An investigation of unsteady 3D effects on trailing edge flaps

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Abstract.
The present study investigates the impact of unsteady and viscous three-dimensional aerodynamic effects on a wind turbine blade with trailing edge flap by means of CFD. Harmonic oscillations are simulated on the DTU 10 MW rotor with a flap of 10% chord extent ranging from 70% to 80% blade radius. The deflection frequency is varied in the range between 1p and 6p. To quantify 3D effects, rotor simulations are compared to 2D airfoil computations. A significant influence of trailing and shed vortex structures has been found which leads to a reduction of the lift amplitude and hysteresis effects in the lift response with regard to the flap deflection. In the 3D rotor results greater amplitude reductions and less hystereses have been found compared to the 2D airfoil simulations.

1. Introduction
The reduction of ultimate and fatigue loads plays an important role in today’s wind energy research. In the background of economic efficiency, load alleviation systems bare potential to reduce rotor weight and costs, to increase the turbine reliability or allow a further enlargement of the rotor radius and thus power output. One promising concept to reduce dynamic load fluctuations are trailing edge flaps applied to the outer part of the rotor blade. As flaps are able to increase or decrease the local lift by adapting the deflection angle, it is possible to partly compensate load variations due to variations of the effective inflow angle.

Over the last years several investigations showed the potential of the flap concept, e.g. [1]. In aeroelastic simulations fatigue load reductions up to approximately 30 % have been found for a trailing edge flap covering up to 25 % of the blade span of a 5 MW turbine [2]. In most of the numerical studies the aerodynamic loading was computed by blade element momentum (BEM) codes, which have been extended with different engineering models to account for the unsteady flow. As viscous and unsteady aerodynamics have a great influence on dynamically deflected flaps, it is however important to also apply higher fidelity models and gain knowledge of the flow physics. A recent benchmarking [3] showed that there are still differences between the results of CFD simulations and BEM methods which need to be analyzed. While a previous investigation focused on the analysis of static flap deflection angles [4] by means of CFD, the main objective of the present work is to study the influence of unsteady 3D effects on the example of harmonically oscillating morphing flaps.

Different deflection frequencies ranging from 1p to 6p are analyzed on the DTU 10 MW rotor [5] at rated operational condition. These frequencies are considered a realistic operational
range for active load alleviation [3]. The investigated flap layout consists of a single flap ranging from 70% to 80% blade radius with 10% local chord extent. This limited dimension along the blade span was chosen to obtain a high impact of 3D effects. In all cases the flap oscillates with an amplitude of 10°.

2. Aerodynamic effects of trailing edge flaps

A qualitative illustration of the vortex development around a rotor blade with deflected flap can be given on the basis of potential flow theory. Figure 1 shows the vortex system with positive (downwards) flap deflection in spatial (left side) and temporal (right side) consideration.

![Figure 1. Sketch of bound circulation with trailing and shed vorticity.](image)

Due to the spatial gradient of bound circulation along the blade radius, a vortex sheet trails the rotor blade. In the flap section the bound circulation is locally increased due to the change in camber. This leads to higher gradients at the flap edges and hence greater trailing vortices at these locations. Outboard at the blade tip, the tip vortex is shown. Wake vorticity caused by radially changing bound circulation is commonly referred to as trailed vorticity. The temporal consideration displays an increase of bound circulation caused by an increase of the flap angle. This causes shed vorticity with opposed sense of rotation. Shed vortex structures re-induce velocities at the blade location and lead to a change in the effective angle of attack (AoA) which in turn results in the blade loads. Wake vorticity linked to temporal changes in bound circulation is called shed vorticity. Shed vorticity has been analyzed by Leishman in [6] for the 2D case of an airfoil with flap. In his work he derived an analytical solution for the unsteady lift response caused by sinusoidal flap actuation based on Theodorsen’s theory [7] for thin airfoils. This solution is dependent on the reduced frequency, one of the most important characteristic numbers when it comes to unsteady aerodynamics. The definition is shown in equation (1). It is a measure of the unsteadiness of a problem. In the case of a 2D airfoil, phenomena with a reduced frequency below 0.05 can roughly be classified as quasi-steady. But when it comes to rotor aerodynamics, this assumption has to be critically regarded as the behaviour changes due to the 3D flow. In the present work the regarded flap frequencies correspond to reduced frequencies of \( k = 0.024 - 0.147 \) at mid flap position, which means that unsteady effects are expected.

\[
k = \frac{\pi \cdot f \cdot c}{V}
\]

In his work Leishman derives that the lift amplitude is continuously decreasing with the reduced frequency and it trails the flap deflection signal for reduced frequencies lower then 0.6 in the incompressible derivation.
Generally the efficiency of the flap with regard to local lift increase or decrease is reduced in the 3D case. However the blade parts next to the flap section produce a higher or lower lift for respectively positive or negative flap deflections. This is caused by the sign change of the induced velocities over the flap edge. With regard to integral loads such as power and thrust, this counters the negative effect in the flap section.

