

Spatio-temporal organization of stall cells above an airfoil

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ABSTRACT

This work investigates the dynamical occurrence and spatio-temporal features of stall cells forming on a NACA0015 airfoil. Three-dimensional, time-resolved particle tracking is employed to capture the onset, evolution, and interaction of stall cells. Experiments span a chord-based Reynolds number (Re) range from 1.2 to 1.9×10^5 and angles of attack α from 11° to 18° . The critical (i.e. minimum) value of Re to observe the occurrence of stall cells is revisited here, with stall-cell like behaviour found at Re values significantly smaller than reported in the literature, yet, within a narrow Re - α envelope ($14^\circ \leq \alpha \leq 15.5^\circ$ and $1.2 \times 10^5 \leq Re \leq 1.9 \times 10^5$). Dynamic visualization of the near-surface flow reveals the organization of cellular separation, undergoing unsteady interactions. The data is examined along a near-wall spanwise line at mid chord, yielding two-dimensional (y - t) diagrams that reveal the main spatio-temporal behaviour of the interface between separated and attached flow. Distinct flow behaviors are identified, from stationary cellular separation (steady cells), spanwise motion (drifting cells) and low-momentum flow patches systematically departing from the core of the cell (branching cells). Occasionally, splitting or merging of cells is also observed, but at comparatively lower occurrence. The topology based on the time-averaged velocity field and the instantaneous velocity suggests that the cellular separation is a far more frequent phenomenon than reported so far. For the particular regime of drifting cells, cellular separation is active most of the time albeit the time-averaged flow analysis yields no stall cells. A general criterion is proposed, attempting to categorize the flow regimes in relation to the cellular separation. Although not fully comprehensive of all effects present in the stall cells regimes, it may be taken as a first step towards a more quantitative definition of stall cells regime, thus allowing more generalized comparison among experiments and computer simulations. The criterion highlights the limitations of conventional time-averaged flow visualization techniques and underlines the importance of time-resolved measurements that capture stall cells even when they evolve dynamically.

1. Introduction

Aerodynamic stall occurs when the airfoil or wing incidence exceeds the maximum value for attached flow. This condition is accompanied by loss of lift, unsteady loads and degraded controllability. Prior to stall, flow separation on the airfoil suction side features a spanwise cellular pattern with intermittent attached flow between them. These structures have been identified in the early work of Winkelmann (1981) and denoted as *stall cells* (SC). Their inner structure of the

recirculation is driven by the shear layer bounding the stall cell, typically featuring a pair of counter-rotating regions often recognized by oil-flow visualization (OFV) as the *owl face* (Disotell & Gregory, 2015). Given that they appear at the boundary between attached flow and stall, the stall cells regime has been considered by Taira and Colonius (2009) as an intermediate condition between attached and fully separated flow. This regime persists until the incidence is increased and the stall onset leads to a fully separated flow, eventually featuring coherent shedding in the form of a 2D Kármán wake (Yon & Katz, 1998b).

The presence of stall cells has been reported on wings with various end conditions, including free tips, end plates, wall-to-wall airfoils with or without suction of the boundary layer. Their occurrence is ubiquitous and consensus is found that they do not depend upon specific end conditions, such as tip or wall junction effect. Furthermore, they form on both 2D airfoils and 3D wings, and are considered as a rather intrinsic and persistent flow feature, since no wall condition or sidewall treatment have been found that prevent their formation (Manolesos & Voutsinas, 2014b).

Despite these observations, the occurrence of stall cells and their behavior have been found to depend upon a number of parameters, primarily the angle of incidence α , the airfoil shape (primarily thickness), the wing aspect ratio AR , sweep angle, and Reynolds number (Dell'Orso & Amitay, 2018; Manolesos & Voutsinas, 2014a). Yon and Katz (1998a) indicated that stall cells only form at angles of attack near maximum lift close to the shallow stall region. The shallow stall region was described as occurring over a narrow range of incidence angles (2-3 deg) immediately following the inception of leading-edge separation (Yon & Katz, 1998b). Previous studies have reported that stall cells only occur when trailing edge separation or a combination of trailing-edge and leading-edge separation is present (Broeren & Bragg, 2001). Moreover, when the airfoil incidence nears the value corresponding to maximum lift, a critical value of the Reynolds number Re_{cr} has been indicated as the lower limit below which stall cells are not observed. The onset of stall cells has been observed already at $Re = O(10^4)$ (Elimelech et al., 2012), whereas other works report their formation beginning only above $Re = O(10^5)$ (Dell'Orso & Amitay, 2018) or even higher (Manolesos & Voutsinas, 2014b). Such spread of values for Re_{cr} could be ascribed to many different physical conditions (airfoil profile and surface roughness, turbulence in the free stream) but also to the different methods and techniques used to detect the stall cells. In particular, OFV has been often relied upon as a technique that can be rapidly deployed to depict a clear pattern of lines bounding the separated flow regions. OFV is most effective for experiments featuring steady flow conditions, whereas the visualization becomes less interpretable if the flow exhibits large-scale temporal variations (Zhang & Wang, 2022). In this respect, the analysis of stall cells inception

benefits from the use of techniques that capture both the spatial as well as temporal variations exhibited in this complex flow regime.

A detailed three-dimensional characterization of the flow field was afforded by Dell'Orso et al. (2016) for a NACA 0015 airfoil ($AR = 4$) by employing stereoscopic PIV and OFV methods. The envelope of experiments covered $\alpha = [15^\circ - 20^\circ]$ and $Re = [2 - 5] \times 10^5$ and concluded that $Re_{cr} = 3.2 \times 10^5$ on the basis of the OFV results. Furthermore, they also observed that, for a given Re , stall cells would only occur within a narrow range of airfoil incidence (typically less than 2 degrees). Additionally, Dell'Orso & Amitay (2018) reported an extreme sensitivity of the resulting flow pattern, with changes as small as 0.5 degrees significantly affecting the flow topology.

Near the shallow stall region, the flow pattern seems to abruptly transition from uniformly attached, to cellular separation (stall cells) or other, more complex, types of separated flow over the airfoil suction surface (Yon & Katz, 1998b). Although the experimental studies were done with OFV, similar observations were conducted with tufts visualization (De Voogt & Ganapathisubramani, 2022).

Regarding the aspect ratio, stall cells have been observed on wings with $AR = 1.4 - 12$. Winkelman and Barlow (1980) reported that the number of observed stall cells increased with increasing wing AR , suggesting that a spanwise wavelength is intrinsically related to the airfoil chord rather than its span. Yon and Katz (1998b) and Schewe (2001) performed additional experiments, confirming that the width of the cells is correlated to the airfoil's chord length, yet with some relation to the wing AR .

