Critical evolution of leading edge suction during dynamic stall

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Abstract. Dynamic stall dominates the aerodynamic performance, the robustness, and the wake dynamics of vertical axis wind turbines. To better assess the dynamic stall onset and its associated unsteady effects, this paper analyzes experimentally the evolution of the leading edge suction vector on a sinusoidally pitching airfoil based on time-resolved surface pressure measurements and particle image velocimetry. During the dynamic stall stage, we linked the shear layer evolution with the evolution of the leading edge suction. The dynamic stall development prior to dynamic stall onset consists of two stages: a primary instability stage and a vortex formation stage. The transition between the stages is marked by a maximum in the leading edge suction. During the primary instability stage, the leading edge suction increases linearly while the shear layer height with respect to the airfoil’s surface also increases linearly. During the vortex formations stage, the leading edge suction decreases linearly while the shear layer rolls up and creates a dynamic stall vortex. The maximum leading edge suction increases nearly linearly with the normalized effective unsteadiness. The leading edge suction at dynamic stall onset appears to be independent of unsteadiness of the pitching motion.

1. Introduction
Wind turbines have become ubiquitous features in today’s landscapes. They all aim to convert wind energy into electrical energy, but depending on the local wind conditions, their design, size, and orientation of the rotor axis vary. Although vertical axis wind turbines (VAWT) are less common, they have several advantages over the classical horizontal axis wind turbines (HAWT) [1]. They are insensitive to wind direction, visually and acoustically less intrusive, they produce power at lower wind speeds, and they have a simpler design with fewer moving parts than horizontal axis wind turbines.

Whereas the design and mode of operation of a standard H-type VAWT is much simpler than the current state-of-the-art HAWT, the associated aerodynamics at the blade and rotor level are more complex. The higher level of complexity is attributed to the inherently unsteady flow as a result of large variations in both the angle of attack and the magnitude of the incident velocity at the blade level. These large variations of angle of attack lead to the occurrence of dynamic stall. Dynamic stall dominates the operation, aerodynamic performance, robustness, and wake dynamics of VAWT. The undesirable effects associated with dynamic stall all follow the stall onset. Insights into the timing of dynamic stall onset and its associated unsteady effects are of particular importance to better predict the performance of VAWT by low order models.
The Beddoes-Leishman [2] and Goman-Khrabrov model [3] are two popular low order state-space models used to predict aerodynamic load during dynamic stall. Alternative models are based on the discrete vortex method which describes the step-wise changes of vorticity distribution in the form of discrete vortices that are convected with a local velocity. To improve this latter type of model for vortex-dominated massively separated flows during dynamic stall, leading edge discrete vortices must start shedding at a specific instant to correctly simulate the formation of the dynamic stall vortex.

The initiation of dynamic stall has been linked to the flow parameters at the leading edge [4]. The strength of the suction peak was directly related to the velocity at the leading edge by Evans and Morton [5]. It is also linked to the first term $A_0$ of the Fourier series in thin-airfoil theory [6]. The suction at the leading edge is used as criterion for initiation of the leading edge vortex formation [7]. Ramesh et al. [8] numerically observed a critical threshold of the leading edge suction when a leading edge vortex is being created, by calculating the first term $A_0$ of the Fourier series. They refer to $A_0$ as the leading edge suction parameter (LESP). According to Ramesh et al., the critical LESP value is independent of the frequency of the motion for a given airfoil at a fixed Reynolds number.

In this paper, we analyzed time-resolved surface pressure and PIV data for experimental evidence of a critical leading edge suction parameter. The temporal evolution of the leading edge suction is linked to previous observation of the flow field during dynamic stall development [9]. The critical LESP values have been extracted for different airfoil pitching motions.