3. Numerical approach

3.1. Simulation process chain

Over the last years, a process chain for the simulation of wind turbines has been developed at the Institute of Aerodynamics and Gas Dynamics (IAG), University of Stuttgart [8]. The main part constitutes the CFD code FLOWer, which originates from the German Aerospace Center (DLR) [9].

FLOWer is a compressible code that solves the three-dimensional, Reynolds-averaged Navier-Stokes equations in integral form. The numerical scheme is based on a finite-volume formulation for block-structured grids. To determine the convective fluxes, a second order central discretization with artificial damping is used, also called the Jameson-Schmidt-Turkel (JST) method. Time-accurate simulations make use of the Dual-time-stepping method as implicit scheme. To close the Navier Stokes equation system, several state-of-the-art turbulence models can be applied, as for example the SST model by Menter used in this study. FLOWer offers the use of the CHIMERA technique for overlapping meshes.

Grid generation is widely automated. The generation of the blade grid is conducted with Automesh, a script for the commercial grid generator Gridgen by Pointwise developed at the IAG. The blade grids are of C-type with a tip block and coning towards the blade root. In case of pure rotor simulations as performed in this study, the blade grid is placed in a 120°-model with periodic boundary conditions. This means that the flaps of all blades deflect simultaneously.

On the post-processing side, several scripts are available for the analysis of the simulations. Loads are determined through the integration of pressure and friction distribution over the blade surface. Sectional distributions along the blade span are generated similarly dividing the blade into different radial sections.

3.2. Trailing edge flap model

Trailing edge flaps are modeled based on grid deformation in FLOWer. Therefore, the deformation module [10] was extended by a polynomial function ([11], [12]) to describe the shape of the deflected flap.

\[ w = \varphi(x) \cdot \beta \quad \varphi(x) = \begin{cases} 0 & 0 \leq x < (c - b) \\ \frac{(c-x-b)^n}{b^{n-1}} & (c - b) \leq x \leq c \end{cases} \quad (2) \]

In equation (2) \( c \) represents the chord length, \( b \) the flap length and \( \beta \) the deflection angle. The result \( w \) is then the vertical change in y-direction, while the movement in x-direction is neglected for small deflection angles up to 10°. Using this function requires the chord to be aligned with the x-axis. The polynomial order \( n \) is set to 2 for this investigation. In figure 2 the deformation is shown for a 2D airfoil section. The un-deformed and deformed airfoil surface is shown on the left serving as input to the grid deformation algorithm, which computes the new simulation grid at each time step.

The methodology for the blade mesh is shown in figure 3. There is no separate grid for the flap part as it is integrated into the blade grid. The connection between the moving trailing edge flap and the remaining blade surface is handled by the deformation algorithm which generates a smooth transition. At the location of the flap edges the blade grid is refined along the blade span in order to capture radial gradients in the flow field.
3.3. Code-to-code validation of the simulations

A baseline simulation setup for the DTU 10 MW turbine without flap has been examined and validated by code-to-code comparison within the European FP7 project AVATAR. Therefore a simulation of the power curve on the basis of the stiff straight blade without precone was conducted in steady mode. The comparisons between the different codes of the project partners is presented in [13]. A detailed analysis of the FLOWer results is performed in [14] with a special focus on the comparison of steady and unsteady simulations. A comparison of the simulations with flaps to the AVATAR project partners can be found in [15] and [16].

3.4. Grid generation

For the 2D airfoil simulations, the 75% blade cut of the DTU 10 MW turbine (FFA-w3-241 airfoil) was extracted from the geometry, which is the mid flap position in the chosen trailing edge flap configuration. The airfoil grid was generated with the use of a script in the commercial grid generator Pointwise. Approximately 180,000 grid cells have been used with 417 surface nodes and 205 nodes in wall-normal direction. Boundary layer resolution was chosen for \( y^+ < 1 \). Farfield is placed at 150 chords distance.

