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Kobæk, C. M.; Hansen, Martin Otto Laver

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Numerical study of Wavy Blade Section for Wind Turbines

Kobæk C.M.[1] and Hansen M.O.L[2]

[1]DONG Energy Wind Power
Nesa Allé 1
DK-2820 Gentofte
Denmark
cecko@dongenergy.dk

[2]DTU Wind Energy
Nils Koppels Alle, build. 403
DK-2800 Lyngby
Denmark
molh@dtu.dk

Abstract. The Wavy Blade concept is inspired by the unique flipper of a humpback whale, characterized by the tubercles located at the leading edge. It has been suggested that this shape may have been a result of a natural selection process, since this flipper under some circumstances can produce higher lift than a flipper having a smooth trailing edge and thus could be potentially beneficial when catching food. A thorough literature study of the Wavy Blade concept is made and followed by CFD computations of two wavy blade geometries and a comparison with their baseline S809 airfoil at conditions more relevant for modern wind turbines. The findings in the literature from geometries similar to the hump back whale flipper indicate that the aerodynamic performance can be improved at high angles of attack, but sometimes at the expense of a lower lift slope and increased drag before stall. The numerical results for a blade section based on the S809 airfoil are, however, not as promising as some of the findings reported in the literature for the whale flipper at high angles of attack. These first CFD computations using a thicker airfoil and a higher Reynolds number than the whale flipper indicate that the results may very well depend on the actual airfoil geometry and perhaps also the Reynolds number, and future studies are necessary in order to illuminate this further.

1. Introduction

It is the aim of any research project related to wind energy to help the continuous decrease in the Levelized Cost of Energy LCoE to make wind more and more competitive with traditional production means. This study concerns a possible improvement of the blade aerodynamics by applying a so called wavy surface airfoil. The idea is not new and was described by Fish and Battle [1] when observing the flippers of humpback whales that have large tubercles or protuberances along its leading edge, see the sketch on Figure 1. It was suggested that these tubercles somehow help the hydrodynamic efficiency of the flipper compared to a flipper with a straighter leading edge. This leading edge could be a result of possible genetic optimization or a natural selection process, since a whale with a more efficient flipper will be able to maneuver better and thus be superior when catching its food.

A very thorough literature study highlighting the important conclusions is first given. This is then followed by a CFD computation of the wavy blade concept, but at conditions relevant for a modern wind turbine blade; that is using a rectangular planform instead of directly mimicking the whale flipper and at higher Reynolds numbers. Three different geometries were investigated using RANS and applying the γ-Reθ transition model of STAR CCM+.

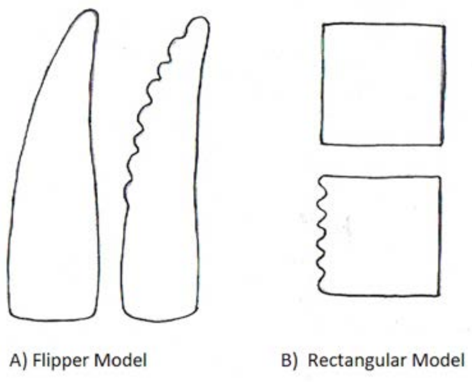

Figure 1: Sketch of the basic geometries referred to in the text. a) Typical flipper, b) Rectangular blade segment