2. Experimental set-up

Unsteady surface pressure and time-resolved particle image velocity measurements (TR-PIV) were conducted in the central cross-sectional plane of a pitching OA209 airfoil with a chord length of $c = 0.3$ m in a uniform flow of $U_\infty = 50$ m/s ($Re = 9.2 \times 10^5$). A thin airfoil section was chosen to compare the experimental results with thin airfoil theory. Experiments were conducted in an open test section with an airfoil with an aspect ratio of 5. Under these testing conditions, the flow is observed to be symmetric in the measurement plane and influences of the sides are minimal.

The pressure distribution was determined by 41 pressure taps at a rate of 6kHz. The leading edge suction is determined by integrating the pressure measurements in the first 10% of the chord covering 13 pressure taps (blue area in figure 1). To resolve the suction gradient in the leading edge region of the airfoil, more than 30% of the pressure taps were placed in the first 10% of the chord. The magnitude of the force coefficient of the leading edge is denoted by $S_{LE}$ and its orientation with respect to the inflow velocity by $\lambda$ (figure 1).

The time-resolved PIV data were evaluated using a multigrid algorithm with a final interrogation window size of 32px $\times$ 32px and an overlap of approximately 80%. The velocity field was measured with a spatial resolution of 1.2 mm or 0.004$c$ and an acquisition rate of 1500 Hz.

The velocity fields are rotated into the airfoil frame of reference, with the $x$-axis along chord,

![Figure 1. Definition of the leading edge suction $S_{LE}$ and the angle $\lambda$ relative to the inflow velocity ($U_\infty$). Markers indicate the locations of the pressure sensors at model mid-span. The blue shaded region defines the leading edge region.](image-url)
a. b. c. d. e. f. g. h.

Figure 2. Temporal development of the lift coefficient (a.) and the chord-normal shear layer distance relative to airfoil’s suction surface (b.) within a single pitching cycle for a sinusoidal motion around $\alpha_0 = 20^\circ$, with an amplitude of $\alpha_1 = 8^\circ$ at a reduced frequency $k = 0.05$. The labels a. to h. in the lift history indicate the timing of the snapshots presented in figure 3. The gray shaded regions refer to the two stages of stall development between the passage of the static stall angle of attack and dynamic stall onset. The transition between the two stages is indicated by $t^*$. The indices of attack of the airfoil was varied sinusoidally around a mean incidence $\alpha_0$ close to the static stall angle with an amplitude $\alpha_1$, and an oscillation frequency $f_{osc}$. A large range of dynamic stall cycles was obtained by varying the motion parameters $\alpha_0$, $\alpha_1$, and $f_{osc}$.

The instantaneous effective unsteadiness was introduced previously by Mulleners and Raffel [10] as a single representative parameter to describe the influence of the motion parameters describing a sinusoidal pitching motion. The instantaneous effective unsteadiness $\dot{\alpha}_s^*$ is defined as the rate of change of the angle of attack at the moment when the static stall angle is exceeded and it is non-dimensionalized by the convective time: $\dot{\alpha}_s^* = \dot{\alpha}_s c/U_0$.