Although stall cells have been well characterized and their regime of occurrence described and modelled, knowledge about their dynamic behavior, including formation, growth, motions and interactions remains limited. The time-dependent behavior of stall cells can be influenced by incidence angle α , AR and Re . Previous studies have reported that stall cells appear or disappear in a seemingly random manner or just to move spanwise. Such unsteady behavior is rather controversial in the low Re regimes. Earlier works (Broeren & Bragg, 2001; Elimelech et al., 2012) did not report unsteady behavior at $Re = (1 - 3) \times 10^4$ with a low turbulence intensity model (T.I. $< 0.15\%$).

Instead, Zarutskaya and Arieli (2005) observed an irregular behaviour at $Re = 0.4 \times 10^6$, classifying two types of unsteadiness based on tufts visualization. The first one was *intrinsic*, i.e. within each one of the stall cells; the second one was *extrinsic*, as associated to the overall spanwise movement of the cells. The latter motion was irregular and oscillatory although no defined time or length scale could be identified (though there was a preferred flow orientation).

Quantitative experiments have been based on stereoscopic PIV to capture the instantaneous velocity distribution in a cross-section of the flow domain (Dell'Orso & Amitay, 2018; Ragni &

Ferreira, 2016). However, given the three-dimensional topology of the velocity and vorticity vectors, the planar approach needs to sacrifice either the streamwise or the spanwise direction at times. Stall cells tend to dynamically vary along the span as well as in height (chord normal direction) and streamwise, when shedding events occur. Furthermore, the time scales associated to the dynamical behavior require observations at a frequency such to capture the rapid changes in the flow organization. A further challenge arises from the representation of such three-dimensional and dynamical system. To this end, modal-decomposition techniques like proper orthogonal decomposition (POD) (Berkooz et al., 1993) have been used to extract the dominant features that govern the flow behavior in the stall cells regime.

The spatiotemporal evolution of stall cells, especially in relation to their three-dimensional evolution, including onset, interaction, and large-scale motions has not been fully ascertained and is investigated in the present work. For this purpose, the experiments employ time-resolved three-dimensional (volumetric) particle image velocimetry to capture the dynamical flow behavior in the stall-cell regimes.

The attention is first directed towards verifying the concept of Re_{cr} and its bounds. The large spread of values from the literature may indicate a dependence on the technique used to identify the presence of a stall cell, among other factors. Therefore, in the present work two approaches will be compared that identify the stall cell pattern either from time-averaged velocity data or directly from the instantaneous flow pattern. Furthermore, a criterion for the stall cell regime is proposed and discussed, based on probability of occurrence for incomplete (viz. cellular) spanwise separation. Finally, a spatiotemporal analysis is performed to highlight the physical behavior, leading to identifying the most recurring patterns.

The next section describes the setup of experiments and the measurement technique. Section 3 presents the results in two parts: first, a time-averaged analysis establishes the $Re - \alpha$ envelope for stall cell formation; second, the instantaneous velocity fields are inspected, yielding the spatio-temporal evolution of the flow. Finally, Section 4 summarizes the findings and provides a concluding interpretation of stall cell dynamics.

2. Experimental setup and procedures

2.1. Flow Facility and airfoil model

Experiments are performed in the low-speed open-jet facility (OJF) operated at the Aerodynamics Laboratory of TU Delft. After contraction, the cross-sectional area of the test-section is 2.85×2.85 m². The OJF delivers a free-stream velocity from 3 to 35 m/s, with an average turbulence intensity below 0.5%. Figure 1 illustrates the experimental layout with the back and side views. The airfoil

is installed vertically 1.5 m downstream of the contraction, with the root connected to an end plate, and the upper tip left free. The airfoil rotates around the quarter-chord point and the angle of attack is controlled within an accuracy of 0.25° . A *wind* system of coordinates is adopted to represent the data in the measurement domain, with the X-axis along the free stream (origin at the leading edge, when at zero incidence). The Y-axis is aligned with the span, pointing upwards. The Z-axis is normal to X and Y, forming a right-handed Cartesian coordinate system. The corresponding instantaneous velocity components are (u,v,w) , and the time-averaged velocity components are denoted by (U,V,W) . The envelope of experiments covers a range of free-stream velocity $U_\infty \in [4 - 16]$ m/s, corresponding to a chord-based Reynolds number of $(0.5 - 1.9) \times 10^5$. The angle of attack α is varied across the range between 11° and 18° , covering attached flow, cellular separation and stall.

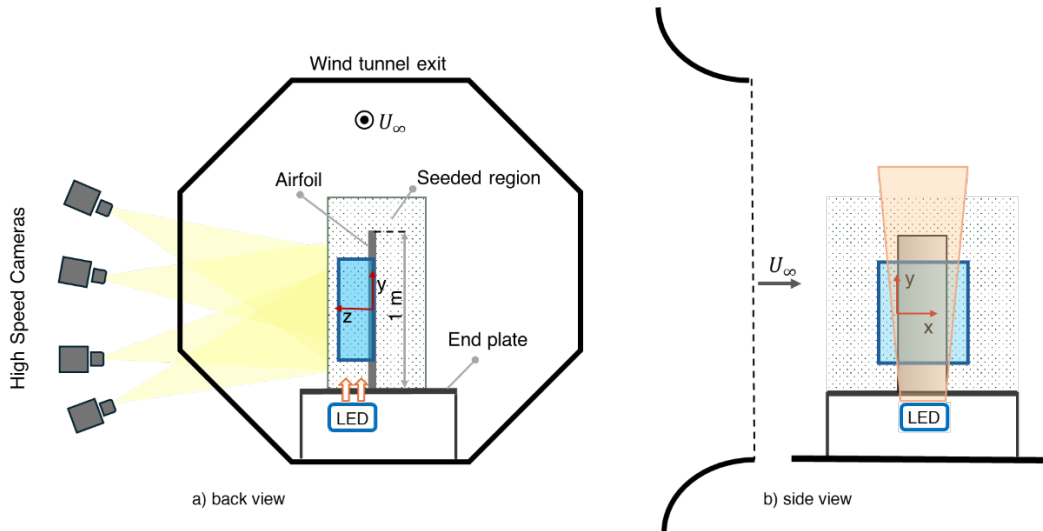


Figure 1 Experimental setup: a) back view and b) side view. Airfoil (grey) with supporting end-plate; HFSB seeding (green); pulsed LED volume illumination; arrangement of CMOS imagers; system of coordinates (red). Schematics are approximately at scale.