Several studies to investigate and quantify a possible hydrodynamic benefit of a wavy leading edge have been done. In one of the first attempts to investigate the possible effect of a wavy leading edge of a humpback whale Watt and Fish [2] performed an inviscid 3-D computation showing a small increase in lift and a reduction in induced drag at an angle of attack of 10 degrees. However, it was also estimated that when accounting for the viscous effects the found drag reduction might not take place. Miklosovic et al. [3] made an experimental wind tunnel study on a model resembling the geometry of the whale flipper with and without tubercles and found a delayed separation and an increased maximum lift. The lift to drag ratio of the model with a sinusoidal leading edge was generally higher than or equal to the ratio of the smooth model, except in a very narrow band of angles of attack between 10 and 12 degrees. The model was based on a NACA0020 profile similar to a real flipper and the Reynolds number was around 500.000, where the effect from transition may be important. Next, Pedro and Kobayashi [4] modelled the experiment by Miklosovic et al. numerically, using the Detached Eddy Simulation turbulence model at the same Reynolds number. The results were in good agreement with the experiments, and further indicated some possible aerodynamic improvements of the scalloping leading edge for the 3-D flipper wing. Appearance of streamwise vortices was observed only for the wavy blade model which might indicate that these are responsible for mixing of the flow and reenergizing the low momentum boundary layer just before separation, in a manner similar to that of a conventional vortex generator. Johari et al. [5] performed an experimental study in a water tunnel at Re=183.000 for seven airfoil sections based on the NACA 63_4-021 airfoil: One baseline having a smooth leading edge and six with a sinusoidal leading edge with two different wavenumbers λ/c=0.25 and 0.5 and three amplitudes A/c=0.025, 0.05 and 0.12, c being the chord. Forces were measured for a large range of angles of attack between -6 and 30 degrees and the conclusions were that the blade sections having a wavy front showed a different stall behavior with lift coefficients up to 50% higher in stall and keeping the drag at the level of the baseline model. In baseline pre-stall, however, the wavy blade lift was lower and the drag higher compared to the baseline. Also the slope $dC_l/d\alpha$ was lower for the wavy front blade sections before stall and was decreasing with increased amplitudes. The effect from the wavenumber seemed to be small, however there was an indication that small wavenumbers could give slightly higher lift and lower drag. Simple flow visualizations using tufts indicated that separation takes place at the troughs in the sinus and that the flow remains attached at the peaks, whereas the baseline model separates along its entire span, and this partly attached flow of the wavy blade explains the higher lift at stall. The conclusions from Johari et al. indicates that a wavy blade section will only be efficient on a wind turbine blade when the flow is expected to always be separated, i.e. at the root of a blade with thick airfoils continuously operating at high angles of attack.

