Boundary Layer Suction by Thick Inboard Wind Turbine Airfoil

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Abstract
boundary layer suction is a proven technique to control stalled areas and increase aerodynamic efficiency. The positive results of 2D wind tunnel tests applying discrete boundary layer suction for direct stall control by a wind turbine airfoil, designed for the root and middle rotor blade sections, are reported. The experiments were conducted with a Reynolds number of $1 \times 10^6$ and AOA up to $16^\circ$. The stalled area was reduced or even avoided and the lift coefficient increased for many cases as a function of the tested AOA and applied suction coefficient. The direct control of the stalled flow with suction openings placed downstream from the separation point of no suction case was effective.

1. Introduction and objectives
Boundary layer suction enables manipulation of the flow for aerodynamic or acoustical improvements. The suction can be realized by a porous wall in the case of continuous suction or by a single or multiple slots or perforated areas in the case of discrete suction [1, 2]. The suction system is usually designed as an active control technique, but can also be passive [3,4]. Suction openings are usually placed on airfoils at the nose region and over a wide region of the suction side in order to delay transition or to relaminarize a turbulent flow. It contributes to thinning and stabilizing the boundary layer, changing the velocity profile and results in drag reduction and lift improvement [1,5]. The use of boundary layer suction for direct control of the stalled flow is considered as very efficient [6]; for this control goal, suction openings are placed downstream from the separation point of the no suction case. By direct stall control, the limiting or suppressing of the stalled area and a lift enhancement are desired [1].

The main goal here is to investigate the use of discrete boundary layer suction on inboard rotor blade section (see Fig.1), focusing on postponing or suppressing flow separation. Figure 1 shows a cross flow initiated in the hub area at the blade suction side for the design tip speed ratio by a multi megawatt turbine. This cross flow usually covers up to 30% of the blade span at the design tip speed ratio of megawatt and multi megawatt turbines. A strong stalled area is observed in the cylindrical blade span positions. Earlier investigations showed the possibility of a slight rotor power improvement as result of the radial limiting of the stalled area [7]. The use of boundary layer suction is a possibility to stabilize the flow and to optimize the rotor efficiency in design and off-design tip speed ratios. It could be interesting as well as in case of sites with two significant wind velocity classes or with high turbulent intensity.

In this work two-dimensional experiments applying discrete boundary layer suction for a thick wind turbine airfoil, designed for the root and middle rotor blade sections, were used. This was in order to confirm the effectiveness of direct control of separation, as well as to define the range of suction flow rate demanded for different angles of attack.
2. Methods

2D wind tunnel experiments applying boundary layer suction were conducted at TU Berlin. Surface flow visualization with a titanium dioxide-oil mixture was applied at the airfoil suction side and nose region. Pressure distributions were measured using 22 pressure-measuring sensors around the model midsection.

The model construction, including the suction system, was also conducted at TU Berlin. The geometry of the airfoil wooden model is based on a wind turbine airfoil with maximum thickness of 35%. The reference airfoil was designed for a Reynolds number of $3 \times 10^6$ and is used in the original or in lightly modified geometries from more than ten different wind turbine manufacturers in the inboard area of their blades. It is possible that the wood construction resulted in slight geometry variations, so that the investigation focuses on comparing the cases with and without the use of boundary layer suction.

XFOIL calculations and 2D RANS based CFD simulations were taken as a preliminary estimate to the location of the suction openings and the required flow rates of suction flow. Based on results of the numerical work, the suction openings were placed at 65% of the chord at the suction side of the airfoil model (See Fig. 2).
Relevant parameters of the test setup and parameters of variation are:
- model with chord length of 0.5 m placed vertical in the wind tunnel
- free-stream Reynolds number of $1\times10^6$ (free-stream velocity around 30 m/s)
- angles of attack (AOA) ranging from $5^\circ$ to $16^\circ$
- free and fixed transition configurations; for the fixed one, transition is imposed at 10% of the chord using a zig-zag band in order to suppress laminar separation bubbles
- two opening form configurations:
  - model with a single slot (width of 1% of chord, suction area corresponding to 1% of the model suction side area)
  - model with discrete perforated area (around 500 holes with 3 mm diameter, corresponding to 0.5% of the model suction side area)
- suction coefficient $c_Q$ from 0.1 to 1.75; suction coefficient defined as the ratio between wall normal velocity of the suction flow and free-stream velocity [1,5,8].

![Airfoil model with suction system](image)

**Fig. 2.** Photo (left) and schemes (right) of airfoil model with suction system

### 3. Results
In tests at a restricted Reynolds number of $1\times10^6$ the stall conditions were reached earlier and the separated area was more strongly developed than compared to simulations at the airfoil design Reynolds number of $3\times10^6$. As result AOA from $5^\circ$ to $16^\circ$ could be tested.

For the AOA of $5^\circ$ a positive effect was reached by applying suction for small suction coefficients of 0.1 and 0.25 (see Fig. 3 and 4). For higher AOA of $10^\circ$ and $13^\circ$ and fixed transition, a suction coefficient of 1.75 was required to influence the flow positively. In the free transition configuration and an AOA of $16^\circ$ an optimized flow structure was reached for a suction coefficient of 1.75 (see Fig. 5).
**Fig. 3.** Visualization of flow in reference case (left) and by discrete suction with a single slot (right) at an angle of attack of 5°

**Fig. 4.** Visualization of flow in reference case (left) and in cases of discrete suction with perforated area (middle) and with a single slot (right) at an angle of attack of 5°

**Fig. 5.** Visualization of flow in reference case (left) and by discrete suction with perforated area (right) at an angle of attack of 16° and clean configuration (free transition)
In positive cases, the suction peak grows wider and is intensified by applying boundary layer suction; a lift coefficient enhancement between 70 and 140% was measured according to the tested AOA and suction coefficient.

The suction openings at 0.65 of the chord were located downstream from separation zone for the tested AOA. For the reference airfoil the suction position was effective for direct stall control.

6. Conclusions and Outlooks
In 2D wind tunnel tests applying boundary layer suction to a reference thick inboard airfoil, the stalled area was reduced or even avoided and the lift coefficient increased for many cases as a function of the tested AOA and applied suction coefficient. The direct control of the stalled flow with suction openings placed downstream from the separation point of no suction case was effective.

According to the author’s earlier investigations of flow control at the root area, the lift improvement is expected to be smaller in 3D than the in the 2D case. Three-dimensional tests of suction systems at the inboard area are of importance and interest in further investigations. The conduction of three-dimensional tests with an active suction system, as well as with a passive suction system at the root area coupled with exhaust at the tip blade region [4], exploring the effects of centrifugal forces, is encouraged. By first estimations the lowest suction coefficients considered at the experiments can be reached with a passive suction system solution with exhaust at the tip blade region for a megawatt wind turbine rotor.

References
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