For the pure rotor simulations the setup used in the code-to-code validation was modified in order to simulate a rotor with trailing edge flap. Flap edge refinements were included into the blade grid and a higher resolved background grid was chosen to accurately capture wake effects. A separate grid convergence study of the blade grid was performed with a steady flap deflection \(+/- 10^\circ\) and the results are presented in [3]. The final setup used in the present study amounts approximately 21.65 million cells.

3.5. Temporal discretisation of the simulation setup with flaps

Another critical issue with regard to the unsteady simulations is the temporal resolution meaning the choice of time step. Unsteady simulations in FLOWer make use of the Dual-Time-Stepping method as implicit scheme. In this approach a pseudo-time is introduced into the equation system at each time step for which a steady solution is obtained. The method allows the choice of significantly higher time steps than those dictated by the CFL condition in explicit schemes. However, the actual eligible size is problem dependent. In most cases the time step is a trade-off between simulation accuracy and computational time and it is necessary to determine
the greatest possible time step that can still resolve the unsteady flow effects sufficiently. To analyze the influence of the temporal discretization within this study, a sensitivity study has been performed based on 2D and 3D simulations.

At first the 2D airfoil case is described. The simulations have been performed at realistic inflow conditions extracted from the 3D rotor case to connect the 2D and 3D results. The Reynolds number was determined to 15.4 millions, Mach number to 0.2 and the AoA to 6.47°. For the determination of the time step influence a high flapping frequency corresponding to the sixth of the rotational velocity at rated operational point (6p) was chosen, which corresponds to a reduced frequency of 0.147. Results for the lift coefficient $c_l$ and drag coefficient $c_d$ are shown in figure 4. Four different time steps have been selected for the study and 100 inner iterations are performed in the Dual-Time-Stepping scheme for all investigated time steps except the small step of 0.028° for which 30 inner iterations are regarded sufficient.

As the results are transferred to the 3D case later on, the different time steps are designated by the corresponding azimuth step in a rotor simulation at rated rotational speed. A time step of 0.028° is for example equivalent to 4.8e-4s. This very small step correlates to 100 steps per convective time unit, which is in this case the chord length. With regard to the computational effort this time step is not realistic for the 3D case, but serves as reference in this 2D study. All other discretizations are applicable for pure rotor simulations. In both aerodynamic coefficients the influence of the time step size is apparent, but the effect on drag is more distinct. While lift agrees well for all resolutions except 1°, drag shows noticeable differences at 0.5° and minor differences at 0.25°.

Another parameter of influence is the amount of inner iterations in the Dual-Time-Stepping scheme, which has also been analysed for the time step of 0.5° with three different amounts of inner iterations, 50, 100 and 200. As a similar convergence of the results with increasing amount of inner iterations was experienced, no detailed analysis will be presented. In general it was observed that the temporal accuracy is more dependent on the total amount of iterations per convective unit, than the choice of time step or inner iterations. This conclusion can however not be transferred to stalled flows, for which a small time step is needed to resolve effects correctly.

Based on these outcomes, simulations of the pure rotor model have been conducted in order to get an impression of the 3D case. The flap is again oscillating with 6p frequency at rated operational condition. Similar time step sizes as in the 2D case have been chosen replacing 0.028° by including 0.125° as further halving. 100 inner iterations are performed. Figure 5 shows the resulting driving and thrust force variations at mid flap position. The forces are normalized with the total mean value to allow an easier assessment of the differences. While the thrust force shows a good agreement for all time step sizes, higher deviations are observed in the driving component in which the drag differences have a bigger impact. However a convergence of the curve progressions with decreasing time step size can be observed leading to small differences between 0.125° and 0.25°. To conclude the temporal discretization study, a time step size of
0.25° for a flapping frequency 6p shows sufficient accuracy in 3D simulations as trade off to computational time. This corresponds to 240 steps per flap oscillation. In 2D simulations smaller time steps correlated to the convective unit are feasible and consequently used.

Figure 5. 3D Influence of time step, 6p, 75% blade cut, normalized driving and thrust force.