2.2. Measurement system

Time-resolved three-dimensional (3D) particle tracking is used to measure the instantaneous velocity field on the airfoil suction side. The measurement system is composed of a helium-filled soap bubble (HFSB) generator, which releases approximately 10^7 bubbles/s in the settling chamber (Caridi et al., 2016) forming a stream tube with a cross section of approximately 1.2×0.6 m² after the wind tunnel contraction, at a concentration of approximately 0.1-0.4 tracer/cm³. The bubbles have a median diameter of 0.4 mm and are neutrally buoyant, which renders them accurate to trace aerodynamic flows in the chosen range of velocity (Faleiros et al., 2019). The tracers are

illuminated along the airfoil span by a LaVision *Flashlight 300* LED array placed below the transparent end plate. The region of illumination is delimited by a knife-edge rectangular mask. The 3D imaging system comprises four Photron *Mini AX* CMOS cameras (1Mpx at 5,400 fps, 12 bits, pixel pitch $20\ \mu\text{m}$) equipped with Nikon 50 mm lenses with $f_{\#} = 16$. The cameras are installed on a vertical beam at approximately 1.5 m distance from the airfoil, subtending a total angle of 42° . Illumination and image acquisition are synchronized with a LaVision programmable timing unit, *PTU-X*, and *DaVis 10* software. The measurements are performed in single-frame mode to achieve time-resolved motion of the tracers. The measurement frequency is set between 1 - 4 kHz depending on the free-stream velocity (1 kHz at 4 m/s). Short measurements for dynamic visualization comprise sets of 1,000 images. Longer sets of 15,000 are intended for converged statistics.

Table 1 3D particle tracking system hardware and measurement parameters

Tracers	HFSB, nominal diameter 0.4 mm
Seeding density	0.1 -0.4 tracers / cm^3
Illumination	Pulsed LED array 6×12 , LaVision <i>Flashlight</i>
Imager	Photron <i>Mini AX</i> CMOS
Number of cameras	4
Total angle	42°
Camera lens	50 mm Nikon
Numerical aperture (focal depth)	16 (DZ = 18 cm)
Magnification factor	0.066
Measurement domain	$35\text{ (X)} \times 70\text{ (Y)} \times 15\text{ (Z)}\ \text{cm}^3$
Recording frequency	1 - 4 kHz
Number of images per recording	1,000 (15,000)
Bin size, overlap factor, vector pitch	5 mm, 75%, 1.25 mm

The 3D system calibration is performed using the *DaVis 10* software registering the position of a reference target. Residual disparity is reduced to less than 0.1 pixels using the volume self-calibration technique (Wieneke, 2008). The particle image motion analysis is performed using the Lagrangian particle tracking method with the Shake-the-Box (STB) algorithm (Schanz et al., 2016) in the *DaVis 10* software. Background reflections are eliminated by subtracting a sliding time-minimum value for each pixel. At a free-stream velocity of $U_\infty = 15\ \text{m/s}$, the analysis tracks

approximately 10^4 particles in the region of interest, corresponding to an instantaneous spatial concentration of 0.3 tracers/ cm^3 . Figure 2 a sample of the particle trajectories (color-coded by normalised streamwise velocity $U^* = (U/U_\infty)$) for the case of $Re = 1.7 \times 10^5$ and $\alpha = 15^\circ$.

The data is rendered onto a Cartesian grid partitioning the domain into cubic bins. For the instantaneous velocity, data inside a bin of 5 mm length is accumulated during a short-time segment of 11 frames, corresponding to a path length of 5 mm in the free stream. The time-averaged velocity field is computed over $\Delta t^* = 25$, where the normalized time t^* is defined as $t^* = \frac{U_\infty t}{c}$. Adjacent bins overlap by 75%, which yields a vector grid with 1.25 mm spacing. The spatial velocity distribution inside each bin is fitted to a 2nd-order polynomial function to reduce spatial averaging effects, and the temporal evolution is fitted to a 1st-order-polynomial function.

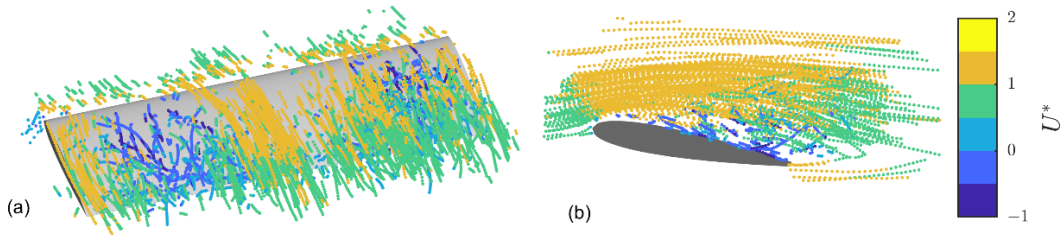


Figure 2 Perspective (3D) view of particles trajectories over the airfoil (left) and sectional (2D) view (right). Conditions: $\alpha = 15^\circ$, $Re = 1.7 \times 10^5$. The total number of tracks has been down-sampled 100:1 for clarity of representation.

3. Results and discussion

The experimental results are provided in two main categories. Section 3.1 presents the $Re - \alpha$ envelope, based on the time-averaged analysis of the flow, categorized into three main flow regimes. In Section 3.2, a definition of the stall cell regime is given based on the occurrence of reverse velocity near the airfoil. Next, the unsteady flow features are extracted from the experimental data and the instantaneous flow field is analyzed.

3.1 Time-averaged flow topology

The flow regime is first classified based on the time-averaged velocity. Figure 3 shows the time-averaged velocity field by iso-surfaces and the near-surface streamlines at various incidences across the stall range ($\alpha = \{13^\circ, 15^\circ, 18^\circ\}$) and $Re = 170,000$. The surface streamlines are calculated following the extended Runge-Kutta method (Wu et al., 2023) by integrating the velocity in 3D, and then projected onto a surface offset by 4 mm from the airfoil to avoid vanishing velocity and spurious data in close proximity of the solid wall. In this range, three different flow conditions are

identified: 1) at $\alpha = 13^\circ$ (Figure 3-a) the flow is fully attached, featuring straight streamlines contouring the airfoil; 2) at $\alpha = 15^\circ$ (Figure 3-b) spanwise inhomogeneous separation is observed. The patches of reverse flow appear at interval with attached flow in between, which is the condition denoted as *stall cells*; 3) at $\alpha = 18^\circ$ (Figure 3-c) no interruption or intermittency of separation line is observed, albeit the reverse flow exhibits some visible spanwise patterns.

An additional oil flow visualization at $\alpha = 15^\circ$ is presented in Figure 3-d. The black color in the background is the wing. The fluorescent green corresponds to the illuminated oil which is showing the separation line on the airfoil. The blue light on the left side of the image is from the UV lamp reflections on the wing surface.

The result indicates a relatively uniform separated region with the inception line towards the aft part of the airfoil, at approximately $x^* = 0.7$. This result contrasts with the PIV measurement in the corresponding conditions (Figure 3-b).

