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Active aerodynamic control of wind turbine blades with high deflection flexible flaps

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The implementation of an innovative aerodynamic control technique in wind turbines is a point under extensive investigation since the conventional wind turbine blade technology is reaching its limits. Almost all the effort of the wind turbine industry in the field of aerodynamics is related to the development of blades which offer better performance, increased reliability and faster control of larger wind turbines. Currently, however, most of the research effort is focusing on the implementation of aerodynamic elements for dynamic load alleviation during wind turbine operation rather than rotor stall control or even more the complete wind turbine power regulation which is the ultimate target of the current project. The current document presents the test process, methodology and results of wind tunnel test campaigns on the investigation of the flexible flap configuration as a possible means of aerodynamic control of wind turbines. The test campaign took place at the HFI/TU Berlin wind tunnel. Measurements were performed with a model of the DU96W180 airfoil as well as with the modified-DU96W180 test airfoil section equipped with the flexible flap assembly in flow with Reynolds number Re equal to 1,300,000. The The flexible flap was tested in various positive and negative deflections in order to extract its complete operational curve. The results showed significant influence on both lift and drag as well as strong variations on the pitch behavior of the wing. The paper also discusses the possible benefits of the integration of flexible flap systems in wind turbine blade structures.

Nomenclature

Re	Reynolds Number
A	Cross-sectional area of the measurement section $[m^2]$
l	Length of the measurement section [m]
$U_{s_{max}}$	Free stream velocity $[m/s]$
AoA	Angle of attack $[^o]$
a	Test wing span [m]
c	Wing chord [m]
b_1	Distance between left outer wall and splitter wall [m]
b_2	Distance between right outer wall and splitter wall [m]
u_{b_1}	Flow speed at the Pitot tube $[m/s]$
u_{b_2}	Flow speed at the Pitot tube $[m/s]$
C_l	Lift Coefficient
C_d	Drag Coefficient
C_m	Moment Coefficient

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C_l/C_d Lift - Drag Ratio (Airfoil Efficiency)

I. Introduction

The size of wind turbines is constantly increasing following the increasing demand for higher installed power capacities and lower cost of wind energy. However, the traditional wind turbine blades and blade pitch control systems are approaching their mechanical limits. The enormous length of the single-piece blades creates many logistic problems and the pitch systems often are incapable of properly positioning the blades in order to efficiently extract the kinetic energy of the wind. Furthermore the inability of the conventional blades to adapt to the spatial inconsistencies of the oncoming air stream of the rotor lead to significant fatigue loads.

The implementation of plain flaps in wind turbines has been a topic under extensive investigation. The use of plain flaps in aviation is very common and they have also been already tried in helicopter rotors[1]and more recently in wind turbine blades as well.[2–5] In the case of wind turbines there have been several research efforts that led to significant scientific results and even prototypes, but no commercial product is yet available. The effectiveness of plain flaps in wind turbine applications is considered to be significant both in relation to power regulation as well as to load alleviation.[2] In addition to that, small flap deflections are able to delay, up to a certain extend, the early laminar-turbulent transition caused by the increased leading edge roughness of the wind turbine blades due to contamination and erosion.[6] The main aerodynamic disadvantage of the rigid plain flap is the significant increase in drag which is caused for flap deflection angles higher than 10^o due to flow separation at the low-pressure side of the flap,[7] which forms a low pressure volume (pressure drag). In addition to that the relatively complex mechanical structure of the plain flaps in combination to their intolerance of the significant span-wise bending of wind turbine blades makes them less attractive for wind turbine applications.

A possible solution which maintains the advantages of plain flaps while reducing their drawbacks is that of flexible flaps. The primary motivation for altering the airfoil geometry is to improve the airfoil efficiency during off-design operation as well as to offer better control of the produced lift and drag. From the aerodynamics' point of view, the flexible flaps also increase the local camber of the airfoil thus modifying the Kutta condition for the flow and the circulation of the airfoil.[8] The feasibility of the utilization of modern "smart" flaps for the control of the airflow has been investigated extensively by many aerospace companies both for the implementation of such techniques in helicopter rotors[9] as well as in aircraft wings.[10,11]

A number of researchers focus on the flexible flap concept[2] and try to implement it on existing wind turbine blade structures. Currently however, most of the research efforts are aiming on the implementation of flexible flaps for dynamic load alleviation during wind turbine operation[5,12,13] rather than rotor stall control[4] or even more the complete wind turbine power regulation which is the ultimate target of the current project.