4. Results

4.1. 3D rotor simulations with oscillating flap

At first, results of the different flap frequencies are compared for the 3D pure rotor simulations. All simulations have been conducted at rated conditions with 11.4 m/s wind speed and 9.6 rpm. The blade pitch angle is set to 0°. As ambient conditions an air density of 1.225 kg/m³ and a temperature of 288.15 K are used. The simulations were started as steady state computation on two multi grid levels with 5000 iterations respectively and a flap angle of 0°. This steady solution is then restarted in unsteady mode and simulated for the amount of revolutions required for converged loads. Please note that while in the previous time step study a cosine function is used as deflection signal, now a sinus function is applied (see eq. (3)).

\[ \beta(t) = 10^\circ \cdot \sin \left( 2\pi t \frac{N}{T_{Rotor}} \right) \quad N = [1, 2, 3, 6], \quad T_{Rotor} = 6.25s \] (3)

The frequencies correspond to reduced of frequencies of \( k = 0.024(1p) - 0.147(6p) \) at mid flap position. Figure 6 shows the results of integral power and thrust plotted over one rotor revolution. The effect of the flap can be clearly seen in both diagrams. Power and thrust are oscillating with the respective frequency. A higher frequent fluctuation is also apparent in the graphs, which results from flow separation at the cylindrical blade root. As illustrated in the surface stream trace plot in figure 7, unsteady separation is dominant there.

Due to this superposition of effects in the integral forces, it is necessary to regard sectional forces at a blade cut belonging to the flap part in order to investigate the flap effects. In the following again the 75% cut as mid flap position was extracted from the simulations. Figures 8 and 9 show the results of the local driving and thrust force at this location. While thrust shows the expected amplitude decrease and a phase shift with increasing frequency, larger differences are observed in the driving component. For the 3p and 6p case a second superimposed oscillation is visible from \( t/T_{Flap} \approx 0.8 - 1.2 \) (respectively 0.2 in fig. 8). This results from the high impact of drag at rated condition. As seen above (fig. 4), drag shows a significant amplitude increase at higher frequencies and additionally \( c_l \) and \( c_d \) experience a different phase shift. The superposition of the in-plane force components leads to this phenomenon.

In figures 10 and 11 sectional distributions of driving and thrust force are shown for 1p and 6p case respectively. Four instantaneous solutions are plotted for maximum, minimum and 0° flap deflection. Once more the strong influence of drag on the driving component can be seen. For maximum positive deflection the related drag increase causes a driving force reduction in
the flap section. The change of sign in induced velocity caused by the flap edge vortices is also apparent in the driving force as steps appear at the transition between flap and rigid rotor part. In both force components the positive effect of the flap deflection on neighboring blade sections can be seen as it is described in chapter 2. While 3D effects reduce the effect of the flap in the flap section compared to 2D, the efficiency of the sections next to the flap part is increased due to the induced upwind/downwind for respectively positive/negative flap angles. The differences caused by unsteady effects can also be observed in the plots. Larger variations of the forces are seen in the 1p compared to the 6p case over the whole blade part influenced by the flap.

To study these unsteady phenomena in more detail and to analyse the main effects in the 3D case, the rotor simulations are compared to 2D airfoil simulations. For this purpose again the mid flap position is extracted from the simulations and contrasted with 2D computations. To compare the results directly it is necessary to extract realistic 2D inflow conditions at the blade cut from the 3D simulations, meaning the AoA and inflow velocity. In case of an oscillating flap both values are however not steady as dynamic inflow effects lead to a variation of the local AoA and effective inflow velocity over a flap period.

4.2. Influence of varying angle of attack 3D
To analyse the influence of the varying AoA, the 1p case is regarded in the following. An instantaneous AoA extraction is performed by the reduced axial velocity method [17]. This
A method for steady simulations has proven to show reasonable results [4] and as in the 1p case the reduced frequency is still very low with value of 0.024, a quasi-steady approach is appropriate. The results for the inflow velocity and AoA are shown in figure 12. While the inflow velocity shows no major variations, the AoA oscillates with an amplitude of 0.6°.

Figure 12. 1p Instantaneous inflow conditions

Figure 13. 1p Comparison of lift and drag, 3D, 75 % radius.