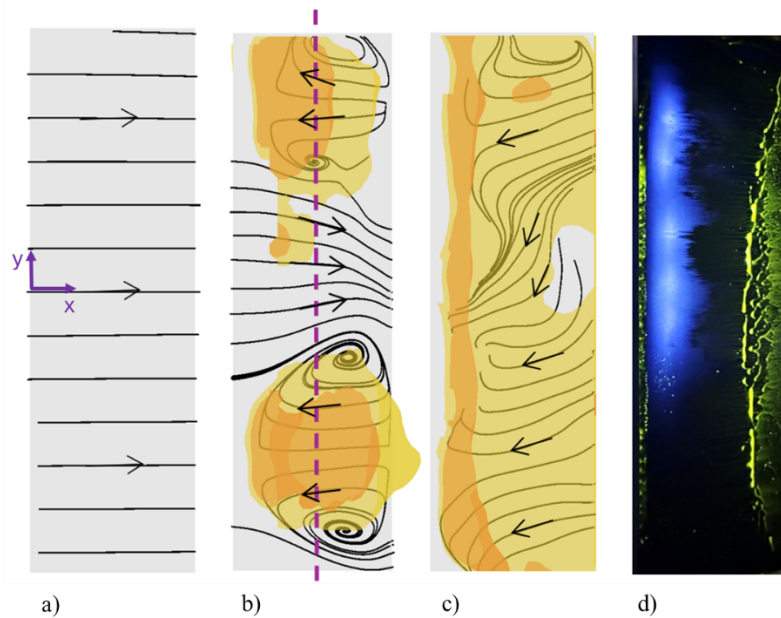


Figure 3 Surface flow patterns and velocity field with varying incidence $\alpha = 13^\circ$ (a), 15° (b) , 18° (c). $Re = 1.7 \times 10^5$.

Yellow and orange iso-surfaces represent $U^* = -0.1$ and -0.3 respectively. Purple dashed line is located at $x^* = x/c = 0.5$. (d) is an OFV image at $\alpha = 15^\circ$ and $Re = 1.7 \times 10^5$

The marked difference is ascribed to the low velocity in the free stream and in turn the weak wall shear in the present experiments ($U_\infty = 4 - 16$ m/s), making OFV unfavourable, due to effects of gravity. Furthermore, oil accumulation is known to form a small ridge on the separation line, which may prompt and stabilise laminar boundary layer separation from a uniform line. In the remainder of the present work it is also shown that SC undergo significant fluctuations in their position and structure, corroborating the hypothesis that in this low Reynolds regimes the patterns

obtained with OFV may depart from the actual flow topology as a result of temporal filtering and the unfavourable balance between the flow shear and disturbing effects such as gravity and surface tension.

3.2 A definition of stall cells regime

The visualizations presented above, while providing a clear qualitative understanding of the flow organization across the separated regimes, remain inherently descriptive. To enable a more rigorous differentiation between distinct separated flow regimes that facilitates comparison across experiments and simulations, we propose a quantitative definition based on the spanwise fraction of reverse velocity near the airfoil. This approach potentially allows the comparison of results obtained under varying laboratory conditions relying on a quantitative criterion.

Let U denote the time-averaged distribution of the streamwise velocity component near the wall, and let b represent the spanwise extent covered by the experiments (with $b \gg c$ in most cases). Flow separation, in the mean sense, is identified by the occurrence of $U < 0$ at a position along the chord. In the present analysis, a control line (purple dashed line in Figure 3-b) is chosen at $(x^*, h^*) = (0.5, 0.025)$, where h^* denotes distance in the z -direction from the airfoil surface. Such control line intercepts through most separated regions and the choice also corresponds with the planar (stereoscopic) PIV data from Dell'Orso and Amitay (2018).

The spanwise fraction of attached (i.e. forward) flow along this line is quantified by the dimensionless integral parameter $\bar{L}$, defined as:

$$\bar{L} = \frac{1}{b} \int_0^b \text{sgn}(U(x^*, y, h^*)) dy \quad (1)$$

Where sgn denotes the *signum* function ($\text{sgn}(U) = 0$ if $U > 0$, and $\text{sgn}(U) = 1$ if $U \leq 0$). Based on such definition $\bar{L} \in [0, 1]$. The flow is completely attached if $\bar{L} = 0$. Conversely, the fully separated condition is denoted by $\bar{L} = 1$. In principle the occurrence of partial separation is already defined when $0 < \bar{L} < 1$. A conservative margin needs to be introduced to only consider conditions where both separated and attached flow portions are significant. It is proposed here that the portions of separated and attached flow shall be comparable within a ratio 4:1. Therefore, a criterion that identifies flow regimes where partial spanwise separation (stall cells among them) is significant, may be introduced as:

$$0.2 < \bar{L} < 0.8 \quad (\text{SC detection criterion}) \quad (2)$$

Some words of caution need to be given about the hypothesis of validity of the criterion. The choice of the control line position is made such to maximise the probability to intercept stall cells. The distance from the wall by 2.5% of the chord length is chosen as to allow most velocity measurement techniques to capture such a position. Furthermore, experimental evidence shows that the typical thickness of SC varies between 5 and 10% of the chord (appendix A).

3.3 α - Re envelope of flow regimes

The current experiments are categorized according to the given criterion and the results are classified into attached, partially separated or SC, and fully separated conditions. The resulting map in the α - Re plane is depicted in Figure 4.

The map includes results from the current experiments (solid markers) as well as some pertinent data from the literature (hollow markers). Current experiments are labeled in blue for the fully attached flow condition, green where SC are observed and orange for the fully separated condition.

The results from Dell'Orso & Amitay (2018) were obtained on the same airfoil as in the present work, at a slightly lower aspect ratio ($AR = 4$) and a higher Reynolds number ($300,000 < Re < 450,000$) using OFV. Regimes where the stall cells were present (hollow green triangles) based on the visual inspection of the oil flow pattern and spanned a wide range of incidence (15° to 22°). They concluded that a minimum (critical) Reynolds number for the occurrence of SC could be considered $Re_{cr} = 320,000$.

The data from De Voogt & Ganapathisubramani (2022) is also reported, who investigated a NACA0012 wing at small aspect ratio ($AR = 2.6$) in a relatively wide range of Reynolds ($100,000 < Re < 500,000$). Their findings are based on tufts. The hollow green diamonds in Figure 4 represent the conditions where stall cells were observed. In this case a value of Re_{cr} as low as 100,000 could be inferred. The above suggests that the extent of the SC regime is still under debate and it might be dependent upon the chosen measurement technique. While OFV is affected by gravity and time-integration effects, the surface tufts position does not suffer from time history, while specific materials can be chosen to reduce the effects of gravity.

