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# PERFORMANCE OPTIMIZATION OF WIND TURBINE ROTORS WITH ACTIVE FLOW CONTROL

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## ABSTRACT

*This paper presents a series of investigations performed at the Hermann Föttinger Institute of TU Berlin. The initial scope of the investigations was the identification of Active Flow Control (AFC) solutions with significant implementation potential on wind turbine rotors. Several Active Flow Control solutions were thoroughly investigated based on extensive literature research. The performance of all the investigated solutions was ranked according to objective performance criteria and then the best performing solutions were selected for further numerical and experimental investigation. The selected Active Flow Control solutions were experimentally investigated with steady state wind tunnel measurements as well as steady state CFD simulations. The results of these investigations and the potential of each AFC solution are presented and discussed. The steady state tests were followed by a dynamic wind tunnel test campaign where the performance of one AFC solution (active Gurney flap) on a pitching test wing was investigated. The results of the static and dynamic investigations were very positive and proved the large load reduction potential of AFC on wind turbines.*

## NOMENCLATURE

AoA  Angle of attack in degrees
AFC  Active Flow Control
BEM  Blade Element Momentum Theory
c  Airfoil chord length
Cd  Drag coefficient
Cl  Lift coefficient
Cl/Cd  Lift - Drag ratio (Glide Ratio)
DIC  Direct Inverse Controller
$f$  Pulsing frequency
$F^+$  Reduced pulsing frequency
$k-\omega$  Two equation turbulence model
PID  Proportional Integral Derivative controller
RANS  Reynolds Averaged Navier Stokes
SMA  Smart Material Actuators
$U_\infty$  Free stream velocity
U  Velocity over an airfoil surface
Y+  Dimensionless wall distance

## INTRODUCTION

Modern wind turbines have reached sizes and installed capacity levels previously un-imaginable. Currently the largest rotors have diameters larger than 150m and installed capacities of more than 6MW. The combination of large rotor dimensions, turbulent inflow field, terrestrial boundary layer profile and rotor yaw misalignment cause extremely high aeroelastic loads on wind turbine blades. In addition, the blades of modern wind turbines are extremely cost intensive components and a potential aerodynamic/aeroelastic load reduction could be very beneficial for the cost-competitiveness of the entire wind turbine.

To reduce the loads and/or increase the performance of modern wind turbines, many PFC and AFC solutions were investigated. An extensive literature research was performed in combination with basic simulations to estimate the AFC solutions with the best potential. A second investigation phase was then initiated to analyze the best performing AFC solutions and to investigate their potential use on HAWT rotors.

## PRELIMINARY AFC SELECTION

The preliminary selection process was aimed at filtering the bulk of proposed aerodynamic solutions investigated. The initial AFC solutions were selected based on extensive literature research and in some cases simulations performed by the authors and finally a total of 10 elements was listed (Fig.1). The preliminary selection filtered out the solutions that were clearly out of the scope or specifications of the current project thus maintaining only the ones which would be further investigated.

The proposed elements were:

1. Rigid Flap
2. Split Flap
3. Flexible Trailing Edge Flap
4. Gurney Flap/Micro Tab
5. Inclined & L.E. Spoiler
6. Stall Rib
7. Flexible Leading Edge Flap
8. Blow-Type & Suction Type Flow Control
9. Synthetic Jets
10. Plasma Actuators

To rate and categorize each flow control solution, each one was rated in respect of the most important performance areas such as Aerodynamics, Mechanical & Electrical Components, Blade Integration, Operation and Cost. The sum of the individual points provided the final relative ranking of the AFC solutions and the ones with the highest ranking were promoted to the 2nd phase of investigation.

To create an objective comparison between the different AFC solutions, a set of constraints was set. These were:

1. Performance increase
2. Load reduction capacity
3. Power regulation capacity
4. Operation under icing conditions
5. Operation without being affected by lightning strikes
6. Operation under heavy rainfall
7. Operation in dusty, humid, high salinity and contaminated environment
8. Operation for extended periods $(6-12$ months) without maintenance
9. Resistant to mechanical loads during transportation or even better be implemented on the field during wind turbine erection

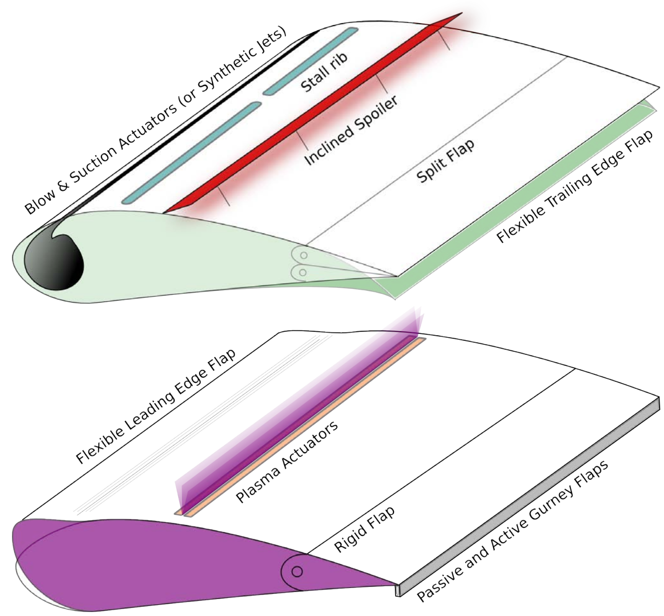


**FIGURE 1**. SCHEMATIC REPRESENTATION OF THE VARIOUS AFC ELEMENTS INVESTIGATED DURING THE PRELIMINARY RESEARCH OF THE CURRENT PROJECT.

The detailed description of the rating system and the detail point distribution for each AFC solution is not presented in the current document for space economy. However the following paragraphs briefly analyze the performance estimation of all the aforementioned flow control solutions.