II. The Flexible Flap Mechanism

The mechanical realization of the flexible flap can be technically achieved in various ways, some of which have been already proposed in various publications, prototypes and patent applications. From all the different proposed solutions the most extensively developed and tested are:

- The multiple link design of the German Aerospace Center (DLR) mechanism[11] comprising a number of hinged links and covered by a flexible "skin".
- The belt rib concept developed by DLR and others.[14,15]
- The mechanical/hydraulic concept of EADS.[16]
- The sliding linkage concept of SAAB.[17]
- The serrated rib mechanism developed by Boeing.[18]
- The Smart Material Actuator (SMA) wing system, developed by NASA and DARPA.[19]

- The piezo-actuated flexible flaps developed by $RIS\oslash$ and TU Delft.[20]

The integration of flexible flap modules on the wind turbine blade structure is generally similar to the integration of plain rigid flaps. However, in the case of flexible flaps and due to the fact that the implementation of rotating shafts mounted at the sides of the flaps is not necessary (contrary to plain flaps), it is possible to produce them in modules which attach to the blade structure only via a single connecting surface. In this way a largely conventional blade structure with continuous truncated trailing edge could be equipped with multiple flexible flap modules without further modifications.

The flexible flap mechanism of the current test blade is based on a pneumatically actuated flexible flap mechanism which deforms an outer skin (Figure 1).

Figure 1: The test wing with the flexible flap mechanism extended at the fully extended positive position

III. Experimental Setup

The wind tunnel test campaign took place at the wind tunnel facility of TU Berlin (HFI). The closed loop wind tunnel has a closed test section with cross-section A equal to $2 \times \sqrt{2}\ m^2$, length l of the measuring section equal to 10m and contraction ratio of $6,25:1$. The wind tunnel fan is powered by a 500kW speed regulated DC motor. The maximum free stream velocity $U_{s_{max}}$ achieved in the wind tunnel is 50 m/s and the turbulence level of the free stream is below 0.5%.

The test wing had a constant DU96W180 airfoil section and was built with eleven 8mm thick laser-cut ribs mounted on a 50mm x 50mm hollow main beam. The airfoil skin was aircraft rated plywood supported by auxiliary beams. The airfoil surface was sanded, impregnated with epoxy resin and painted with several layers of primer and paint thus achieving good surface quality and shape accuracy. The test wing comprised two segments, the front main segment extending from $0\%c$ to $76\%c$ and the detachable rear segment extending from $76\%c$ to the end of the trailing edge. Two detachable segments where constructed one of which incorporated the flexible flap while the other was the reference part built to the dimensions of the standard DU96W180 airfoil. The test wing occupied the complete span between the wind tunnel splitter walls (a=1.554m) and was attached to an external 6-component balance de-coupled from the wind tunnel construction (Figure 2). The gap between the test wing and the splitter walls was sealed in order to avoid pressure leaks from the pressure side of the airfoil. The test wing chord c was 0.6m with both the rigid and flexible trailing edge segments thus achieving a similar Re of 1,300,000 for both wing configurations.

