An experimental and numerical investigation on the formation of stall-cells on airfoils

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Abstract. Stall Cells (SCs) are large scale three-dimensional structures of separated flow that have been observed on the suction side of airfoils designed for or used on wind turbine blades. SCs are unstable in nature but can be stabilised by means of a localized disturbance; here in the form of a zigzag tape covering 10% of the wing span. Based on extensive tuft flow visualisations, the resulting flow was found macroscopically similar to the undisturbed flow. Next a combined investigation was carried out including pressure recordings, Stereo-PIV measurements and CFD simulations. The investigation parameters were the aspect ratio, the angle of attack and the Re number. Tuft and pressure data were found in good agreement. The 3D CFD simulations reproduced the structure of the SCs in qualitative agreement with the experimental data but had a delay of ~3deg in capturing the first appearance of a SC. The error in Cl max prediction was 7% compared to 19% for the 2D cases. Tests show that SCs grow with Re number and angle of attack. Also analysis of the time averaged computational results indicated the presence of three types of vortices: (a) the trailing edge line vortex (TELV) in the wake, (b) the separation line vortex (SLV) over the wing and (c) the SC vortices. The TELV and SLV run parallel to the trailing edge and are of opposite sign, while the SC vortices start normal to the wing suction surface, then bend towards the SC centre and later extend downstream, with their vorticity parallel to the free stream.

Keywords: Stall Cells, Wind tunnel testing, 3D CFD

1. Introduction
When it comes to airfoil wind tunnel testing the use of two dimensional rectangular models has been the common practice for decades. From early on, however, questions were raised regarding the validity of such tests under three dimensional separated flow conditions and in particular when stall cells (SCs) are formed [1]. SCs, also known as ”mushrooms” or ”owl's eyes”, are large scale structures of separated flow that consist of two counter rotating vortices. Among other cases, they are formed in the separated flow region of airfoils that exhibit trailing edge (TE) stall type [2]. Airfoil sections for wind turbine blades belong to this type as they are designed with flat-top loading to achieve smooth stall behaviour. Indeed, as found in previous studies [3–5] SCs have been observed on the suction side of such airfoils.

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Due to their specific interest for wind turbine blade design, a combined investigation on SCs has been carried out including wind tunnel testing and CFD computations. The investigation concerned an 18% thick airfoil designed at NTUA for multi MW wind turbines. Wind tunnel testing included pressure and Stereo PIV measurements along with tuft flow visualization tests. On the computational side a (U)RANS solver with the Spalart Allmaras [6] model was used.

The present paper reports on the main findings in the course of this investigation. In the next section the rationale behind applying the localized disturbance to the flow is given. Then the description of the experimental and the computational approach follow. Results are presented and discussed in the following section before the final part where the main conclusions are drawn.

2. Phenomenology

All published reports on SCs for Reynolds (Re) number higher than $0.3 \times 10^6$ agree that SCs are dynamic structures ("moving in the spanwise direction", [7]) and/or unstable as they form and disappear or merge in a seemingly random manner ([1], [8]). These findings were confirmed by the tuft flow visualisation data of the present study. Subsequently an attempt was made to stabilize the separated flow as this would facilitate the study of its structure.

Recent theoretical results suggest that SCs could be the result of spanwise flow instability [9]. Weihs and Katz [10] suggested that the spanwise instability leading to SCs could be a Crow like instability between the two intense shear layers of the separation bubble. Also recently, Elimelech et al. [11] showed on the basis of measurements at low Re numbers that the amplification of a two dimensional perturbation cannot justify the formation of structures of such a large scale as the SCs and that SCs could be explained as result of a spanwise 3D perturbation.

Based on the above findings it was decided to add a constant spanwise disturbance to the flow in the form of a zigzag (ZZ) tape located at the centre of the wing span, on the suction side. Indeed this led to the formation of a stable SC downstream of the ZZ tape. This is the case studied in this project.

3. Test set up and measuring procedures

3.1. General set up

All experiments were carried out at the 1.4mx1.8m test section of the National Technical University of Athens wind tunnel. The wind tunnel is of the closed single-return type and the free-stream turbulence level in the 3.75 m long test section is 0.2%.

The tests concerned an 18% thick airfoil optimized for use on variable pitch and variable speed multi MW blades [12]. The wing model had a chord of 0.6m and spanned the test section vertically in order to minimize blockage. In order to suppress the effect of the wind tunnel boundary layers side fences were added, shown in Figure 1. Figure 2 shows a schematic side view of the test set up. By varying the fences position different aspect ratio (AR) values could be achieved. In this paper pressure and tuft data are reported for AR 1.5 and 2.0 and Re numbers of 0.5, 1.0 and 1.5 million. More details on the pressure measurements and tuft data can be found in [13] and [14], respectively.