### Rigid Flap

The conventional rigid flap configuration is one of the oldest concepts of airflow control. It is universally used in aviation and it has been already tried in helicopter rotors [1, 2] and more recently in wind turbine blades as well [3–7]. The effectiveness of rigid flaps for wind turbine applications is considered to be high both related to power regulation as well as load alleviation [3]. In addition, small flap deflections are able to overcome, up to a certain extent, the early laminar-turbulent transition caused by the increased leading edge roughness of the wind turbine blades due to contamination and erosion [8, 9]. The main aerodynamic disadvantage of the rigid flap is the significant increase in drag which is caused at deflection angles higher than $10^o$ [10] due to flow separation at the suction side of the flap, which forms a low pressure volume.

In terms of manufacturing rigid flaps are simple. Their actuation mechanisms can be either based on electromechanical drives, servomotors, hydraulic/pneumatic cylinders, pneumatic muscles [11, 12] or even piezoelectric actuators [13]. Their implementation however on wind turbine structures introduces manufacturing challenges mostly due to the strict scarce-maintenance reliability requirements. In terms of actuation means, the pneumatic actuation systems appear to be very attractive due to their reliability and robustness and lack of sensitive electrical wiring.

The integration of rigid flaps in the wind turbine blade structure is not very complicated in terms of manufacturing. Several modifications in the mold structure are required to create the necessary spaces which will incorporate the flaps. In addition to that the blade structure has to be appropriately modified to ensure that the cut-outs for the flaps will not cause stress concentration and potentially lead to local fatigue failure. One major issue regarding the operation of a wind turbine blade equipped with rigid flaps is the issue of span-wise bending which can cause damages to the conventional hinge based rigid flap systems.

### Split Flap

The split flap configuration is one of the simplest and oldest [14] flow control solutions. The aerodynamic behavior is comparable to the behavior of the simple rigid flap and its effectiveness is derived from the large increase of camber and in some cases (translatable split flap) from the effective increase in wing chord [10].

The $Cl/Cd$ curve of an airfoil equipped with split flap is similar to that of an airfoil with a plain flap at the low Cl region while at the high Cl region the split flap is superior to the plain flap since it produces a lot more lift but not as much drag[1]. Due to the fact that one surface (usually the suction side) remains unchanged, the activation of the split flap creates a divergent trailing edge which acts as a bluff body in terms of drag [10]. This means that an airfoil equipped with a split flap would be able to operate in permanent high lift state at the inner part of a wind turbine rotor, where drag is not of such high importance [15–17], while being also able to regulate the lift of that part of the rotor. The implementation of the split flap concept at the outer portion of a wind turbine rotor would achieve significant lift control as well as drag control, thus sufficiently controlling the rotor power and possibly also the edge-wise blade vibrations. For a turbine emergency shut down ability a double split flap [18] would be necessary. The aerodynamic benefits of a suction side aileron and a pressure side split flap (double split flap configuration) would definitely be aerodynamically superior and enable a very high level of wind turbine rotor control [19]. Additionally the simultaneous counter-deflection of both flaps would create a form of aerodynamic brake thus achieving the complete deceleration of the rotor.

The mechanical structure of the split flap systems is generally similar to that of the plain flaps. The integration of the split flap and the double split flap system on the wind turbine blade structure is almost identical to the integration of the plain rigid flap. The spatial requirements for the double split flap would be slightly higher due to the fact that double mechanical components and actuators are needed, but generally the differences are only in the detailed implementation design issues.

### Flexible Trailing Edge Flap

The idea of the flexible flaps and the extension of that which is the morphing wing goes back to the beginning of aviation [20] and is related to the investigation of the morphing behavior of the bird wings. One of the first actual implementations of the concept was done by H.F. Parker [21] in 1919 who proposed a chord-wise flexible wing with variable camber. Many more efforts in this direction took place the following years [22–24] and the research in this field is still very active [7].

From the aerodynamics' point of view, the flexible flaps also increase the camber of the airfoil thus modifying the Kutta condition for the flow and the circulation of the airfoil [20]. The feasibility of the utilization of modern flexible flaps for AFC has been investigated extensively for use on helicopter rotors [25] as well as on aircraft wings [26–29]. The implementation of flexible flaps on wind turbines is also a point under currently extensive investigation. From the big bulk of relevant research projects, a great amount of research is focused on the flexible flap concept [3]. Currently, most of the research efforts are focusing on the implementation of flexible flaps for load alleviation during wind turbine operation [6,30,31] rather than rotor stall control [5] or even wind turbine power regulation which is the ultimate target of the current project [11].

The mechanical realization of the flexible flap can be technically achieved in various ways, many of which have been already proposed in the course of time through publications, prototypes and patent applications. Some of the actuation concepts include multiple link designs [28], mechanical and hydraulic actuation [24], Smart Material Actuators (SMA) [32], piezo-electric actuation [13,33] and pneumatic muscle actuation [11].

The integration of Flexible Flap modules at 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 there is no need for implementation of rotating shafts mounted at the sides of the flaps (like the ones usually used for mounting plain flaps), it is possible to produce the flexible flaps in modules which attach to the blade only via a single connecting surface. The successful operation of the flexible flap concept has been demonstrated during various research projects in the past. In the field of wind energy recent investigations of Barlas et al. [34] also prove the fact that flexible trailing edge mechanisms can be effectively used at least for load alleviation purposes.

[1]This is true only for small split-flap deflections.

## Gurney Flap / Micro-Flap

The Gurney flap is a simple flat plate on the order of 1% of the chord length which is located perpendicular to the pressure side of the airfoil at the trailing edge. When properly sized, the Gurney flap will increase the total lift of the airfoil while reducing the drag [35]. Storms [36] found a lift increase in the order of 13% for a Gurney flap size of 0.5%c with minimal to no drag penalties for the low and moderate Cl values. Mayda and van Dam [7, 37] based on the research of Bechert et al. [38] investigated the effects of serrated and slit Gurney flaps (i.e. micro tabs) to eliminate the 2D vortex shedding from the solid Gurney flaps which can cause vibration and noise. Additionaly van Dam et al. [39] investigated the implementation of Micro Flaps (i.e. active Gurney Flaps) and deployable Micro Tabs as means for load alleviation in wind turbine blade structures. They found that both micro flaps and micro tabs are suitable for the task of load alleviation mostly due to their fast actuation capabilities. The main difference between these two configurations is the slight aerodynamic lag of the micro tabs due to their position (more fore than the micro flap).