Also Hansen et al. [6] made an experimental study of a series of airfoils (NACA 0021 and NACA 65-021) with various sinusoidal leading edge configurations using hydrogen bubble visualizations and direct force measurements at Re=120.000. Similar to [5] they found a more smooth stall and a greater post-stall lift for the wavy blade sections compared to the baseline, but again at the expensive of a lower pre-stall lift and a small degree of increased drag for some angles of attack. Especially the NACA 0021 experienced a considerable degraded pre-stall lift also compared to a wavy NACA 65-021 airfoil, indicating that the effect of a sinusoidal leading edge also depends on the applied airfoil geometry. Another conclusion was that the maximum lift, stall characteristic and drag were until a certain point improved for the NACA 0021 airfoil when reducing the wavelength. Further, Zverkov et al. [7] performed an experimental analysis of a wavy blade section at Re=170.000 based on the TsAGIR-3a-12 airfoil. A clean baseline airfoil was compared to a wavy blade section, where the wave humps were not only at the leading, but extended all the way to the trailing edge. Oil film visualizations showed a separation bubble and stall at an angle of attack of 15 degrees for the smooth blade, while separation bubbles were first observed at an angle of attack of 28 degrees and only in the grooves for the wavy blade section. For angles of attack of 0 and 15 degrees the flow structures were reported to be similar. A laminar separation was observed for the smooth blade and in the grooves of the wavy blade, while the flow on the humps remained attached. Hot wire measurements indicated that transition and subsequent reattachment happened earlier for the separated flow in the grooves compared to the smooth blade, and it was thus assumed that the wavy blade is more capable of withstanding the adverse pressure gradient on the suction side and thus delay separation. However, no measured lift and drag data were made, so it is not known if the pre-stall maximum lift is lower as indicated in some of the previous studies. Also some numerical studies on wind turbine blades have been made, like Zhang and Wu [8] who computed the NREL phase VI rotor with and without a sinusoidal leading edge. In good accordance with previous studies on wave blade geometries they seem to find some improvement after stall, but a decreased performance for the lower wind speeds, where a good turbine is supposed to work most efficiently. However, in contrary with previous findings they report the beneficiary post stall aerodynamic properties to increase with increasing amplitudes and wavelengths. Asli et al. [9] computed the S809 airfoil, the one also used on the NREL Phase VI rotor, using the k-ω DES turbulence model and applying an amplitude $A/c=0.025$ and wavelength $\lambda/c=0.25$ typical for a humpback whale. Again a smoother stall was observed compared to baseline geometry, but at the cost of an earlier stall and associated lower $C_{l,max}$. In the baseline post stall regime flow over the wavy blade remained attached, which according to the authors is because the leading edge bumps act as vortex generators. A numerical LES simulation of the flow over a NACA 0021 rectangular wing with leading-edge undulations at an angle of attack of 20 degrees was made by Skillen et al. [10] at a Reynolds number of Re=120.000. The sinusoidal leading edge undulations had an amplitude $A/c=0.015$ and a wavelength $\lambda/c=0.11$. The high angle of attack was selected to ensure a post stall condition and a 58% increase in C_l and a 59% decrease in C_d were reported in comparison with a baseline wing. This was achieved by a reduced area of flow separation for the wavy wing compared to the smooth baseline. The momentum transfer mechanisms driving this reduction, by re-energizing the boundary layer, were identified as: First, the wavy leading edge geometry giving rise to a span-wise pressure gradient which leads to the formation of a secondary flow replacing low-inertia near-wall fluid with high momentum fluid from above layers. Secondly, the strong acceleration between leading edge peaks increases the turbulence levels and hence the mixing and boosting of the boundary layer. Additionally, it was reported that fluctuations in the produced lift were substantially reduced for the wavy wing. The above mentioned literature studies seem to point to that the aerodynamics for a blade section with a wavy leading edge is improved in stall compared to the same blade section having a straight leading edge in the form of a softer stall, increased lift and perhaps decreased drag. However, in most of the papers is also stated that this happens at the expense of an earlier stall, a lower $C_{l,max}$ and sometimes a higher drag for the lower angles of attack before stall. The effect is explained by the sinusoidal leading edge creating streamwise vortices mixing high momentum flow into the boundary layer in a similar manner as conventional vortex generators. Also the transition from laminar to turbulent flow is reported to be affected by the different leading edge geometries. Only one paper [7] indicates that it may be beneficial to continue the sinusoidal waves all the way from the leading to the trailing edge. To further investigate the effect of applying a wavy blade, three geometries were investigated numerically by the authors using RANS and applying the γ-Re_θ transition model of STAR CCM+.

2. Geometries and numerical model

The S809 airfoil was chosen, since this was also used in one of the previous studies [9] and because this is an airfoil designed especially for wind turbines. Three geometries were modelled: 1) baseline S809 with a straight leading edge, 2) Wavy Front WF, where only the leading is modified to have a sinusoidal undulation and 3) Wavy Blade WB, where the sinusoidal undulation continues to the trailing edge. Figure 2 shows the WF and the WB geometries, respectively. Based on the findings in the literature a small amplitude of $A/c=0.015$ was used for both the WF and WB geometry. The wavenumber $\lambda/c=0.125$ is kept at a value similar to others tested in literature, and further this parameter should according to the literature study be of less importance than the amplitude.

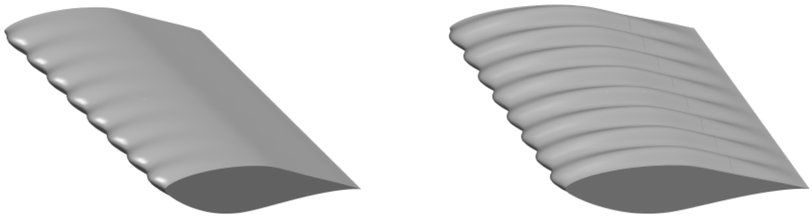

Figure 2: The two different wave blade geometries based on the S809 airfoil. The WF geometry to the left and the WB geometry to the right.