3. Results and discussion

3.1. Shear-layer evolution during stall stage

The evolution of the lift coefficient during a single cycle or period $T$ of a pitching motion described by $\alpha_0 = 20^\circ$, $\alpha_1 = 8^\circ$, and $k = 0.05$ is presented in figure 2a. The timing is also indicated in terms of the non-dimensional convective time $t_c = t c/U_0$ with respect to the moment at which
Figure 3. Representative snapshots of the velocity and vorticity field during different stages of the dynamic stall life cycle. The timing of the snapshots is indicated in the lift history in figure 2a.
the static stall angle is exceeded. The lift history displays the classical hallmarks of dynamic stall. At \( t/T = 0 \) the angle of attack is minimal, the flow is attached to the airfoil, and the lift coefficient increases with increasing angle of attack. At \( t_s \), the static stall angle of attack is exceeded but the lift coefficient continues to increase, yielding a lift overshoot with respect to the maximum attainable lift coefficient under static conditions. Stall is delayed under dynamic conditions to \( t_s \). The timing of dynamic stall onset was determined directly from the velocity field based on a characteristic mode of the proper orthogonal decomposition of the velocity field \([10]\). The interval between the passage of the static stall angle \( t_s \) and the dynamic stall onset \( t_d \) is called the stall development stage. This stage is characterized by the emergence and development of a shear layer at the interface between the decelerated flow near the airfoil surface and the free-stream flow. Based on the behavior of the shear layer, the stall development was observed to be a two-stage process \([9]\). This two stage development is clearly illustrated by the temporal evolution of the chord-normal distance between the shear layer and the airfoil surface \( \Delta z \) (figure 2b.). The chord-normal distance of the shear layer from the surface is calculated in individual snapshots based on the location of the clockwise rotating vortices. The location of these vortices were determined based on Eulerian vortex criteria \([9, 11]\). The chord-normal distance of the shear layer from the airfoil’s suction surface \( \Delta z \) at a given time is the average of the chord-normal distances of all vortical structures identified in the snapshot of the velocity field at that time instant.

In the beginning of the dynamic stall life cycle up to \( t_s \), the flow is attached (figure 3a.) and \( \Delta z \) is close to zero. In figure 3, there is a white band directly above the airfoil’s suction surface which indicates the region where no valid data was recorded due to reflections of the laser light at the surface. It is not a region of low vorticity. After passing the static stall angle of attack, a region of flow reversal grows until it spans almost the entire chord length (figure 3b.-c.) causing the chord-normal distance of the shear layer to increase linearly with time. The growth rate of \( \Delta z \) increases rapidly when the shear layer starts to roll up and form a large scale dynamic stall vortex (figure 3d.-e.). The chord-normal shear layer distance still increases linearly with time during the shear layer roll-up, but with a significantly larger slope than in the first part of the stall development. After the primary dynamic stall vortex sheds (figure 3f.), which marks dynamic stall onset, the flow is fully stalled (figure 3g.) and \( \Delta z \) remains high until the flow reattached from the leading edge towards the trailing edge (figure 3h.).

The first stage of the stall development is characterized by the growth of the recirculation region and the development of a primary instability or Kelvin-Helmholtz-type instability of the shear layer. This stage was therefore called the primary instability stage. The second stage of the stall development is characterized by a secondary shear layer instability which causes it to roll-up into a large scale dynamic stall vortex. This stage was called the vortex formation stage. The transition between the two stall development stages \( t'_s \) is identified by the sudden increase in the growth rate of the chord-normal shear layer distance and determined as the intersection of the two linear fitting curve of \( \Delta z \) as indicated in figure 2b. The stall behaviour just described is also observed by Gupta and Ansell \([12]\) for NACA airfoils.

### 3.2. Leading edge suction evolution during stall stage

Figure 4 presents the temporal evolution of the magnitude \( S_{LE} \) and orientation \( \lambda \) of the leading edge force coefficient during the end of the upstroke of the same pitching motion described earlier. The gray lines represent different motion cycles and the thick black line represents the phase-averaged value. Up to dynamic stall onset, there are no noticeable cycle-to-cycle variations. The leading edge suction force development is highly repetitive until the dynamic stall vortex is shed at \( t_d \). After stall onset, the cycle-to-cycle variations increase.

During the attached flow stage and the first part of the stall development stage, the leading edge suction magnitude increases linearly and the angle \( \lambda \) remains constant around 85°. This
Figure 4. Magnitude $S_{LE}$ of the leading edge suction force and its orientation $\lambda$ relative to the inflow velocity for a pitching motion described by $\alpha_0 = 20^\circ$, $\alpha_1 = 8^\circ$, and $k = 0.05$. The thick black line represents the phase average of the results of multiple cycles represented by the gray lines.