The actuating mechanism in the case of micro flaps requires low actuation force due to the small size of the element. Alternatively the implementation of sinking micro tabs [39] could further simplify the actuation process. The integration of Gurney flaps and Micro Tabs in the blade structure is a relatively simple process. These elements and their actuators are very small, therefore only minor changes need to be made in the current blade structures. Especially in the case of Micro Flaps (i.e. active Gurney Flap), the flap mounting point can easily be integrated at the trailing edge region of the blades and the actuators could be mounted externally without significant aerodynamic penalties for the blade. To achieve a significant load reduction during the operation of the wind turbine a fast and reliable control and actuation system is needed. From the aerodynamic and mechanical point of view Gurney flaps and Micro tabs are suitable for fast control and actuation.

## Spoilers

**Inclined** Spoilers are universally used in aviation and have therefore been extensively investigated. The aeroelastic however behavior of spoilers is a significant research topic mostly due to the various parameters which can alter the investigation results. Extensive experiments [40] and numerical simulations [41, 42] have shown that special design and control strategies can be implemented to significantly reduce their adverse aeroelastic effects.

The implementation of spoilers on wind turbine blades is also not a new idea [43, 44]. Contrary to the crude, more conceptual proposals of the past, modern proposals [9, 45, 46] in the field are mostly focused on more refined designs intended to reduce the lift of the blades thus regulating the power of the turbine while eliminating or significantly reducing the adverse aeroelastic effects.

The actuation of inclined spoilers is a relatively simple process with low technical risk. The actuation can be accomplished with various actuation principles utilizing mechanical, electromechanical, pneumatic or hydraulic actuators which are readily available as commercial products. The main consideration regarding the operation of wind turbine blades equipped with inclined spoilers is related to aeroelastic phenomena. Extensive tests performed at NREL in the past with pultruded blades equipped with spoiler configurations [47] showed that the creation of a feasible wind turbine blade design with spoilers is possible but requires extensive research to prevent the initiation of flutter.

**Leading Edge Spoiler** The implementation of leading edge spoilers in the form of conventional spoiler structures or passive stall strips is a relatively common practice especially in the general aviation industry [48]. The leading edge spoilers offer large reduction of the aerodynamic lift with usage of small sized elements since it is easy to trigger separation near the leading edge of most airfoils. In the field of wind energy stall strips as a form of leading edge spoilers have been extensively investigated by RISOE during the KNOW-BLADE project and the results of these investigations have been published in various reports [49].

These elements also create a flow detachment which under some circumstances could reattach thus forming a leading edge bubble. The complex flow-field of such configurations on wind turbines makes it very difficult to analyze their performance thus the design, sizing and positioning of such elements is a task which involves some risk and uncertainty [49, 50].The small size of the leading edge spoiler elements requires small modifications of the conventional blade structure for their implementation. The leading edge region however is aerodynamically very critical, therefore the installation of an AFC element at this region could have adverse effects. Another consideration which needs to be taken into account is the effect of leading edge icing to the operation of the spoiler mechanism. Finally, in addition to the icing problem another critical issue with the leading edge spoilers' operation has to do with their operation under blade strong blade deformations.

## Stall Rib

The first implementations of deformable/inflatable membranes as airflow deflectors, to the authors' knowledge, were the aircraft air brakes described at the US Patent documents of Hunter in 1943 [51] and Campbell in 1944 [52]. In 1961 Barber [53] proposed an inflatable spoiler at the suction side of an aircraft wing which was intended as a lateral control device. The implementation of the inflatable rib in Wind Turbine blades was first proposed by Holzem in 1990 [54] as a means of stalling the complete wind turbine rotor to avoid over-speed. The proposed system could operate either as an open system with an open membrane and vertical air blowing (combination of pneumatic spoiler and deformable membrane) or as a closed system with air-tight deformable membrane.

Inflatable ribs have significant aerodynamic potential as flow control elements however thorough investigations are required to analyze possible adverse effects due to the implementation of the inflatable stall ribs on wind turbine blades. One of the main benefits of the inflatable stall rib is the simplicity of the actuation mechanism. The integration of such small elements in the wind turbine blade structure is a relatively simple procedure with minimal changes in the production process of existing wind turbine blade structures.

### Flexible Leading Edge Flap

The first efforts to produce airfoils with variable leading edge camber or leading edge hinged flaps date back to the early 1920s [55] and they generally coincide with the various proposals for variable camber airfoils of that time [56, 57]. The examples of the various proposed concepts and ideas are numerous and vary from semi hinged leading edge flaps with mechanical actuators [58–60], to inflatable leading edge flaps [61] and even elastic deformable leading edge with sliding internal shape mechanism [62]. Recently, even SMA (Smart Material Actuators) were proposed for the deformation of the leading edge of airfoils [63] but the development of such solutions seems to be currently under slow pace.

In the wind energy industry more or less similar concepts were proposed, such as the leading edge flap of Coleman [64] but until now none of these aerodynamic devices has been used on large scale production on wind turbine blades. The general aerodynamic effect of the leading edge flaps and variable camber leading edge devices is the increase of maximum lift and the delay of stall [10] due to variations of the relative position of the stagnation point relative the the leading edge [65]. The actuating mechanisms for leading edge flap systems can be of various designs and working principles. The most important characteristics of such an actuating mechanism should be simplicity, reliability and low cost construction.

### Blow-Type & Suction Type Flow Control

**Suction Type FC:** The principle of suction-type flow control was first introduced in 1904 by L. Prandtl [66] as a means to prevent flow separation from the surface of a cylinder. The boundary layer looses kinetic energy due to skin friction phenomena thus its "exhausted" molecules are prone to separation. By introducing one or more slots on the solid wall surface and applying suction it is possible to remove the low energy boundary layer and thus replace it with a "fresh" high energy boundary layer from the free flow [10, 67, 68]. The result of the "energetic enhancement" of the boundary layer is separation delay as well as the extension of the laminar boundary layer regions. Regarding the airfoil performance this leads to reduced drag and increased effective AoA due to separation suppression. Suction-type flow control also enables the effective operation of airfoils with thick or highly curved trailing edges since the circulation can be adjusted by the boundary layer suction system and the rear stagnation point can be defined by a small sized flap or a sharp edge. In this way airfoils with elliptic or even circular cross sections can generate very high lift coefficients [69].