The commercial flow solver STAR CCM+ was used applying the k-ω, SST turbulence model together with their γ-Re_θ transition model. An unstructured computational grid of approximately 9.2 mill. cells was used, but applying a prism layer at the blade surface to align the computational cells in the boundary layer with the flow and to control y^+ values which were kept below one on most of the blade. The aspect ratio, width over chord, was one, symmetry boundary conditions were applied on the lateral surfaces and the external parameters were set to give a Reynolds number of 10^6.

3. Results and discussions

The numerical setup was initially verified by comparing the baseline geometry with a straight leading edge with measurements from Ohio State University [11], another CFD code EllipSys [12], [13], [14] and up to stall also to XFOIL, the latter two both using the e^9 transition model. The two wavy geometries WF and WB were computed for an angle of attack between -2 and 24 degrees and compared to the baseline results in Figure 3.

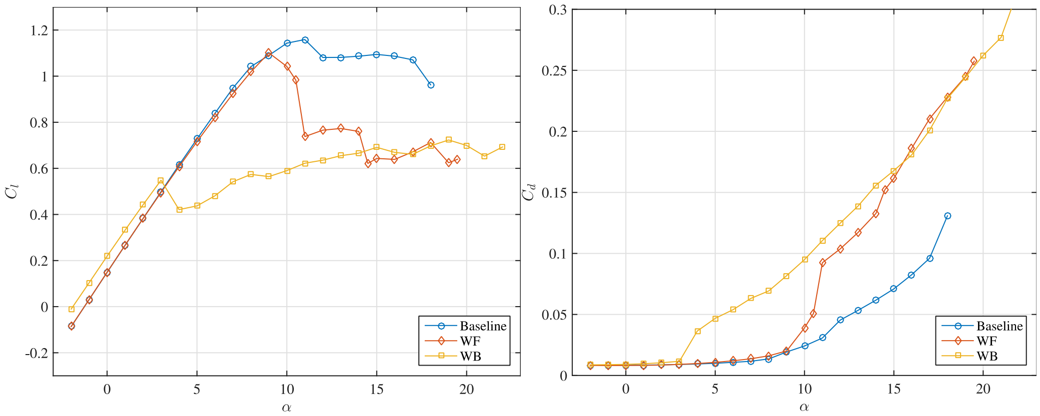

Figure 3: The computed lift and drag as function of angle of attack for the baseline 809 airfoil, the WF and WB geometry, respectively.

From Figure 3 is seen that for the S809 airfoil the WB geometry is doing a very bad job, since it prematurely stalls at an angle of attack around 4 degrees and the lift is much lower than the baseline airfoil and the WF up to at least 20 degrees. The drag is also consistently higher than the baseline and the WF at least up to around 15 degrees where the results from the WF and WB geometry become similar. Comparing the baseline S809 with WF geometry, it is seen that they agree very well up to approximately 9 degrees angle of attack where the WF starts to separate a few degrees earlier than the smooth blade thus having a lower $C_{l,max}$, but what is more surprising is that the WF seems to stall more abruptly than the baseline blade. This is in contradiction to what is reported in most other studies [5], [6] and [9] and could be a result of the chosen baseline airfoil that itself has a smooth stall. It may be that in really deep stall the curves will cross so that the WF and WB geometries become better than the baseline airfoil, but this is not computed in this work and should be done with at least a DES model. It seems, based on the finding in this work and what is found in literature, that the efficiency of the wavy blade concept depends on the baseline airfoil and only appears to be working better in stall. That is, such a concept should only be considered near the root of a wind turbine blade, where separation is taking place for all wind speeds. This paper deals only with the obtained lift and drag for the two different wave blade geometries, but a natural next step will be to investigate in details the flow over the airfoils to be able to explain the physics behind the different results and perhaps use that in an improved version of the concept.

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