Figure 5. Temporal evolution of the leading edge suction parameter $A_0$ and the chord-normal shear layer distance for a pitching motion described by $\alpha_0 = 20^\circ$, $\alpha_1 = 8^\circ$, and $k = 0.05$. The thick black line represents the phase average of the results of multiple cycles represented by the gray lines for $A_0$. 
means that the leading edge force is almost perpendicular to the free stream, with a small component in the direction of the free stream. The rate of increase of $S_{LE}$ is slightly lower after $t_c=0$ than during the attached flow stage.

Between the maximum of the leading edge suction and dynamic stall onset, the leading edge suction magnitude decreases followed by a smaller local maximum (figure 4a.). This local maximum directly follows the dynamic stall onset. The angle of the the leading edge suction shortly decreases during the second stage of stall development and increases rapidly after $t_a$. This means that the leading edge suction force is directed slightly more in the direction of the free stream during the shear layer roll-up and turns more towards the trailing edge once the flow fully separates. Due to flow separation, the leading edge suction force decreases.

The leading edge suction parameter evaluated by Ramesh et al. [8] is based on $A_0$, measured here as $A_0 = 2/\pi S_{LE,x}$ from [13]. The temporal evolution of $A_0$ is presented in figure 5 together with the temporal evolution of the chord-normal distance of the shear layer to highlight the correlation between the results from the pressure measurement and PIV data. The temporal evolution of the leading edge suction parameter $A_0$ and the temporal evolution of the chord-normal distance of the shear layer $\Delta z$ are both characterized by two linear regimes during stall development. The timing and duration of those regimes range from $t_s=0$ to $t^*$ and from $t^*$ to $t_a$. The transition between these regimes occurs almost at the exact same time.

Results based on the airfoil surface pressure measurement and PIV data of flow field above the entire airfoil surface independently reveal a two-phase stall development. The critical time scales and the transition location from both the pressure and the velocity field data coincide.

### 3.3. Evolution of the critical leading edge suction with the motion of the airfoil

For the representative dynamic stall cycle presented here, the maximum leading edge suction coincides with the start of the dynamic stall vortex formation. In figure 6, we now compare the maximum LESP ($A_0$) values, the values at the static stall angle, and the values at dynamic stall onset for various deep dynamic stall pitching motions in function of the normalized effective unsteadiness.

The LESP at the static stall angle stays constant for all motions. Maximum $A_0$, corresponding to the critical LESP, increases with 20% for the range of normalized effective unsteadiness $\dot{\alpha}_s^*$ studied here. The LESP measured at dynamic stall onset is smaller than the LESP at static stall

![Figure 6. Comparison of characteristic LESP ($A_0$) values measured for various deep dynamic stall pitching motions represented by their normalized effective unsteadiness ($\dot{\alpha}_s^*, c/U_0$).](image-url)
and tends to decrease with increasing normalized effective unsteadiness. For a Reynolds number ≈ 10^6, leading edge vortex formation thus seems to depend on the unsteadiness of the airfoil’s motion.

4. Conclusions
Based on experimental time-resolved surface pressure and time-resolved PIV data, we linked the generalized flow dynamics during dynamic stall with the evolution of the leading edge suction, which is related to the pressure force generated by the airfoil. The two-stage stall development which was observed in previous investigations based on velocity field data, is confirmed here based on the evolution of leading edge suction with is solely based on surface pressure measurements.

The first part of the stall development is called the primary instability stage and is characterized by the increase of leading edge suction and a constant leading edge suction angle. The second part of the stall development is called the vortex formation stage and starts just after the leading edge suction reaches a maximum. The vortex formation stage is about 1/5 shorter than the duration of the primary instability stage.

Prior to stall onset, there are no cycle-to-cycle variations of the leading edge suction, and its maximum can be used as a robust critical value to identify the start of the dynamic stall vortex formation. This critical value increases linearly with the normalized effective unsteadiness of the pitching motion.

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