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A Study of Morphing Trailing Edge Flaps Applied on Offshore Wind Turbine

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Abstract: **Wind turbines are operating in a highly unsteady flow environment which causes dynamic load fluctuations relevant to the overall wind turbine design. Fatigue loads play an important role in the aeroelastic rotor development and contribute significantly to the turbine costs as blade loads cascade down through the entire turbine system. A reduction of fatigue loads can thus have a positive influence on the rotor weight, costs and system reliability or allow a further increase of the rotor diameter. Active trailing edge flaps (ATEFs) represent a very promising approach for the reduction of fatigue and also ultimate loads. By adapting the deflection angle it is possible to adjust to the current inflow situation and reduce load fluctuations. The present study investigates the influence of three-dimensional aerodynamic effects on a wind turbine rotor blade with trailing edge flap by means of CFD. Different flap extensions in chord and radial direction can be analyzed on rotor blade. The study shows that to 2D airfoil simulations at mid flap position shows that vortices which develop at the flap edges have a significant influence on the aerodynamic characteristics. They reduce the lift increase or decrease caused by the flap deployment and thus the flap effectiveness. As compared to 2D, 3D effect shows reduction in lift variation.**

Keywords: CFD, Trailing edge flaps, Load reduction

I. INTRODUCTION

The wind energy market grew significantly in the last decade, with the wind energy contribution to the global energy market being larger and larger. Wind energy research has focused in improving the integration of wind turbines in the electrical grids and in reducing the cost of wind energy, in an effort to increase even more the share of wind energy in the world. Increasing the rotor size, and thus the swept area, for the same drive train and rated power, has been one of the solutions to decrease the cost of wind energy, especially at low turbulence sites. The leading wind turbine manufacturers now market turbines with rotor diameters over 100 m and nominal power from 3 to 6 MW. Increasing the rotor area increases the energy harvested by the rotor, but also increases significantly the fatigue and extreme loads of the wind turbine [1].

Wind turbines rotor size has increased significantly over the last years in order to harvest more energy and to reduce the cost of wind energy. A large part of modern wind turbines have now blades longer than 40 m. This increase in blades size results in an increase in both fatigue and extreme loads in the main components of the turbine: blades, drive train, tower, foundations etc. Decreasing those loads is important in order to keep the cost of energy low [2].

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 10^0.

II. 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. Due to the spatial gradient of bound circulation along the blade radius, a vortex sheet trails the rotor blade [6]. 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.

Figure 1: Sketch of bound circulation with trailing and 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 of frequencies of $k = 0.024 - 0.147$ at mid flap position, which means that unsteady effects are expected.

$$k = \pi \cdot f \cdot c / V$$

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 [8-10]. 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.

III. 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, 10]. 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 [11-15]. 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 [14]. 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.

IV. 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 to describe the shape of the deflected flap.

$$w = \varphi(x) \cdot \beta \qquad \varphi(x) = \begin{cases} 0 & 0 \le x < (c-b) \\ \frac{(c-x-b)^n}{b^{n-1}} & (c-b) \le x \le c \end{cases}$$

In the above equation, c represents the chord length, b the flap length and β 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 [16]. 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 [17].

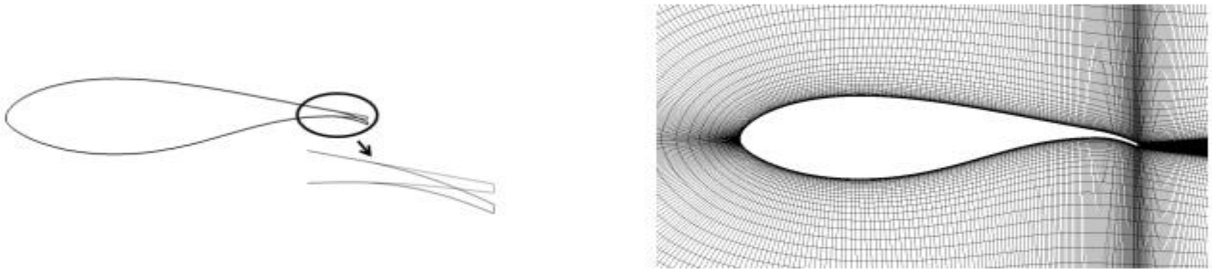

Figure 2: Methodology for 2D deflection

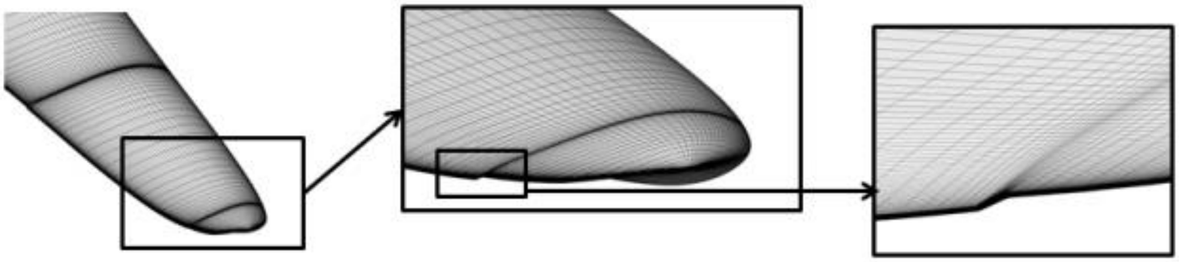

Figure 3: Methodology for 3D deflection

V. CONCLUSION

In the present study the high influence of three-dimensional effects on trailing edge flaps is shown. The flap deflection and the corresponding change of aerodynamic coefficients causes strong gradients in bound circulation along the blade span resulting in a vortex-downwash at the flap edges. These vortices reduce the flap effectiveness with regard to the two-dimensional airfoil case. Generally the effect increases with a smaller radial flap size as seen in the comparison of the lift increase or decrease between the 2D and 3D case. Consequently with regard to the flap design, a larger extension along the blade span is favorable. Flow separation becomes more and more important at higher chord extensions.

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