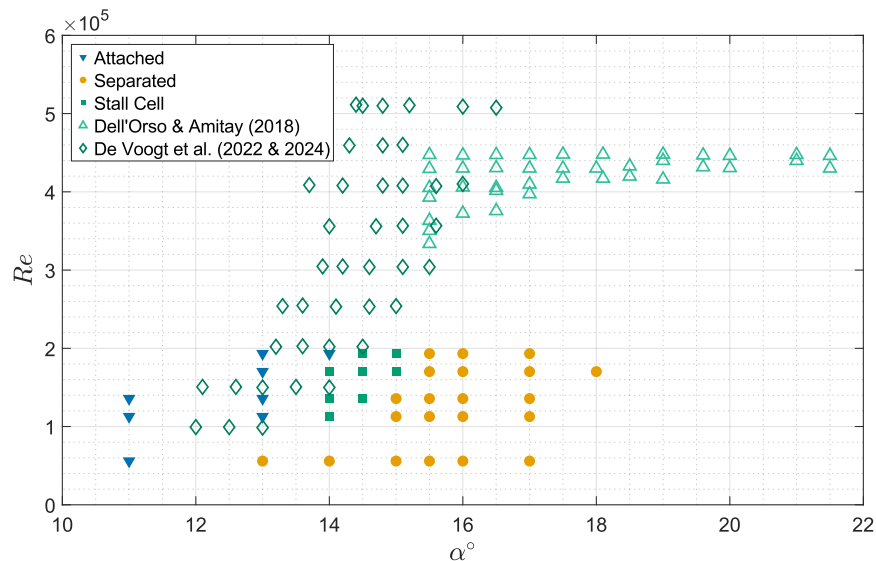


Figure 4 Envelope ($\alpha - Re$) of experiments (solid symbols) based on $\bar{L}$ values and comparison with literature data (hollow symbols).

Finally, the current experiments are conducted in a relatively lower range of Reynolds number ($120,000 < Re < 190,000$) using PIV. The latter is known not to depend upon gravity effects (neutrally buoyant tracers) and the velocity measurement can be considered instantaneous, given that the tracer’s response time has been reported to stay within 20-50 ms (Faleiros et al., 2019). Furthermore, accumulation of soap fluid on the airfoil leading edge has been carefully minimised for fluid accumulation not to play a role. However, PIV measures the near-surface flow only indirectly and the pattern of friction lines needs to be inferred from the velocity at a few millimetres from the wall.

Table 2 Summary of the present and relevant studies specifications

Study	airfoil	Re	α	AR	method
Present	NACA0015	$(1.2 - 1.9) \times 10^5$	$11^\circ - 18^\circ$	5	3D PTV, OFV
Dell’Orso & Amitay (2018)	NACA0015	$(3 - 4.5) \times 10^5$	$14.5^\circ - 21.5^\circ$	4	OFV, SPIV
De Voogt & Ganapathisubramani (2022)	NACA0012	$(1 - 5) \times 10^5$	$11.5^\circ - 21^\circ$	2.6	Tufts
De Voogt & Ganapathisubramani (2024)	NACA0012	$(3 - 10) \times 10^5$	$10^\circ - 20^\circ$	2.5	URANS, pseudo tufts

Therefore, spatial resolution is critical to resolving the flow in proximity of the boundary layer region. The stall cells regime mostly occurs in the bounded range $\alpha = 14^\circ - 15^\circ$ featuring a fan like distribution originating at $\alpha = 14^\circ$ and $Re = 120,000$ and expanding to the above range at $Re = 190,000$. It can be concluded from the present experiments that $Re_{cr} \sim 120,000$, in some agreement with De Voogt and Ganapathisubramani (2022). The above discussion is summarized in Table 2.

4. Instantaneous flow behavior

The time-dependent flow behavior is examined first by inspecting selected sequences where the separated region exhibits significant spatio-temporal fluctuations. The time-resolved three-dimensional data allows representing iso-surfaces of the reverse flow regions ($u^* < 0$) from snapshots separated by $\Delta t^* = 10$, as illustrated in Figure 5. This visualization lays the groundwork for the later analysis of the spatio-temporal rendering. An extended visualization is available in the form of digital content (Khaleghizadeh et al., 2026).

A stall cell is often identified as a spanwise patch of separated flow that embeds slowly recirculating fluid. The latter mostly features a pattern of two counter-rotating circulations. For a spanwise uniform airfoil no preferential position of such cell exists, unless boundary conditions from the span edges come into play, as abundantly discussed in the literature investigating low AR wings (Dell'Orso & Amitay, 2018; Manolesos & Voutsinas, 2014a). Due to the unsteady nature of the separated shear layer bounding the cell, the orderly structure mentioned above emerges more clearly after the turbulent fluctuations in the shear layer have been time-averaged. However, the analysis of the topological structure remains meaningful only when the cell position, size and shape do not vary significantly during such averaging process. Investigations with the specific purpose to stabilize the position of the stall cell have been conducted by Manolesos and Voutsinas (2014b) and Esfahani et al. (2018).

In the present work, SC evolve freely in time and space, and the spatio-temporal evolving structure of the flow is captured by the time-resolved PTV data. A short-time segment ensemble averaging is needed to eliminate small-scale data jitter and capture the large-scale structure of the stall cell. A time-sliding filter based on the average of 11 frames (10 ms or $\Delta t^* = 0.2$ at $U = 4$ m/s) fulfil the purpose, while preserving the time-dependent behavior of the overall flow pattern. The spatio-temporal behaviour of the stall cells is described combining reverse flow ($u^* < 0$) isosurfaces, alongside near-wall streamtraces (Figure 5). Three values of the airfoil incidence ($\alpha = [14^\circ, 15^\circ, 16^\circ]$) are selected at $Re = 1.7 \times 10^5$, and time advances moving down in each column.

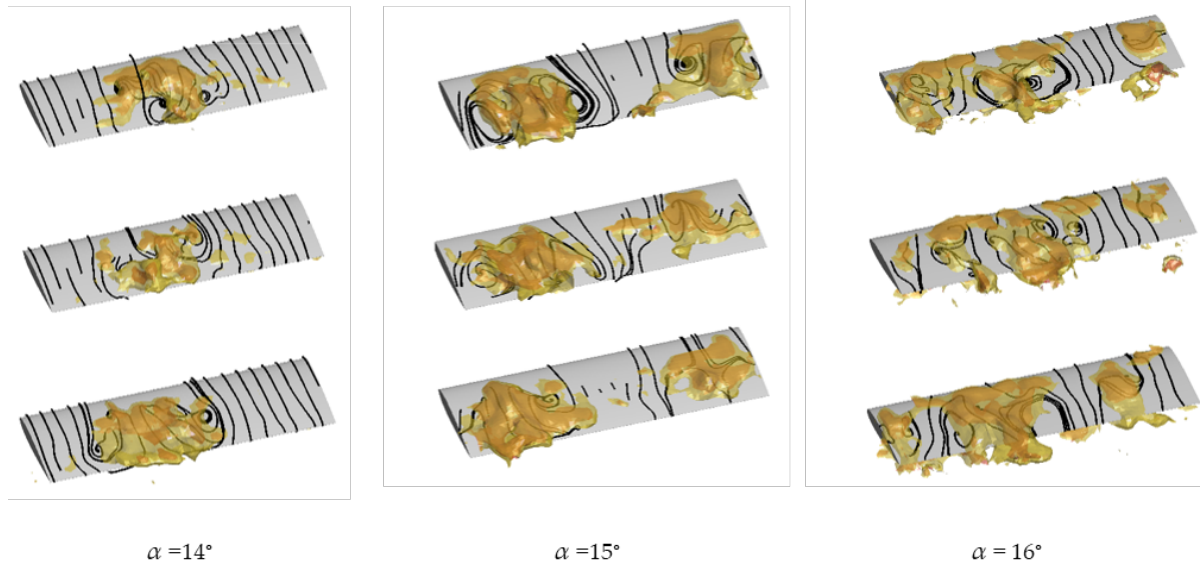


Figure 5 Spatio-temporal evolution of SC for varying incidence at $Re = 1.7 \times 10^5$. Snapshots are separated by $\Delta t^* = 10$.