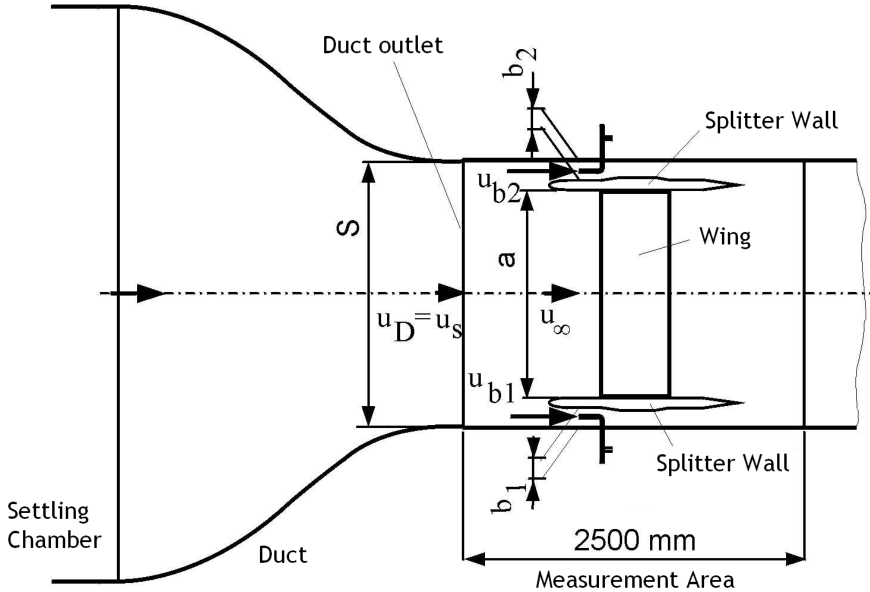


Figure 2: Detailed Diagram of the HFI/TU Berlin Wind Tunnel measurement section.

IV. Results

A. Reference Measurements of the modified DU96W180 Airfoil

Reference measurements were performed for the test blade with the flexible trailing edge attached and set to its neutral position. The airfoil shape with the flexible flap installed was slightly different compared to the original DU96W180 airfoil therefore the results were expected to have small discrepancies. The measurements revealed that the lift values for the original DU96W180 airfoil and the modified one with the flexible flap at neutral position were almost identical. The drag of the modified airfoil slightly increased but was still very close to the drag values of the original airfoil. Similar behavior was noted for the C_m measurements as well, where the trend closely followed the reference measurements of the original airfoil.

B. Flexible Flap: Positive Deflections

The flexible flap was measured in two different positions of positive deflection which are referred as "slight deflection" and "full deflection". With flexible flaps it is not easy to define a deflection angle contrary to the conventional flaps hence the precise definition of the flap position is hard to be achieved. In addition to that the air flow exerts significant loads on the deflected trailing edge flap thus slightly modifying its curvature during the measurements. Furthermore the shape deviation due to air flow loads is not constant but it slightly changes depending on the instant AoA. Efforts were made in order to minimize and document these effects and investigate the extend of the uncertainty which they introduce to the measurements. It was subsequently found that the repeatability of the measurements was hardly affected by the flexible flap and the measurement discrepancies were insignificant.

All the measurements were performed in double AoA sweep in order to investigate any possible hysteresis effects, which were found to be insignificant. The measurements for the blade with the flexible flap were performed in an AoA range of -9^o to $+16^o$ contrary to the measurements of conventional configurations which were measured between -10^o and $+22^o$ AoA. This was done due to the significant blocking effect caused by the blade with fully deflected flap at high AoA.

The behavior of the "slightly deflected" flexible flap in terms of lift is relatively consistent with the theory since the linear part of the C_l curve is displaced upwards (Figure 4a). The Cl_{max} appears in slightly lower AoA and the post stall lift reduction is more "pronounced" even though the lift remains stable after $+11^o$ AoA. The cause of the relatively abrupt post-stall lift loss is the faster progression of the separation from the trailing edge toward's the leading edge due to the increased trailing edge camber caused by the flap deflection. The behavior of the "fully deflected" flexible flap follows the same trend at higher absolute lift