**Blow Type FC:** Numerous design concepts have been proposed during the last 80 years and many of them have been extensively investigated [7, 68]. The effectiveness of wings can be greatly improved by using blow-type flow control, while if the intensity of the blown jet is high enough, even the lift predicted by potential theory can be surpassed (i.e. the *"jet flap effect"*) due to the initiation of *"super circulation"* [67]. Stream-wise blowing however can require large amounts of air and energy thus reducing the overall benefits of the flow control solution itself. Additionally, the effect of *"Virtual airfoil shaping"* can also be utilized to aerodynamically thicken the airfoil via blowing at high AoA [70].

### Synthetic Jets

The development of Synthetic Jets for flow control is a direct product of the research on "traditional" suction-type and blow-type flow control techniques and the existence of synthetic jets is mostly due to the inherent disadvantages of aforementioned "traditional" techniques with respect to energy consumption, fluid consumption and overall cost. The main characteristic of synthetic jets is the intermittent (or quasi stable - high frequency) operation, the utilization of the surrounding fluid (air) for the creation of the synthetic jet and in some cases the "zero net mass flux" operation which is caused by the oscillating diaphragm operation principle. Various synthetic jet systems have been developed and tested so far [7] in various technical applications.

The application of periodic jets for flow field modifications on airfoils has been investigated by many researchers in the past [71] and it was found that there exists a significant potential for controllable lift increase in addition to stall control via this method. Even more significant benefits can be achieved by the "aero-shaping" concept [72]. Another solution currently under investigation is the utilization of synthetic jets at the trailing edge region (tangential blowing) as means of circulation control [73] thus increasing the airfoil lift. Another relevant concept is the "pneumatic Gurney flap" [74] which utilizes the high pressure air-sheets created by synthetic jets at the trailing edge region to modify the *Kutta condition* thus leading to lift variations. Finally synthetic jets are also used as "pneumatic vortex generators" leading to stall suppression when they are activated [75].

One of the designs oriented toward's wind energy applications is the passive system designed by GE Wind in collaboration with the University of Stuttgart [75]. This system utilizes a secondary flow to influence the direction of the main flow. Such elements have very low production cost and the absence of many moving parts makes them very attractive for wind turbine applications.

Pulsed flow control solutions often prove to be more effective means of flow control than continuous suction or blowing [7]. The addition of vorticity into the boundary layer (apart from the momentum injection) is believed to be the main benefit of pulsed flow control solutions over continuous. Most of the synthetic jet and ZMF actuators perform better at a specific actuator forcing frequency. It is therefore common to use the reduced forcing frequency $F^+$ to describe their optimal operation point. The reduced frequency is given by the following equation:

$$F^+ = \frac{f \cdot X}{U} \tag{1}$$

where $f$ is the pulsing frequency of the fluidic actuator, X is the representative length scale (usually the distance between the actuator and the airfoil trailing edge) and U is the flow velocity over the actuator (or often the free stream velocity $U_\infty$). For most synthetic jet and ZMF actuators the optimal frequency of operation is achieved for $F^+$ values of 0.8 to 0.9 [7].

## Plasma Actuators

A recent development in the field of aerodynamic flow control is that of the plasma actuators. These were first developed in the late '60s from Velkoff and Ketchman [76]. The basic principle of the plasma actuators is the creation of electric field between two electrodes by applying large electric potential between the electrodes. The electric field that is consequently created induces an "electric wind" close to the wall surface due to the impact forces of the colliding plasma ions with air molecules and particles in the actuator region. This ion induced flow mobilizes the surrounding air creating a zero net-mass flux jet which is able to modify the boundary layer of the flow thus offering a means of separation control [7, 77].

Plasma actuators can be used in various types of flow control and flow modification applications depending on their type and positioning. The main use of plasma actuators is stall prevention by means of the downdraft caused by the "electric wind" between anode and cathode. Other types of actuators such as the plasma wall jet actuators are able to create plasma sheets, vertical or at angle with the wall surface thus achieving effects similar to vortex generators in delaying stall [7, 77].

Regarding to wind turbine applications, plasma actuators are under extensive research [7, 78, 79] and their applications in this field seem to be relatively promising. Apart from the apparent application in place of the popular passive vortex generator solution, there is also the possibility to use them as means of drag and vorticity reduction at the blade root region. Recent experiments from Thomas, Kozlov and Corke [80] have shown that the existence of plasma actuators could reduce the Karman vortex structures behind a bluff body such as a cylinder, therefore the application to the cylindrical part of the blade root seems possible [79].

**TABLE 1**. SPECIFICATIONS OF THE WIND TUNNEL OF H.F.I TU BERLIN.

| Wind tunnel | GroWiKa (TU Berlin) |
|---|---|
| Test section dimensions [m] | $2m \cdot 1.44m$ |
| Contraction Ratio | 6.25 : 1 |
| Reynolds number | $1.3 \cdot 10^6$ |
| Turbulence Intensity | $< 0.5\%$ |
| AoA Range | $-8^o$ to $25^o$ |
| Wake blockage correction | Yes |
| Solid blockage correction | Yes |

## WIND TUNNEL AND CFD INVESTIGATIONS

The preliminary AFC solution selection methodology lead to a rational selection of the best performing elements for further experimental and numerical investigations. The AFC solutions which were selected for the second phase of the investigations were:

1. Flexible Trailing Edge Flap
2. Gurney Flap & Micro Tabs
3. Stall Rib
4. Flexible Leading Edge Flap

The second phase of the investigations involved wind tunnel measurements at the wind tunnel facilities of Hermann Föttinger Institute at TU Berlin (Tab. 1) and numerical simulations with XFOIL [81] and OpenFOAM [82]. Both the experimental and numerical investigations were steady state and their purpose was the in-depth analysis of the performance of these AFC solutions to better estimate and investigate their effectiveness when installed on wind turbine blades.