Near surface flow visualization by streamwise velocity iso-surfaces at $u^* = -0.1$ (yellow) and $u^* = -0.3$ (orange).

Streamtraces at 4 mm height from the surface are given to aid topological interpretation. Animated visualization available as digital content (Khaleghizadeh et al., 2026).

Mild ($u^* = -0.1$) and more intense ($u^* = -0.3$) reverse flow regions are depicted by the yellow and orange isosurfaces respectively. The three snapshots, selected at equally spaced time intervals, illustrate the temporal evolution and instantaneous topology of the separated flow. At $\alpha = 14^\circ$, the flow features a single separation cell located near mid-span. The cell inception line is close to the leading edge and the streamlines surrounding the cell form a mushroom-shaped pattern with the more intense reverse flow in the downstream stem and a strong deflection around the two foci, separated in this case by a distance of approximately $0.7c$. The shape and extent of this reversed-flow region exhibit only mild variations in time, mostly at scales smaller than the cell width. The event captured at $\alpha = 15^\circ$ represents two distinct cells separated by a region of roughly one chord, which remains approximately constant in time. Also in this case the cells inception lines are placed near the leading edge and the reverse flow extends beyond the trailing edge, following the pattern observed on a stalled airfoil. The larger cell, on the left side, features a larger distance between foci as well as more intense reverse flow. A different time-dependent behavior is observed for the two cells. While the left cell maintains a stable separation line, the cell on the right exhibits a more erratic behavior, with the separation point moving along the chord line and spanwise. Increasing the angle of attack to $\alpha = 16^\circ$ results in a noticeably more unstable pattern: the core of the reversed-flow structure migrates along the span, indicating a dynamical three-dimensional

behaviour of the recirculating flow below the separated shear layer. Although convective motions are not apparent from Figure 5, a dynamical visualization available as digital content (Khaleghizadeh et al., 2026) illustrates some convective motions within the stall cells and at their interface with the attached flow.

3.4 Evolution in the y - t domain

To facilitate the presentation of unsteady behavior, the instantaneous velocity is extracted at a spanwise control line intersecting the separated region. The collated data is presented in a y - t diagram. The location corresponds to that used for the SC detection criterion (Figure). A discussion on the sensitivity of results on the position of the control line is provided in appendix A.

The spatio-temporal evolution of stall cells—including their onset, mutual interactions, and associated large-scale dynamics—is pursued here, to examine the time-dependent flow behavior. To this end, the resulting contours of u^* are presented in Figure 6, with nondimensional time t^* on the horizontal axis the spanwise coordinate $y^* = y/c$ on the vertical axis. A coarse, three-level discretization of velocity contours is chosen with the purpose to clearly distinguish attached flow (blue, $u^* > 0$) from interface flow (yellow, $-0.3 < u^* < 0$) and the core of reverse flow (orange, $-0.6 < u^* < -0.3$). The white regions correspond to data gaps randomly occurring and caused by instants of occasional poor presence of seeding. Figure 6 presents results selected at a fixed value of $Re = 1.7 \times 10^5$ and varying the airfoil incidence across the attached-separated flow regimes ($\alpha = [13^\circ-17^\circ]$).

At $\alpha = 13^\circ$ the flow is fully attached (blue contours) with no occurrence of reverse flow. As α increases to 14° , a first region of separated flow makes its appearance. The streamwise velocity exhibits a dynamic behavior, it fluctuates in intensity and the forward-reversal flow interface varies in time along the span. Occasional appendices indicate patches of low momentum being released from the core of the stall cell. Their duration is estimated between $2-3t^*$ and form an angle of $10-20^\circ$ in the y - t diagram, indicating a sideward velocity of approximately 0.25 of the free stream. For an additional increment ($\alpha = 15^\circ$) separated and attached flow fractions appear to be in balance ($\bar{L} \sim 0.5$). Two distinct cells are observed, with rather stationary position and width. The upper cell also features an appendix branching and persisting in the same position, while slowly migrating in the middle position between the two cells. Further increasing to $\alpha = 16^\circ$, the fraction of separated flow becomes dominant, with clear, yet intermittent, streaks of attached flow.