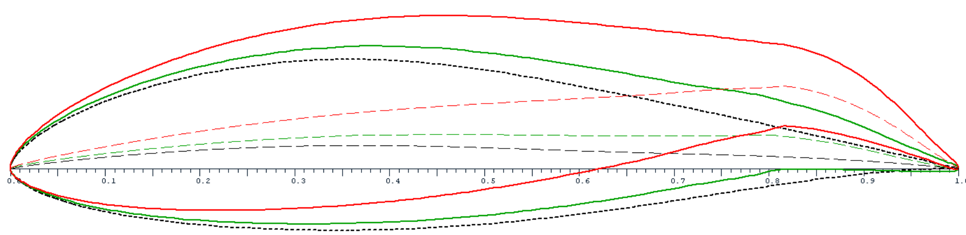
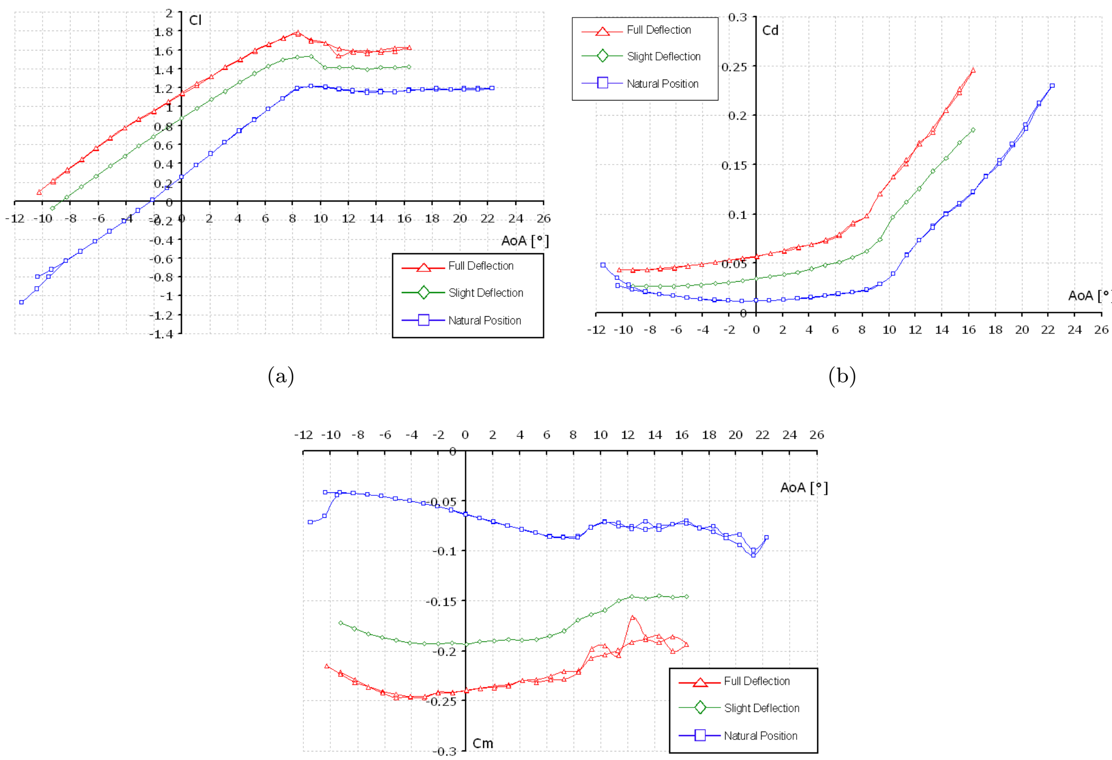


Figure 3: Overlapping airfoil contours. The original DU96W180 airfoil appears with dotted contour (black line) together with the airfoil with the Slightly Deflected Flexible Flap (green line) and the the airfoil with the Flexible Flap in Full Deflection (red line)



(a) (b)

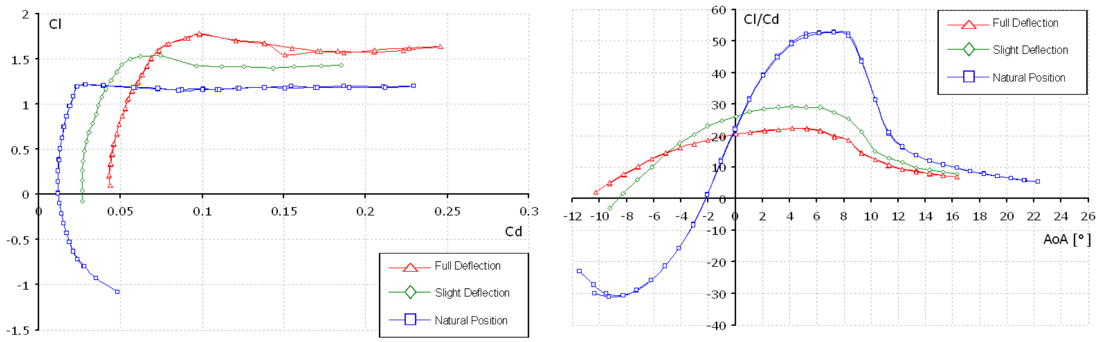
(c)