## The experimental setup

For the steady state wind tunnel measurements three constant chord, zero twist quasi-2d test wings were machined out of Obomodulan™with a high precision CNC milling machine. The chord of the test wings was 600mm and the span 1540mm. The constant airfoil sections of the test wings were the DU96W180,

**TABLE 2**. SPECIFICATIONS OF THE TEST WINGS USED DURING THE CURRENT INVESTIGATIONS.

| Airfoil | DU96W180 | AH93W174 | $NACA63_3618$ |
|---|---|---|---|
| Chord [m] | 0.6 | 0.6 | 0.6 |
| Thickness [%c] | 18%$c$ | 17.4%$c$ | 18%$c$ |
| Span [m] | 1544mm | 1544mm | 1544mm |

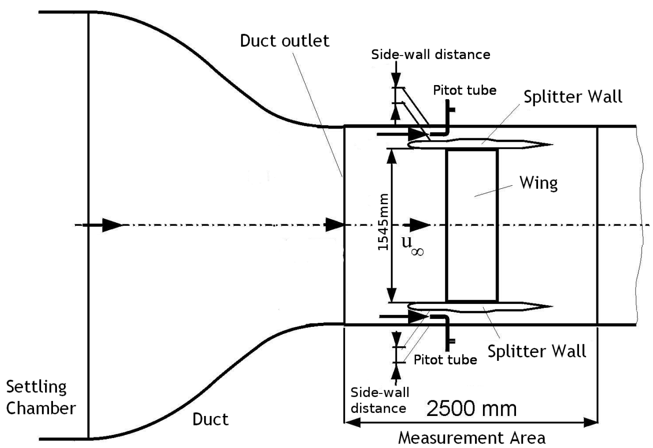


**FIGURE 2**. SCHEMATIC REPRESENTATION OF THE NOZZLE AND TEST SECTION OF THE WIND TUNNEL OF H.F.I - TU BERLIN.

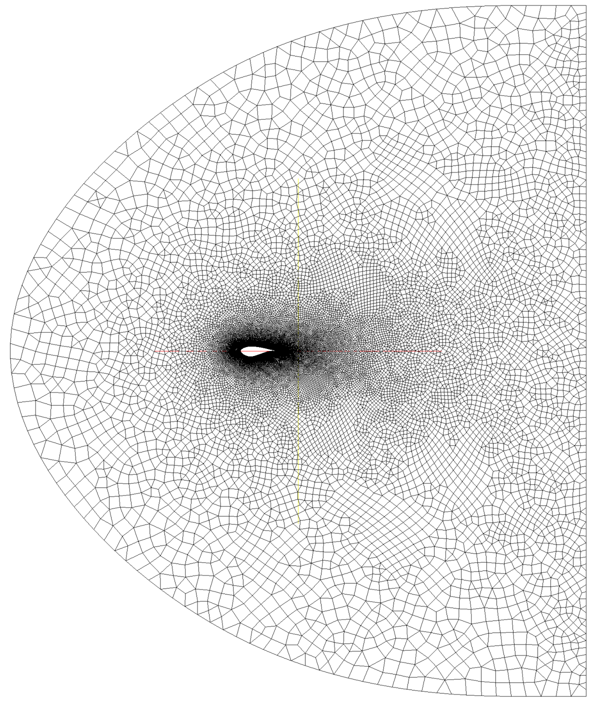

**FIGURE 3**. VIEW OF THE UNSTRUCTURED GRID OF $1.3 \cdot 10^6$ CELLS USED FOR THE CFD SIMULATIONS.

the AH93W174 and the $NACA63_3618$. These airfoils are considered to be popular wind turbine airfoils and mostly represent airfoil shapes that are typically found at the mid and outboard blade sections. Table 2 shows the main characteristics of these test wings.

The test wings were mounted on the 6-component force balance of the large wind tunnel facilities of the Hermann Foettinger Institute - TU Berlin. The wind tunnel test section is equipped with additional splitter walls to reduce the effects of the wind tunnel boundary layer and the spanwise flows due to blockage to the measurement results (Fig.2). The lift, drag and moment coefficients were measured at 1.3 million Reynolds Number with the digital balance at a sampling rate of 10kHz for 20,000 samples/AoA and the results were averaged and corrected for wake blockage and solid blockage [83].

## Numerical Simulations

The steady state simulations of the AFC solutions were initially done with XFOIL [81] to get a first performance estimation. Through this panel method code, the lift and drag polars were computed for moderate angles of attack. Furthermore the boundary layer thickness was computed thus providing a good estimation about the necessary grid refinement for the CFD computations. The low computational effort required for the XFOIL computations allowed the investigation of various configurations, which lead to a better understanding of the performance of each flow control solution.

The main simulations however were done with the OpenFOAM [82] CFD library and the SIMPLE solver. The configurations were simulated with a quasi 2D grid (i.e extruded 2D grid). The wing configurations and the grid boundaries were generated with a custom script. The initial 2D grid was generated with GMSH [84]. This was an unstructured grid which included 9,000 surface elements along the airfoil contour. The Y+ value for the grid was kept lower than 1 and the total number of elements was in the range of 1.3 million (Fig.3). The 2D grid was extruded to a 100mm thickness with EnGrid [85]. The CFD simulation did not include any span-wise flow components and the side boundaries of the grid were set as “empty” boundaries.

The SIMPLE solver of OpenFOAM is a Reynolds Averaged Navier Stokes (RANS) solver. For the current simulations the turbulence model used was the $k-\omega$ SST. No laminar-turbulent transition model was used (fully turbulent BL case). All the configurations were tested at $1.3 \cdot 10^6$ Re with uniform inflow velocity (i.e. no free stream turbulence). The computations were executed at a 4-core, 3GHz CPU desktop computer with 64bit Linux based OS and 6GB RAM and each AoA calculation lasted approx. 120 min.