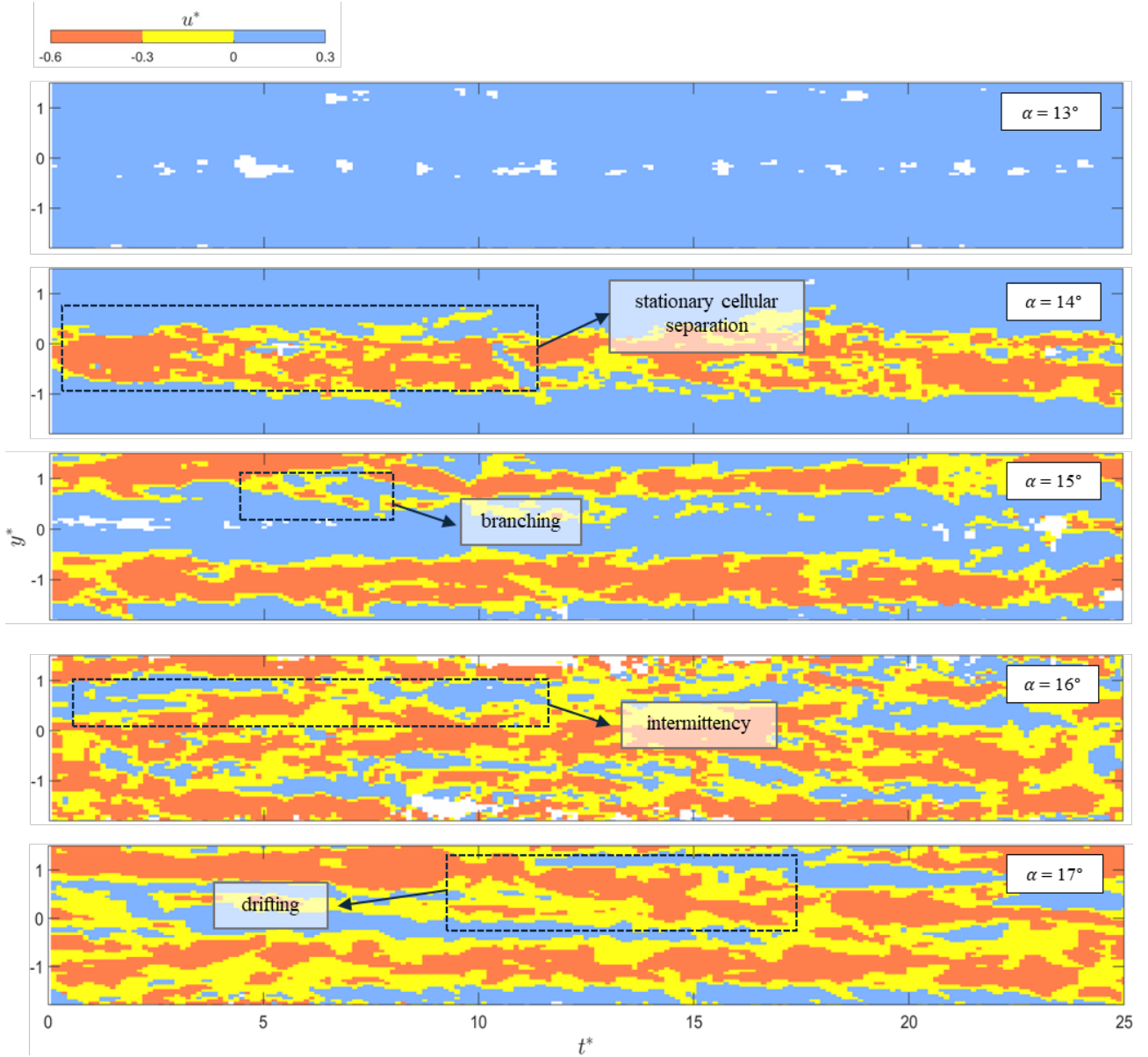


Figure 6 Streamwise velocity contours over time at $x^*=0.5$ and $h^*=0.025$, for $Re = 1.7 \times 10^5$ and increasing α .

An instantaneous analysis of this condition would still return a non-negligible fraction of attached flow, although the $\alpha-Re$ map of Figure 4 (based on time-average velocity) already categorizes this condition as fully separated. Finally, at $\alpha = 17^\circ$ the flow is fully separated along the span and no cellular separation can be identified. Yet a streaky structure of occasional attached regions is present and similar conditions as for the previous case apply. Furthermore, diagonal drifting of low- and high-momentum regions is observed, alongside merging of reversal flow events.

In synthesis four types of flow behavior are observed in the above results:

1) *stationary cellular separation*, where the flow is partially separated along the span and the location of this cellular separation is rather constant over time.

2) *branching*: the flow exhibits shedding in the form of diagonal stripes. This shedding emanates from the patches of cellular separation and can alter the initial position and width of the cellular separation regions.

3) *drifting*: where the location of the cellular separation changes along the span.

4) *intermittent attached-separated flow*: contours of attached and separated flow are observed intermittently over time. A sketch of the above categories is provided below (Figure 7) in the y - t domain.

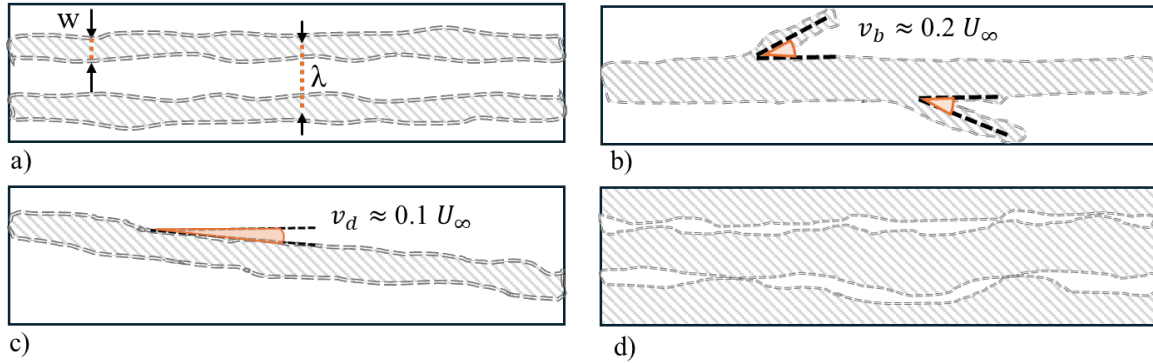


Figure 7 sketch of the 4 types of flow behavior: a) stationary cellular separation, b) branching, c) drifting and d) intermittent separated flow. Hatched texture represent separated flow, and white space represents attached flow.

Although based on quantitative data, these observations remain qualitative in nature as to describe the phenomenon of SC. Characterising these motions by means of statistical operators may be necessary to support comparison with other studies as well as to advance a formulation of the physical mechanism. Such analysis, however is left out of the scope of the present study.

3.5 Dynamic SC detection

The above analysis reveals a significant difference between the time-average and time-dependent representation of the stall cells characteristics. Such difference is further scrutinized by defining again the spanwise integral parameter of separated flow fraction $\bar{L}$ (Equation 2), this time based on the spanwise distribution of the instantaneous velocity $u^*(y^*, t^*)$. First, the spanwise fraction of separated flow at each time step is calculated and subsequently averaged over the entire measurement sequence, resulting in $\tilde{L}$:

$$\tilde{L} = \frac{1}{T} \int_0^T \frac{1}{b} \int_0^b \text{sgn}(u(x^*, y, z^*)) dy dt \quad (3)$$

Based on the above operator, the criterion introduced in Equation 2 can be invoked again to examine the experimental data. The conditions of attached, partially separated and fully separated are inquired again in light of the value of $\tilde{L}$ and a new classification is obtained in the α - Re map. Owing to the fundamental differences in how $\tilde{L}$ and $\bar{L}$ are defined, the resulting regime maps exhibit certain variations. The metric based on time-averaged velocity $\bar{L}$ departs from that based on the dynamic definition of separated flow, specifically when the separated flow exhibits large unsteady fluctuations. In particular the cases where the spanwise position and extent of the reverse-flow region vary significantly over time, produce the largest departure. Under such conditions, $\bar{L}$ may misrepresent the actual separation behavior, leading to a mismatch between the inferred flow regime and the instantaneous flow dynamics. In contrast, $\tilde{L}$ inherently accounts for temporal variability and therefore provides a physically sound basis for classification. The resulting α - Re map derived from $\tilde{L}$ is illustrated in Figure 8 with hollow markers (blue triangle, green square and orange circle). The flow classification based on $\bar{L}$ values are represented with solid markers here for comparison.