Figure 4: Comparison of the behavior of lift, drag and moment coefficient with varying AoA for various positive deflections of the Flexible Flap.

values. It should be noted however, that the relative lift increase does not increase linearly with the flap deflection but it is somewhat reduced due to the almost constant separation at the suction side of the flexible flap, which was identified during flow visualization at this part of the wing.

The drag (Figure 4b) is generally increased but follows the general trend of the reference measurement. In both deflection cases the drag increase is not constant but increases more at higher AoA and this is mostly due to the prevailing pressure drag component which is caused by the increasing volume of separated flow at the flexible flap region.

The moment coefficient C_m for the wing with "slightly deflected" flexible flap generally follows the trend of the reference measurement with just a higher pitch-down attitude due to the flap deflection, which is even more pronounced at higher AoA (Figure 4c). The "fully deflected" case has a similar trend but the high deflection of the outflow causes some slight instabilities which appear at the hysteresis check.



(a) (b)

Figure 5: Comparative diagrams of the lift-drag ratio over AoA (airfoil efficiency) and polar curves for different positive deflections of the Flexible Flap.

The lift-drag ratio diagram (Figure 5a) shows that the aerodynamic efficiency generally increases at negative AoA while it is significantly reduced at positive AoA. A noteworthy behavior is that of the airfoil with "fully deflected" flexible flap which appears to have a relatively high C_l/C_d ratio at AoA lower than -5^o due to the high deflection and the fact that the low AoA forces the attachment of the flow on the suction side of the flexible flap. Contrary to that the same configuration cannot outperform the configuration with "slight flap deflection" for higher AoA where it suffers from increased separation.

C. Flexible Flap: Negative Deflections

The flexible flap configuration was also tested at negative flap deflections in order to investigate the effectiveness of the flexible flap mechanism in reducing the lift produced by the test wing. Such a quality is necessary for the effective regulation of a wind turbine rotor as well as for the emergency rotor deceleration. For the experimental setup, "full negative deflection" represents the deflection achieved with the flap control actuator fully extended, whereas the "slight negative deflection" represents an arbitrary position between the full extension and the Neutral Position of the flap. Measurements in additional intermediate positions were also performed but they are not presented in the current paper since their results are in agreement with the general trends of the two configurations previously mentioned.