**FIGURE 4**. THE DU96W180 TEST WING WITH THE FLEXIBLE FLAP AT FULL DEFLECTION.

The following paragraphs present the experimental and numerical results of all the AFC solutions tested at the second research phase of the project.

### Flexible Trailing Edge Flap

The DU96W180 airfoil with the flexible trailing edge flap (Fig. 4)was measured in the wind tunnel and it was found that the flexible flap mechanism achieved very high control authority [11]. The flexible flap was deflected towards the pressure side as well as towards the suction side to investigate its performance in high lift and low lift mode. It was found that the flap deflection towards the pressure side (high lift) caused significant lift and drag increase. Additional wind tunnel measurements with vortex generators (VGs) at 60%c (suction side) revealed that despite the smooth flap curvature, the large flap deflection caused high pressure gradients, thus large separation (i.e. high drag) at the suction side (Fig. 5). When deflected towards the suction side (low lift), the flexible flap massively reduces the generated lift. It is worth noting that at the angle of maximum $C_l/C_d$, where wind turbine airfoils usually operate, the flap deflection reduced lift to zero(Fig.6). Such a large lift variation would allow the complete wind turbine power regulation thus eventually eliminating the need for a traditional pitch system.

The OpenFOAM simulations revealed what was anticipated from the wind tunnel investigations. The flow-field plots of the airfoil at high AoA with the flexible flap deflected towards the pressure side show that there is a large separation region at the suction side of the flexible flap(Fig.7). The computed polar curves matched quite well with the experimental ones for small and relatively high AoA values, but are not presented due to space economy.

### Gurney Flap & Micro Tabs

During the wind tunnel investigations for Gurney Flaps, several flap shapes (Fig.8), sizes and positions were tested at the trailing edge region of the DU96W180 test wing (both pressure and suction side). The results of some of these investigations are presented in Fig.9. The same Gurney Flap configurations were tested on all three test wings to study the relative differences in the performance between different airfoils, however the results are not presented here.

Gurney flaps are thoroughly investigated aerodynamic elements and as was anticipated the results of the current wind tunnel investigations and OpenFOAM simulations agree with the results of other researchers (e.g. [39]). Overall, Gurney flaps and micro flaps offer a very attractive AFC solution for wind turbine applications mostly due to their relatively high aerodynamic control authority in combination with their simple design and low force actuation.

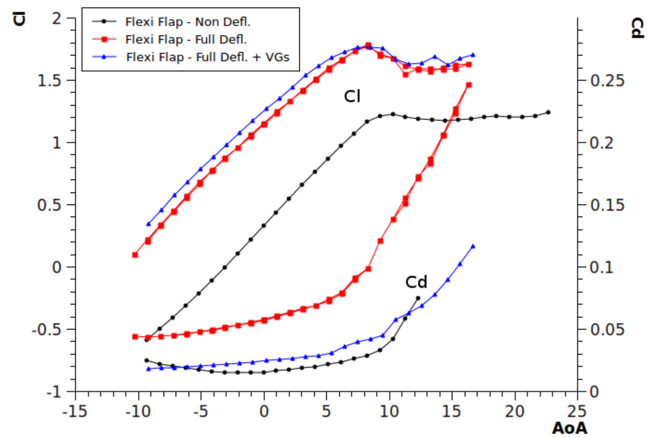


**FIGURE 5**. EXPERIMENTAL PERFORMANCE CURVES (WIND TUNNEL TEST) OF THE FLEXIBLE FLAP AT FULL DEFLECTION TOWARDS PRESSURE SIDE (HIGH LIFT).

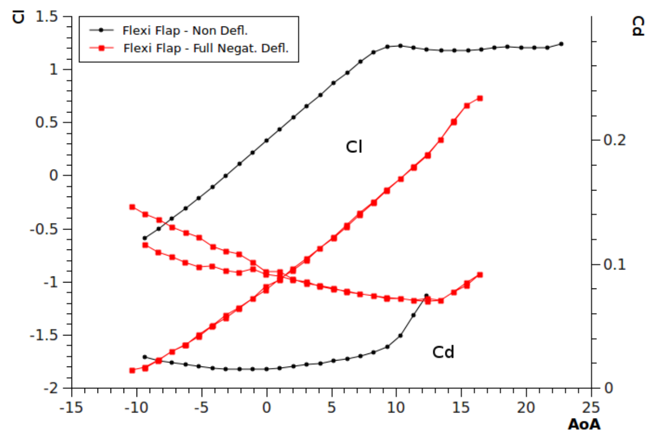


**FIGURE 6**. EXPERIMENTAL PERFORMANCE CURVES (WIND TUNNEL TEST) OF THE FLEXIBLE FLAP AT FULL DEFLECTION TOWARDS SUCTION SIDE (LOW LIFT).

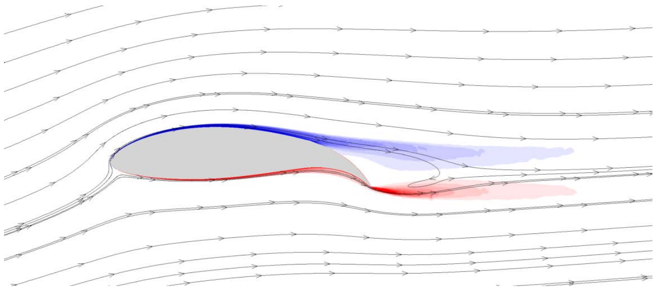

**FIGURE 7**. NUMERICAL SIMULATION OF FLEXIBLE FLAP AT FULL DEFLECTION TOWARDS PRESSURE SIDE (HIGH LIFT).

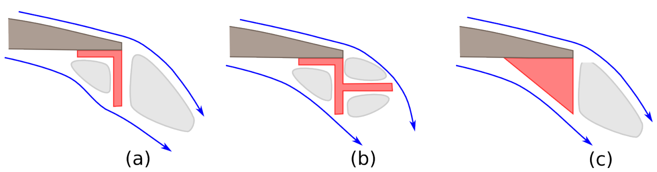


**FIGURE 8**. SOME OF THE GURNEY FLAP CONFIGURATIONS TESTED IN THE WIND TUNNEL. A)TYPICAL GURNEY FLAP, B) GURNEY FLAP WITH SPLITTER PLATE, C) WEDGE SHAPED GURNEY FLAP.

