutral simulation. In the 3P case (Figure 8) MaPFlow predicts slightly higher maximum amplitude at both positive and negative flap angles.

Results show that the influence of the flap motion is extended much further from the flap region which is in-line with previous findings [6]. This influence does not occur in a symmetrical way around the flap centre: maximum increase in thrust occurs more outwards, approximately at 78% of rotor radius, whereas its maximum decrease is predicted slightly inwards, approximately at 73% of rotor radius (Figure 5a and Figure 7a). The above indicate a strong influence of trailing vortices at the flap edges changing the effective AoAs at sections further from the flap region. Both CFD codes predict that the maximum decrease in thrust (negative flap) is larger than its maximum increase (positive flap) by approximately 9%. This is more pronounced in the predictions of the driving force (Figure 6a and Figure 8a). Another effect of the 3D flow along the blade span is the significant reduction of hysteresis predicted by both CFD codes when compared to the hGAST which simulates the flap movement using a section by section 2D aerodynamic approach. This is attributed to the effect of the “trailing vorticity” along the span and is depicted on the “narrow” loops of the sectional loads at the flap centre (Figure 5b, Figure 7b) confirming the results of a previous study for the DTU 10 MW turbine [6].

![Figure 4](image1.png)

**Figure 4:** Neutral simulation (no flap) - Comparison between MaPFlow and FLOWer predictions for the sectional loads

![Figure 5](image2.png)

**Figure 5:** 1P case - Variation of sectional thrust: (a) Radial distribution of thrust along blade span for zero and ±10° flap angle (b) Variation of thrust with flap angle at the flap centre (75% blade span)
Figure 6: 1P case - Variation of sectional driving force: (a) Radial distribution of driving force along blade span for zero and ±10° flap angle (b) Variation of driving force with flap angle at flap centre (75% blade span)

Figure 7: 3P case - Variation of sectional thrust: (a) Variation of thrust along blade span for zero and ±10° flap angle (b) Variation of thrust with flap angle at flap centre

Figure 8: 3P case - Variation of sectional driving force: (a) Variation of driving force along blade span for zero and ±10° flap angle (b) Variation of driving force with flap angle at flap centre

As also mentioned in [6], in 3D simulations there is an additional downwash or upwash in the flap section leading to a respectively lower or higher effective AoA which induces additional drag in relation to the baseline AoA. The adverse effect of trailing vortices in the flap section is, however,
countered by a positive effect in the blade parts adjacent to the flap section. Therefore, in the flap section, the effect of the flap is reduced compared to a 2D simulation. However, the sections neighboring to the flap part produce higher/lower lift due to the induced upwash/downwash for respectively positive/negative flap angles. Such a 3D effect cannot be represented by the 2D flap simulation approach of the engineering model hGAST. By comparing the results of the CFD codes to hGAST (Figure 5a, Figure 6a), it is clear that the 3D effect results in a smoothening of the radial distribution at the flap edges and a reduced amplitude in the flap region, which subsequently decreases the slope of the thrust loop at the flap centre (Figure 5b, Figure 7b). The sign change of the induced velocity caused by the flap edge vortices is also apparent in the driving force as sharp variations at the transition between the flap and the rigid rotor part (Figure 6a, Figure 8a). In the 3P case, the predictions of the sectional driving force present a behavior opposite to that of thrust. When thrust increases locally in the flap area, the driving force decreases compared to neighboring sections. This results again from the strong influence of drag on the driving component. Compared to hGAST, CFD predictions of the driving force present reduced amplitude and a lower slope of the loop (Figure 6, Figure 8).

The increase of flapping frequency from 1P to 3P has a twofold effect: it reduces the loading amplitude and significantly increases the hysteresis, as shown by the broadening of the corresponding loops (Figure 5b, Figure 7b for thrust and Figure 6b, Figure 8b for driving force). A similar effect has been observed in the parametric study of the 2D oscillating flap in D3.3[11]. However, in the 3D simulation the reduced amplitude leads to less shed vorticity and less hysteresis compared to the 2D case. This can justify the fact that the loops of thrust and driving force predicted by hGAST are wider compared to those predicted by the CFD codes, especially in the 3P case (Figure 7b, Figure 8b).