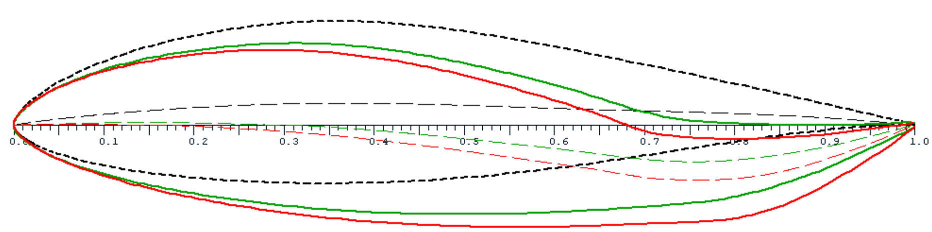
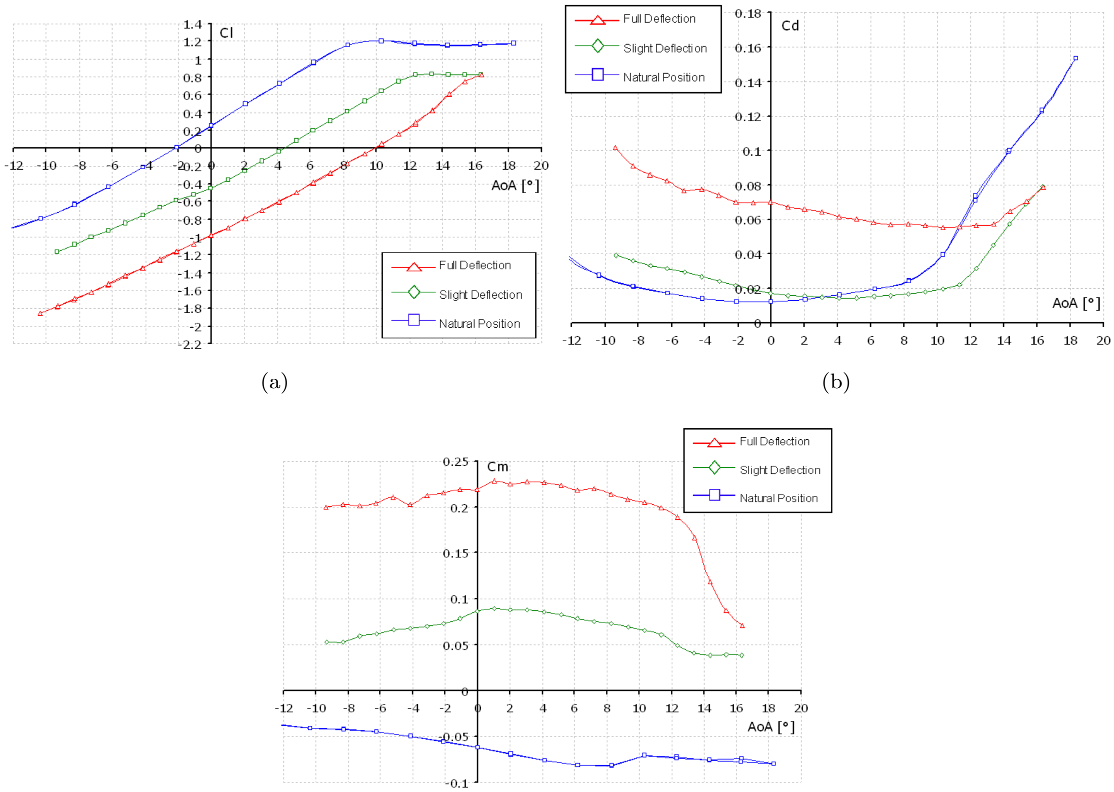


Figure 6: Overlapping airfoil contours. The original DU96W180 airfoil appears with dotted contour (black line) together with the airfoil with the Slightly Deflected Flexible Flap (green line) and the the airfoils with the Flexible Flap in Full Deflection (red line)

The lift curve produced by the configuration with "slightly deflected" flexible flap is shifted down and to the right (Figure 7a) denoting that the lift coefficient is significantly reduced compared to the reference measurements and the stall angle is delayed, which is of course the opposite behavior compared to the tests with positive flap reflection. The wing now stalls at $+13^o$ AoA and the post stall behavior is generally smooth (i.e. no significant drop in lift after stall). When the flexible flap is "fully deflected" the lift is reduced even more and it even becomes negative near the design point of the reference airfoil (i.e. the angle of maximum



(a) (b) (c)

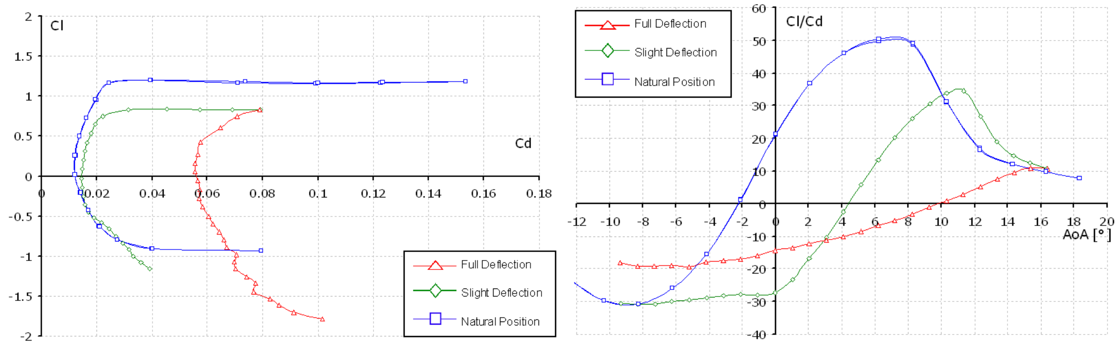
Figure 7: Comparison of the behavior of lift, drag and moment coefficient with varying AoA for various negative deflections of the Flexible Flap.

lift-drag ratio). Such a significant lift reduction would be extremely beneficial for the wind turbine rotor control since it would allow the rapid deceleration of the rotor in case of emergency.