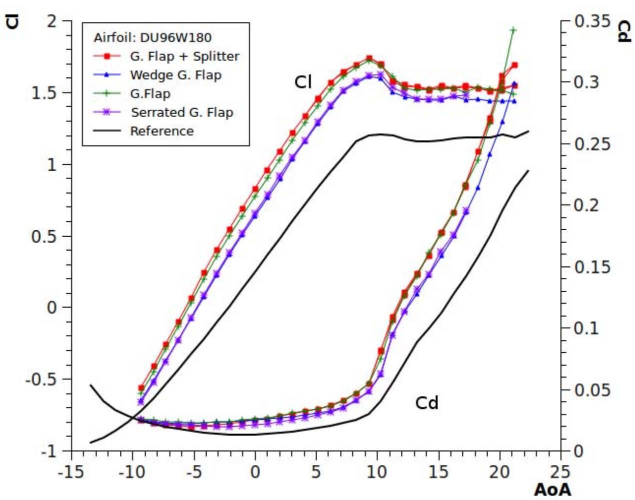


**FIGURE 9**. EXPERIMENTAL PERFORMANCE CURVES (WIND TUNNEL TEST) OF SEVERAL GURNEY FLAP CONFIGURATIONS.

## Stall Rib

To investigate the effect of active stall ribs on lift and drag, several stall rib shapes (Fig.10) were built. They were attached on the test wings and their effect was measured in the wind tunnel in steady mode. The stall ribs were tested at several chord-wise positions to identify their optimal placement. The wind tunnel measurements showed that the stall rib shape is a critical

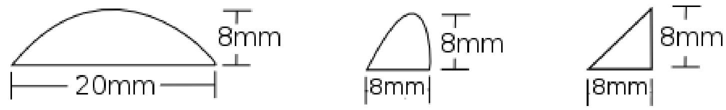


**FIGURE 10**. VARIOUS STALL RIB SHAPES EXPERIMENTALLY AND NUMERICALLY TESTED.

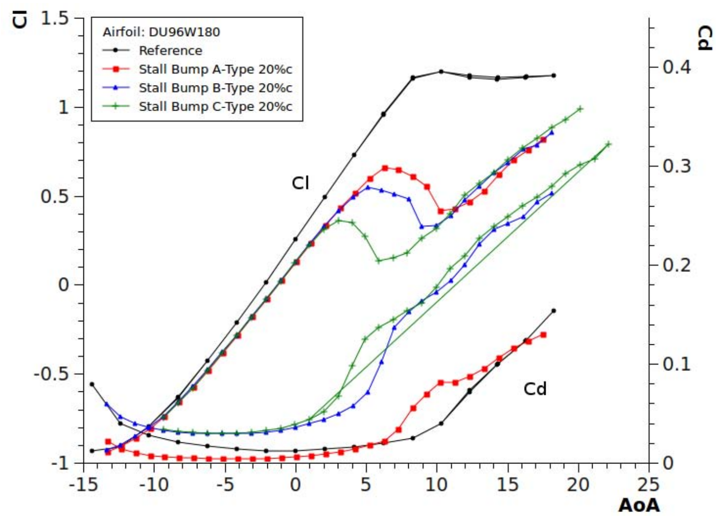


**FIGURE 11**. EXPERIMENTAL PERFORMANCE CURVES (WIND TUNNEL TEST) OF SEVERAL STALL RIB CONFIGURATIONS.

deign factor since it strongly affects the stall angle of the airfoil (Fig.11). In addition to that the wind tunnel tests proved the high AFC potential of the stall ribs especially on wind turbine blades where they can easily control the lift thus acting as a very effective load management solution.

Numerical CFD simulations with OpenFOAM showed that the flow past a stall rib separates and depending on the location of the stall rib it may re-attach or remain separated (Fig.12) thus significantly reducing the generated lift. Parametric CFD investigations revealed that stall ribs should be placed at the chord-wise position of maximum airfoil thickness or slightly up-flow of that.

## Flexible Leading Edge Flap

The Flexible Leading Edge Flap was mounted on the $NACA63_3618$ test wing and it was tested in the wind tunnel (Fig.13) at various flap deflections. The actuation mechanism was an innovative custom design with pneumatic actuation and fail safe characteristics (i.e. automatic stall mode in case of loss of pressure). This design concept was developed by the authors and the engineers of Smart Blade GmbH especially for use on wind turbine blades. The wind tunnel results showed that an increase at the leading edge camber due to the deflection of the leading edge flap causes a lift increase at high AoA and delays

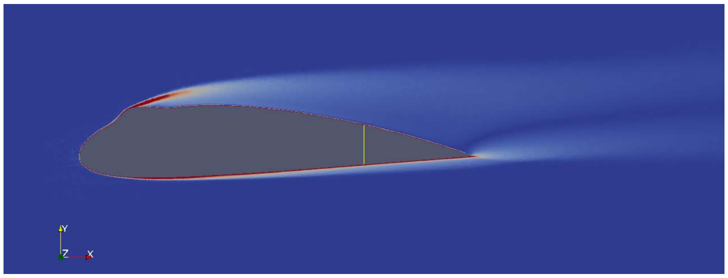

**FIGURE 12**. NUMERICAL FLOW SIMULATION OF A STALL RIB (VORTICITY CONTOURS).


**FIGURE 13**. THE *NACA*$63_3$618 TEST WING WITH THE FLEXIBLE LEADING EDGE FLAP IN THE WIND TUNNEL.

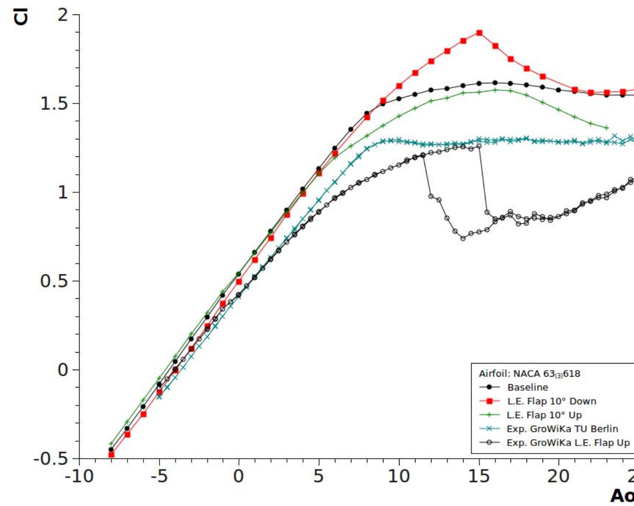


**FIGURE 14**. COMPARISON OF EXPERIMENTAL AND NUMERICAL RESULTS FOR THE *NACA*$63_3$618 WING WITH FLEXIBLE LEADING EDGE FLAP.