![Figure 1: The airfoil profile and the wing fences dimensions (1.7c long, 0.7c wide)](image_url)

![Figure 2: Side view of the test set up. The fences, tufts and the localized disturbance are indicated with arrows.](image_url)
Concerning the tuft data, the following metrics are examined:

- The most upstream \( x/c \) location of the SC boundary (earliest separation point)
- The SC area as \% of the wing planform area

\[
SC_{relative \ area} = \frac{SC_{actual \ area}}{Wing_{planform \ area}}
\]  

They are defined in Figure 3, where a snapshot from the tuft visualisation experiments is shown (case: AR 2.0, Re 1.0 \( 10^6 \), 9.0° with ZZ tape). More photos and videos are available in [4, 13].

3.2. Stereo PIV set up

The Stereo-PIV equipment included a TSI 30mJ Nd:YAG PIV laser with dual cavities which produced a 2 mm thick light sheet at the measurement position. The seeding consisted of oil droplets of mean diameter of 1μm and a double sided side dual plane calibration target was used for calibration. Two TSI Powerview Plus™ 4MP Cameras were used, located inside the test section 1.2c downstream of the TE. The camera base was secured on elastic anti-vibrating pads and both cameras were mounted on reinforced Scheimpflug angle adjustable mountings. All Stereo-PIV data were taken at a Re number of 0.87 \( 10^6 \) as at higher Re numbers the camera vibrations were considered too high.

The camera vibration was examined using a procedure similar to that of [15], [16] using the wing TE position as a reference. The TE position could be directly extracted from the PIV images as it was a clear peak in the image light intensity. Thus the camera movement could be quantified in pixels. In all cases for the average flow the error resulting from camera vibration was less than 0.1 m/s (95% confidence interval).

The velocity field was measured in planes normal and parallel to the flow (normal to the wing span), see Figure 4. Due to the vicinity of the measurement planes to the wing surface reflections were an issue and affected areas have been masked out in the results as have areas with insufficient light intensity. For the plane normal to the flow a series of adjacent frames was measured with 25% overlapping. Planes parallel to the flow were measured at five locations, one at the centre of the wing span and four at +/-8cm and +/-16cm of it. A schematic view of the Stereo-PIV set up with the measurement frames (normal and parallel to the flow) is given in Figure 5. Measurement details for all the frames are given in Table 1.

The image post processing was done using TSI Insight 4G software. The overlap between interrogation areas was set to 50% and double correlation validation was used. Spurious vectors were replaced using a 3x3 local mean. 2000 velocity fields were captured for each frame at a recording rate of 1Hz. The data presented here are the averaged results.

| Angle of attack | 7°   | 10°  |
|-----------------|------|------|
| Plane orientation with respect to free stream | Normal | parallel | normal | parallel |
| Lens           | 90mm | 90mm | 50mm | 50mm |
| Focal ratio    | 1/2.8 | 1/2.8 | 1/1.4 | 1/1.4 |
| Camera contained angle | 62° | 62° | 62° | 72° |
| Final interrogation area size [px] | 32x32 | 32x32 | 32x32 | 32x32 |
| Final interrogation area size [mm] | 1.9x1.9 | 1.9x1.9 | 3.9x3.9 | 3.9x3.9 |

3.3. Stabilization of the SCs

SCs are in general unstable unsteady structures as they can exhibit spanwise movement and/or random formation and destruction. As discussed in [4] it is possible to stabilize a SC by using a large enough spanwise disturbance. In the present case a zigzag (ZZ) tape was located centrally for 10% of the wing span. The chordwise location of the ZZ tape (x=0.02c) was selected so that it would always be met by laminar flow (based on XFOIL computations). Its height (0.4mm) ensured that it was exceeded
requirements for transition for all three Re numbers considered. The resulting SC was stable although unsteady and, as it will be shown below, resulted in the same amount of separated flow as the undisturbed cases for intermediate and higher angles of attack.

Figure 3: Schematic view of a SC for AR=2.0, Re=1.0 \(10^6\), a=8.0\(^\circ\), locally tripped at the wing span centre. The direction of the flow is from top to bottom.

Figure 4: Schematic of the PIV measurement planes: sideview of the plane normal to the flow (dotted green line), outline of the plane parallel to the flow for the 10\(^\circ\) case (thick red line), and outline of the plane parallel to the flow for the 7\(^\circ\) case (thin red line).