![Figure 9: 1P case: Temporal variation of (a) integrated thrust and (b) wind turbine power](image)

![Figure 10: 3P case: Temporal variation of (a) integrated thrust and (b) wind turbine power](image)
In Figure 9 and Figure 10, the temporal variations of the integrated thrust and power are presented. For the 1P case, the two CFD codes present a good agreement in the amplitude and phase of oscillations. In comparison to hGAST, the CFD codes predict lower amplitude in the flap region, which is however compensated for by the increased amplitude at the flap edges. As a result the predicted integrated thrust and power present similar amplitudes. For the 3P case, predictions of the two CFD codes show a good agreement in thrust and power amplitudes. However, they present some differences in the pattern and the mean level of the power oscillation. The mean value predicted by MaPFlow is close to that of its neutral simulation, whereas the mean value predicted by FLOWer shows a small reduction. In addition, both CFD codes predict that the power production at the positive flap angles deviates from the pure sinusoidal variation. However, the presence of the additional frequency appears more intensely in the FLOWer predictions. Compared to hGAST, the CFD predictions present larger differences in the amplitude of thrust and power oscillations than those observed in the 1P case. These differences are attributed to the fact that in the 3P case the 3D flow effect induced by the trailing vorticity influences a more restricted extension of the blade (compare Figure 5a with Figure 7a and Figure 6a with Figure 8a). Therefore, the reduced amplitude predicted by the CFD codes in the flap region is not compensated for by the increase of loads at the neighboring to the flap part sections resulting in lower amplitude of the integrated thrust and power.

3.4. Effect of oscillating flap length

In order to assess the effect of the flap length on thrust and power, two additional simulations are performed using MaPFlow CFD code: The flap length is extended to 0.15 and 0.20 of the blade chord for the case of 1P flapping frequency. The radial distributions of thrust and driving force are presented in Figure 11. It is observed that the increase of both thrust and driving force is significantly higher at the negative flap angles. The maximum amplitude of thrust at the negative flap angles is nearly 20% more than its maximum amplitude at the positive flap angles. This percentage is kept constant by increasing the flap length from 0.1 to 0.15 and 0.2 of the blade chord. In terms of the driving force the maximum amplitude at the negative flap angles is nearly 37% more than that occurring at the positive flap angles. By increasing the flap length this percentage augments even more reaching almost 50% for the 0.2 flap length.

The integrated thrust and power present a similar behaviour with the maximum amplitudes of the sectional loads (Figure 12). By changing the flap length from 0.1 to 0.15 chords the amplitude of the integrated thrust increases by 9% with respect to the mean thrust (neutral simulation). Extending the flap length more to 0.2 chords, an additional increase of 8% is predicted. Regarding power, the flap length change from 0.1 to 0.15 chords causes an increase of 10.5% with respect to the mean value. A further extension to 0.2 chords leads to an additional power increase of 9.3%. In line with the maximum amplitudes of the radial distributions, variations of thrust and power are larger at the negative flap angles indicating that the maximum thrust/power decrease is larger than the maximum thrust/power increase. For all flap lengths, the maximum thrust decrease is about 10% higher than the maximum thrust increase (with respect to the mean values of neutral simulation). This effect is more pronounced in power and increases by extending the flap length. Power maximum decrease is 18%, 25% and 29% higher than power maximum increase for flap lengths equal to 0.1, 0.15 and 0.2 chords respectively.

4. Conclusions

A simulation case was defined in order to evaluate the influence of oscillating flap in the loading and power performance of the AVATAR rotor. The predictions of two advanced CFD codes, FLOWer and MaPFlow, and one engineering model, hGAST, were compared in terms of sectional and integrated loads. An overall good agreement was obtained between the two CFD codes regarding the amplitude of oscillations and the flow hysteresis confirming the findings of a previous study for the DTU 10 MW turbine [6]. Significant 3D effects were observed, indicated by the expansion of the flap influence over
the blade span further from the flap region, by the off-center appearance of the maximum increase/decrease of thrust and driving force, and by the reduction of flow hysteresis in comparison to the hGAST results, which are based on a 2D sectional analysis. Both CFD codes similarly reproduced the 3D effects and the flow discontinuity at the flap edges. The increase of flapping frequency from 1P to 3P reduced the amplitude of loading and significantly increased the hysteresis.

For the 1P case the two CFD codes predicted lower amplitude of loading in the flap region and increased amplitude at the section adjacent to the flap compared to the engineering model. The two effects compensated each other resulting in similar predictions of integrated thrust and power. However, in the 3P case, the 3D flow effect occurred in a restricted extension of the blade and did not cancel the amplitude reduction of the loads. Therefore, the engineering model over-predicted the amplitudes of the integrated thrust and power. Thrust and power amplitudes were found higher at the negative flap angles by 10% and 18% respectively. The chordwise extension of flap length showed that the amplitudes of the integrated thrust and power increase by 9-10% per 0.05 chord length increment with respect to the mean value of the neutral simulation. In the case of the AVATAR low induction rotor the low effective AoAs allow for large flap length increments. It should be mentioned though that there is a limit set by the occurrence of flow separation. Finally, the effect of flap is stronger at the negative flap angles, indicating that the maximum thrust and power decrease with respect to the mean value are significantly higher than the maximum thrust and power increase.

Figure 11: 1P case – Radial distribution of loads with flap length (a) thrust and (b) driving force. Predictions by MaPFlow code.

Figure 12: 1P case – Variation of integrated loads with flap length (a) thrust and (b) power. Predictions by MaPlow code.
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