Figure 13 presents the resulting $c_l$ and $c_d$ variations in addition to the resulting variations for an averaged angle of attack of 6.5° and inflow velocity of 68m/s ($c_{l,mean}$, $c_{d,mean}$). As it is visible the AoA oscillations have only a minor influence on the value of $c_l$ but strongly on $c_d$. This is reasonable as for the determination of $c_l$ and $c_d$ in the 3D case, the forces are integrated from the surface solution as driving and thrust component at first and then transferred to the inflow coordinate system. A projection difference of 0.6°, which is the amplitude in the 3D AoA extraction, has only reduced impact on the roughly 100 times larger value of $c_l$ compared to $c_d$. As $c_d$ is however strongly differing it is not possible to draw any conclusions on $c_d$ without knowing the precise transient AoA in the 3D case. An accurate AoA determination, especially in unsteady simulations, is however very delicate as trailed and shed vorticity needs to be accurately considered. With regard to $c_l$ the differences are however small and the averaging approach is
hence considered appropriate. An FFT analysis of the results showed that the averaged and instantaneous solution differ by 1% in lift amplitude and 17% in phase shift in the 1p case. In summary it can be concluded that the lift amplitude extracted from the 3D simulation is only minorly affected by the averaging method, while the phase shift shows noticeable differences and thus the results have to be carefully assessed.

4.3. Comparison to 2D simulations

The 3D results of the 1p and 6p case are next compared to 2D simulations at mean inflow conditions. In both cases the mean flap angle amounts approximately 6.5° and the inflow velocity 68 m/s. This leads to a Mach number of 0.2 and a Reynolds number of 15.4 million. Results of the comparison between 2D static deflection, 2D sinusoidal deflection and 3D sinusoidal deflection are shown in figure 14 for the 1p and figure 15 for the 6p case. For the 1p case additionally an AoA corrected version of the 2D sinusoidal oscillation case is plotted which is computed by formula (4). As for the 6p case the AoA variations are smaller but also as the quasi-steady AoA extraction according to [17] is not eligible, no AoA corrected curve is plotted.

\[ c_{l,2Dsinus,AoAcorr}(t) = c_{l,2Dsinus}(t) + 2\pi (\alpha_{3Dsinus}(t) - \alpha_{mean}) \]  (4)

Figure 14. 1p Comparison of lift 2D/3D, 75 % radius.

Figure 15. 6p Comparison of lift 2D/3D, 75 % radius.

The plots show the expected decrease of lift amplitude from 2D static over 2D sinusoidal to 3D sinusoidal. For the 1p oscillation the comparison of 2D static and 2D sinusoidal results shows the minor influence of unsteady effects. Even though a beginning hysteresis is seen in the 2D sinusoidal results, \( c_l \) amplitude reduction is still small. This result corresponds well to reduced frequency in this case with 0.024. Larger differences are seen by comparing 2D and 3D results which show the decrease of amplitude caused by trailed and shed vorticity. The reduced amplitude leads to less shed vorticity and thus less hysteresis is apparent compared to the 2D solution. The AoA corrected 2D curve shows the approximative result for a 2D simulation including an AoA variation in the inflow. The curve demonstrates less hysteresis and a smaller amplitude compared to the baseline progression, which is reasonable as due to the axial induction the AoA progression is a feedback of the aerodynamic forcing. In a quasi-steady case like this one it is able to react to the instantaneous load and mimic the effects. The smaller slope with regard to the 3D curve can be explained by the decrease of the gradient \( dc_l/d\beta \) in 3D.

In the 6p oscillation unsteady effects become more dominant with a reduced frequency amounting 0.147. Already in the comparison of 2D static and 2D sinusoidal solution a significant amplitude reduction and hysteresis can be observed. In the 3D rotor solutions the amplitude is like in the 1p case further reduced and consequently again less hysteresis is apparent.
For a quantification of these effects $c_l$ amplitudes are shown in table 1. Phase shifts are not evaluated due to their dependancy on the AoA. A continuous reduction of lift amplitude can be observed in 2D and 3D. While it decreases nearly linearly in 2D, in 3D a significant step is seen between the 2p and 3p frequency.

|     | 1p        | 2p        | 3p        | 6p        |
|-----|-----------|-----------|-----------|-----------|
| 2D  | 0.42 (100%) | 0.40 (95%) | 0.38 (90%) | 0.33 (79%) |
| 3D  | 0.30 (100%) | 0.29 (97%) | 0.25 (83%) | 0.24 (80%) |

\[ \frac{d c_l, 3D}{d c_l, 2D} \] 71% 70% 66% 73%

**Table 1.** $c_l$ Amplitude, 75% blade cut, 2D and 3D results.

### 5. Conclusions
Unsteady and viscous 3D aerodynamic effects play an important role on trailing edge flaps. Trailing and shed vorticity has a strong influence and leads to a decrease of lift amplitude and a hysteresis loop. The comparison between 2D airfoil and 3D rotor simulations highlights the significantly higher decrease in the rotor case with an order of 70% of the 2D value for the respective flap frequency.

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