Figure 5: Schematic view of the Stereo-PIV set up with the light sheet (in position for normal plane measurement), measurement frames (normal and parallel to the flow) and the cameras.

4. Computational approach

4.1. Solver and grid
A MPI enabled compressible multi-block finite volume (U)RANS solver [17] applied to hybrid grids was used. The code is equipped with pre-conditioning for low Mach flow conditions and uses the
Spalart-Allmaras turbulence model. The discretisation is 2nd order accurate in time and space while
dual time stepping is added in order to facilitate convergence.

A C-type grid was used that extended 50 chords around the airfoil. The y+ value in the boundary
layer was lower than 1 throughout the wing surface. All results reported here were obtained using a
10^6 cells computational domain assuming symmetry at one end and inviscid wall boundary conditions
at the other. A more detailed description is given in [13].

4.2. Zigzag tape modelling
The flow in the experiments was locally disturbed for 10% of the wing span on the suction side using
a 0.4mm thick ZZ tape of 60°. Several oil film surface visualization studies [18–20], report the
formation of oil stripes downstream of ZZ tape, which are associated with streamwise vortices created
by it. The ZZ tape's "legs" can then be considered as attached vortex generating surfaces to the
incoming flow.

It was hence attempted to model the trip tape in the 3D computations as a vortex generating surface
using the BAY model [21]. Fully resolving every leg of the trip tape in the computational model
would be too costly and out of scope for the present study. The "2-legged" bay model surfaces that
were used are shown in Figure 6. No ZZ tape model was used in the 2D computations. In both 2D and
3D computations the flow was considered fully turbulent.

![Figure 6: Actual trip tape geometry and BAY model surfaces](image)

5. Results and discussion
As already mentioned the use of a ZZ tape as localised disturbance stabilized the flow leading to the
formation of a single SC located at the centre of the wing. Adding the ZZ tape caused three
dimensional separation to occur earlier compared to the undisturbed case. The amount of separated
flow, however, did not change for intermediate and higher angles of attack even for the highest Re
number, e.g. see Figure 7 where the relative SC area variation with angle of attack is plotted for the
case with and without the ZZ tape. This effect was common throughout the test matrix (AR and Re
numbers) and suggested that the 0.4mm ZZ tape did not cause excessive separation even at the highest
Re numbers. It was hence decided to pursue the study of the stabilized structure whose effect was
regarded similar to that of the undisturbed flow.

5.1. Tuft and pressure data
The tuft data were cross checked against pressure data from the mid section of the wing. The tufts
appear to follow the flow even for the lowest free stream velocities, e.g. see Figure 8 where the earliest
point of separation is plotted against angle of attack for the tuft and pressure data.

Tuft flow visualization results suggested that SCs grow asymptotically with angle of attack for all
Re numbers and ARs. A representative graph is that of Figure 9 where the relative SC area is plotted
against angle of attack for AR 1.5 and 2.0 at Re number 1.0 10^6. One observes that at intermediate
angles of attack the lower AR wing suffers from greater amount of separated flow, but for a high
enough angle of attack the relative SC area is independent of the AR. Relative SC area increases with Re number for all ARs tested, see e.g. Figure 10 where the relative SC area is plotted against angle of attack for AR 1.5 and for all three Re number considered.

5.2. CFD vs. experimental data
In Figure 11 steady 2D and 3D CFD simulations are compared to tests on the basis of lift variation. Prior to the formation of the SC ($\alpha<7^\circ$), the agreement is very good. For higher angles of attack, however, the 2D computations fail to reproduce the experimental data while 3D results follow the experimental trend albeit with a positive offset.

In Figure 12 the earliest separation location is plotted as found by tuft, pressure and CFD data. The agreement between tuft and pressure data is very good whereas the 3D CFD solution shows a 3$^\circ$ delay in correctly predicting the size of the SC. For $\alpha>10^\circ$ the agreement with the experimental data is very good. The above observations lead to the conclusion that a qualitative analysis of the SC structure can be based on the 3D CFD data presented here.