stall. A camber reduction or a negative leading edge camber (upwards deflected leading edge flap) causes early stall and rapid loss of lift. The same performance trends were also observed with the OpenFOAM simulations even though the experimental results do not really match the numerical results (Fig.14). This discrepancy is mainly due to the fact that the flexible leading edge flap mechanism was equipped with a flexible outer "skin" which was unable to precisely match the leading edge contour of the *NACA*$63_3$618 airfoil during the experiments . The CFD simulations were naturally performed with the ideal *NACA*$63_3$618 airfoil contour.

## UNSTEADY (DYNAMIC) INVESTIGATIONS

The third phase of the research included the dynamic wind tunnel investigations. During these tests, one AFC solution from the ones previously tested was selected to be dynamically tested with various control strategies. The selected configuration was that of the AH93W174 test wing equipped with an active Gurney Flap (flap chord $= 2\%c$). The active Gurney flap was actuated by four digital electric servos with a maximum deflection rate of $360^\circ/sec$. A custom code was created to allow dynamic AoA variations of the test wing with simultaneous high speed force measurements. In this way, the wind tunnel force balance was used as a lift measurment input. An additional high precision mechanical AoA sensor was attached to the wind tunnel assembly to extract accurate AoA measurements.

To use the measured data as a direct control input, a multi-core approach was followed where each processing core of a quad-core PC was utilized for data acquisition, data processing, control feed and visualization respectively. In this way it was possible to feed an AoA variation pattern around a mean AoA position and through the force measurements of the 6-component balance to calculate the optimal Gurney Flap deflection angle to stabilize the aerodynamic lift [86]. The same configuration was maintained for all the dynamic tests, while the control strategies were varied in order to identify their performance differences.

The AoA variation pattern during the dynamic AFC tests in the wind tunnel was initially set as an adaptable white noise profile. This was used for the initial tests of the various control strategies and for the "teaching" of the Neural Network control systems. The various control strategies were also tested with AoA profiles extracted from a Dynamic BEM Simulation (Dynamic BEM coupled with multi-body structural model). Through this approach it was possible to match as much as possible the actual wind turbine behavior. In this way the performance of the Active Gurney Flap system could be more easily assessed for an actual wind turbine application.

During the dynamic investigations several control strategies were tested, starting from standard PID controllers with

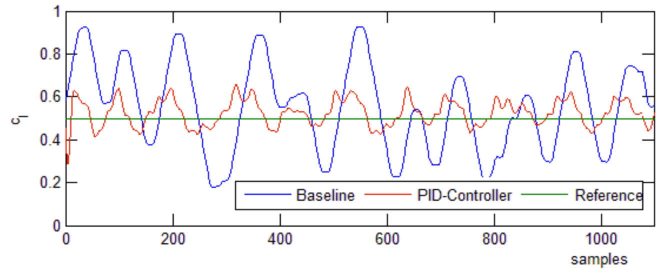


**FIGURE 15**. MEASURED WIND TUNNEL DATA OF LIFT VARIATION DUE TO AOA VARIATION WITH (RED LINE) AND WITHOUT (BLUE LINE) ACTIVE FLOW CONTROL.

semi-empirical parameter tunning models (Ziegler Nicholson method), to DIC (Direct Inverse Controllers) with Neural Network tunning strategies and pure self learning Neural Network controllers [87]. The results of the closed loop measurements using the manually tuned PID-Controller showed a reduction potential for the dynamic lift loads in the range of 70% as well as a stable controller behavior. For the DIC control strategy, Neural Networks were successfuly used to define an inverse model of the considered system. The defined network was modified and used as a closed loop Direct Inverse Controller.The closed loop measurements with this DIC controller showed, that a load reduction of 36.8% is possible with this configuration. Both the control signal however as well as the flap deflection signal indicated a certain controller instability. The DIC controler design strongly depends on the "teaching" data produced by the Neural Networks. Further investigations and optimizations of the Neural Network "teaching" algorihms will probably improve the DIC performance significantly.

The overall results of this phase of the research showed that the currently tested control strategies exhibit good results (Fig.15) with respect to wind turbine applications for load alleviation [86]. At the same time however it has to be noted that there is still a very large potential for improvement of these control strategies.

## CONCLUSIONS

The current paper presents in brief the main steps and a part of the findings during a long term research project conducted by the authors. The main purpose of the project is the overall investigation of several AFC solutions for wind turbines, the selection of the best performing ones according to objective and realistic criteria and the development of proper control strategies and aerodynamic "smart" blade designs. All the research done so far shows that the selected methodology is on the right path and that technically and economically feasible AFC solutions for wind turbines can be developed.

This paper focuses mostly on the general steady state investigations and the basic unsteady (dynamic) investigation of AFC solutions for wind turbine applications. Through wind tunnel tests and CFD simulations the best performing AFC elements were identified. The development of a basic control strategy for a Wind Turbine AFC system was accomplished with the use of an active Gurney flap mounted on a wind tunnel test wing model. The results of this dynamic experiment showed that the load reduction potential of such an AFC system is considerably high. The measurements revealed an advantage of the traditional PID control strategies over the more advances Neural Network - DIC approach. The authors however believe that further development will improve the DIC control system and will reveal its full potential.

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