The fact however, that the stall angle of the wing is delayed is generally unfavorable, especially in the case of the "fully deflected" flap where the lift constantly increases with the AoA without stall. The negative flap deflection caused separation bubbles which were visualized during the wind tunnel experiments but also anticipated based on the existing literature.[6] The flow visualizations also showed that the high local curvature caused by the flexible flap, forced the flow to reattach to the suction side of the wing thus effectively suppressing stall. Since the angle of attack increases while the wind turbine rotor decelerates it is apparent that the aforementioned behavior of lift would have adverse effects for the rotor control, especially regarding the task of "emergency stop".

The drag curve (Figure 7b) of the configuration with "slightly deflected" flexible flap follows the general trend of the reference airfoil but whereas for AoA values lower than 3^o the drag curve is higher than the reference curve this attitude is reversed at higher AoA. The significant drag reduction observed at the high AoA region (above 11^o AoA) is generally not beneficial since this operational area refers to the rotor deceleration regime where high drag is generally desirable. In the "fully deflected" case the situation is less critical however, for AoA values higher than 11^o the produced drag falls significantly below that of the reference airfoil.

The negative deflection of the flexible flap strongly influences the pitching moment of the test wing (Figure 7c) which changes and acquires a pitch-up attitude. This phenomenon is even more pronounced at the "fully deflected" configuration where the positive pitching moment significantly increases. At high AoA however, (higher than 12^o) where the flow at the suction side of the flexible flap is largely detached, the moment coefficient drops to much lower levels. This drop is strongly pronounced in the "fully deflected" configuration which means that in a hypothetical "emergency stop" event the rotor blades would experience torsional loads due to the variation of the pitch moment with the AoA.



(a) (b)

Figure 8: Comparative diagrams of the lift-drag ratio over AoA (airfoil efficiency) and polar curves for different negative deflections of the Flexible Flap.

The diagram of the lift-drag ratio over the AoA (Figure 8a) shows with higher clarity what was discussed previously regarding the inability of the flexible flap system to significantly reduce the lift of the wing at high AoA. In the case of "slight negative deflection" the lift-drag ratio is actually improved over the reference wing for AoA higher than 10^o. When the flexible flap is "fully deflected" the lift drag ratio is significantly reduced but nevertheless still in the vicinity of the values achieved with the reference airfoil.

V. Conclusion

The wind tunnel tests performed at the wing section produced significant data regarding the feasibility of implementation of high deflection flexible flap structures for the aerodynamic control and subsequently the power regulation of wind turbine rotors. It was shown that positive flap deflections can significantly increase lift with considerable drag penalties which decrease the lift-drag ratio. Negative flap deflections offer dramatic lift reduction and could be very effective for wind turbine rotor deceleration. The aerodynamic peculiarities of the configurations with negative flap deflection which were identified at high AoA indicate however, that it is probably not possible to bring the lift-drag ratio to zero, therefore the negative flap deflection alone is not capable of bringing the rotor of a wind turbine to a complete halt. Furthermore the rapid variation of the moment coefficient at high AoA poses another potential problem in the form of increased torsional blade loads.

Despite, however, the peculiar behavior of the flexible flap configurations at high AoA, the large power regulation and load alleviation potential of this solution makes it attractive for future wind turbine blade designs. Further tests and simulations will be conducted in order to investigate the aeroelastic effects of such configurations as well as the aerodynamic behavior of enhanced flexible flap systems (e.g. systems with higher flap deflection or combination of flexible flaps with other flow control elements).

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