In-plane flow lines and surface flow lines are shown in Figure 13 for $\alpha=16^\circ$. The streamlines reveal the existence of three distinct vortices:
- The SC vortex which starts normal to the wing surface
- The Separation Line Vortex (SLV) which is parallel to the wing span and grows towards the centre of the SC
- The TE line vortex (TELV) which is parallel to the SLV but has vorticity of opposite sign. TELV also grows towards the centre of the SC

Figure 14 shows iso-surfaces of the Q criterion ($Q=1$) [22] which permit a qualitative interpretation of the vortex core line location and vortex interaction. Under the influence of the SC vortex the SLV is pulled upwards and grows at the SC centre. At the same region the TELV also grows affected by the SLV growth. Conceivably, the SC vortex starts normal to the wing suction surface, but is quickly
deflected by the SL vortex and the oncoming flow. By the time the SC vortex reaches the wing TE edge, it has moved inboard and its vorticity is parallel to the free stream flow.

5.3. PIV Results

Early Stereo-PIV data come in support of the previous experimental and computational results. Figure 15 shows the velocity and vorticity contours at a plane normal to the flow 0.05c downstream of the TE for \( \alpha = 7^\circ \) and \( \alpha = 10^\circ \). The vorticity contours reveal the existence of the two counter rotating SC vortices. The induced vorticity below the SC vortices is also apparent. Furthermore, comparing the graphs for the two different angles one observes that the SC grows significantly in size from \( 7^\circ \) to \( 10^\circ \) in agreement with the pressure data.

Figure 16 shows the vorticity contours for \( \alpha = 7^\circ \) and \( \alpha = 10^\circ \) as measured in planes normal to the wing span at five locations, namely at mid span (\( z/S=0\% \)) and at +/- 6.7\% and +/-13.3\% span. Here the SLV and the TELV can be seen and it is confirmed that they both grow at the centre of the SC (mid span) as CFD suggested.
Figure 15: Velocity (left column) and Vorticity (right column) contours on a plane normal to the free stream, 0.05c downstream of the wing TE, at Re number $0.87 \times 10^6$ for the $7^\circ$ (top row) and $10^\circ$ (bottom row) cases. In all graphs the TE position is at zero.

Figure 16: Vorticity contours at planes parallel to the flow at different spanwise locations. Re number $0.87 \times 10^6$, $\alpha=7^\circ$ (left column), $\alpha=10^\circ$ (right column).
6. Conclusions
An overview of a combined investigation on the formation of SCs was given. The paper focuses on locally disturbed flows that result in a stabilized single SC which was, however, found to agree in amount of separated flow with the undisturbed case. This justifies the interest in analysing stabilized SCs.

Tunnel testing: Very good agreement was found between tuft and pressure data as regards the earliest separation point and the amount of separated flow. Tuft data indicated that SCs grow in size with angle of attack and Re number and that the relative SC size is greater at intermediate angles for the lower AR case. Stereo-PIV measurements taken at Re 0.87 10^6 offered adequate support regarding the structure of the SC. Averaged flow contours reveal the existence of the three types of vortices, the SC vortices normal to the flow and the SLV and TELV normal to the wing span. It is observed that the latter vortices grow at the centre of the SC, conceivably under the complex interaction with the SC vortices. The significant growth of the SC from 7° to 10° as observed by pressure and tuft data is confirmed by the PIV results.

CFD simulations: As expected, 2D simulations were found correct only at low angles of attack and prior to the first onset of the SC. 3D simulations, using the SA turbulence model were in qualitative agreement with the pressure data exhibiting, however, a ~3 degrees delay in the first formation of the SC and accordingly the area covered by the SC. The error in Cl max prediction was reduced from 19% in the 2D computations to 7% in the 3D ones. Analysis of the simulated field characteristics at 16 deg incidence, suggest a SC structure which could explain the pressure and PIV data.

In particular 3 major structures in the form of slender vortices can be distinguished in the time averaged flow: The SLV and TELV structures, corresponding to the vorticity released along the separation line and the trailing edge respectively, and the SC vortices. The SC vortices spring out normal to the wing surface and extend downstream in the wake in agreement with the model suggested by Yon and Katz [7]. The interaction with the SL and TEL vortices drives a quick bending and contraction of the SC vortices towards the centre plane. By the time the SC vortex line reaches the trailing edge, it has been already aligned with the free stream. In addition due to the vortex interactions, the SL and TEL vortex cores grow towards the SC centre.

Finally concerning the possible implications the above results can have to the design of wind turbines, the following remarks can be made:

a) Wind tunnel measurement of profile polars that will be subsequently used in the design codes of wind turbines should also consider the eventual onset of SCs
b) The eventual onset of SCs can be detected by 3D CFD simulations

7. References
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**Acknowledgements**

The authors would like to thank Onassis Foundation who supported this project through the G ZF 032 / 2009-2010 scholarship grant.