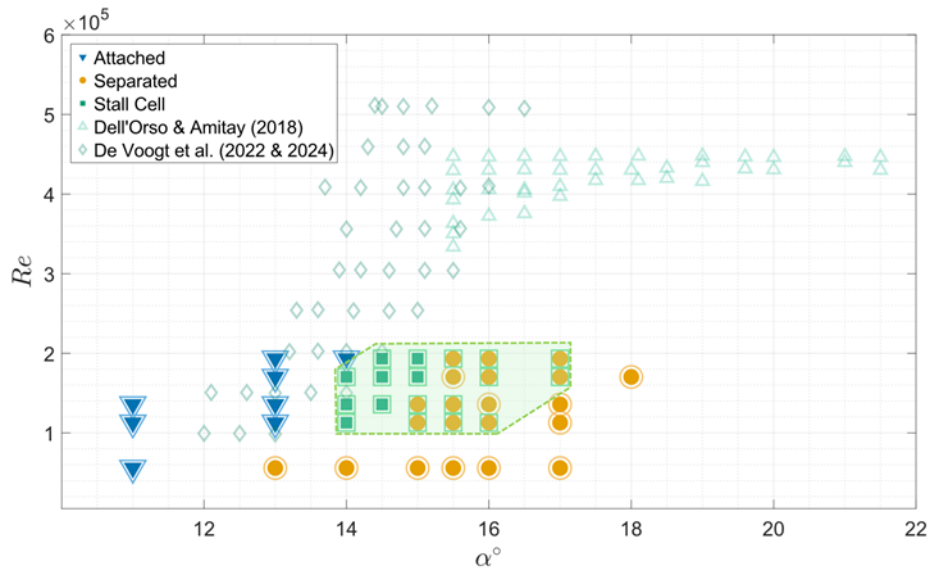


Figure 8 Flow regimes in the $\alpha - Re$ envelope of experiments based on $\tilde{L}$ metrics and comparison with $\bar{L}$.

Based on the instantaneous velocity field metric, the envelope of conditions with cellular separation is significantly broadened (highlighted by the green surface). This can be explained with the nonlinear behaviour of the near wall velocity in combination with a spanwise motion of SC. The conditions of flow separation are characterised by a relatively weak reverse velocity. In contrast, when the flow is attached, the velocity is in the order of the free-stream value. In this context, time-averaging strongly biases the estimate of reverse flow probability, leading to noticeable differences between the two metrics.

The difference between these two parameters may serve as an indicator of the extent of spanwise motion within the separated region. Such discrepancy increases at the boundary between cellular separation and fully separated flow. Figure 9 represents the corresponding values for $\tilde{L}$ and $\bar{L}$ with solid and hollow markers for two different Re numbers respectively. The data for the other two Re numbers is not shown here to avoid repetition.

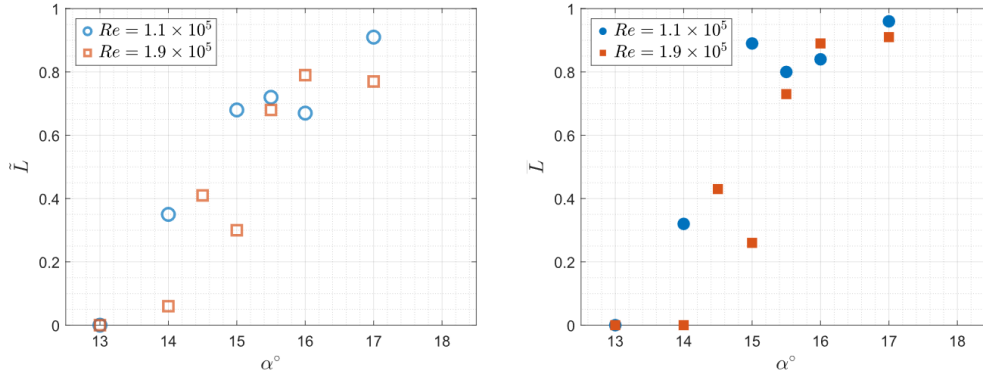


Figure 9 Corresponding values for the instantaneous $\tilde{L}$ (hollow markers) and the time-average $\bar{L}$ (solid markers) metrics for two Re numbers.

4. Conclusions

This study has examined the onset, structure, and dynamical behavior of stall cells on a NACA0015 airfoil using time-resolved volumetric measurements, with the specific aim of clarifying their regime of occurrence and their inherently unsteady nature. The results show that cellular separation does not emerge gradually as a weak modulation of separated flow, but instead occupies a well-defined and comparatively narrow region in the α - Re space. Within the present experimental conditions, when defined on the basis of the time-average velocity field, stall cells are observed only for angles of attack between 14° and 15° and Reynolds numbers between 1.2×10^5 and 1.9×10^5 . Outside this envelope, the flow features either the fully attached or fully separated state.

While this envelope can be identified from time-averaged velocity fields, the time-resolved volumetric data reveal that stall cells are intrinsically unsteady in nature. Rather than remaining fixed in space, they evolve through spanwise migration, intermittent branching of low-momentum fluid, and localized shedding events that alter their size and position over time. Such behavior is largely obscured by conventional visualization techniques and by time averaging, which explains, at least in part, the wide spread of critical Reynolds numbers reported in the literature.

The comparison between time-averaged and instantaneous analyses highlights a central limitation of mean-flow-based stall cell detection. Time averaging suppresses spanwise motion and

intermittency, thereby biasing the estimated extent of separated flow toward attached conditions whenever reverse flow is weak or mobile. As a result, cases characterized by dynamically active cellular separation may appear fully attached or fully separated in the mean, despite exhibiting stall-cell-like behavior for a substantial fraction of time. This discrepancy becomes most pronounced near the boundary between cellular and fully separated regimes, where unsteady migration dominates the flow organization.

To address this limitation, a quantitative criterion for identifying the stall cell regime is proposed accounting for the spanwise fraction of separated flow. The criterion is evaluated from both instantaneous and time-averaged velocity fields. When the separated-flow fraction lies between 0.2 and 0.8, stall cells are consistently observed, whereas departures between the instantaneous and averaged metrics serve as a direct indicator of strong unsteadiness and spanwise reorganization. In this sense, the difference between these two measures does not represent experimental uncertainty, it rather captures the degree to which separation is mobile rather than stationary.

Taken together, the results of this work suggest that stall cells should not be viewed as quasi-steady separation patterns anchored to the airfoil surface, but instead as spatio-temporally evolving structures with multiple degrees of freedom. Their apparent onset, persistence, and disappearance depend not only on aerodynamic parameters, but also on the observational framework used to identify them. Time-resolved, three-dimensional measurements therefore emerge as a necessary tool for accurately characterizing the stall-cell regime and for reconciling differences between experimental and numerical studies. By emphasizing the dynamic nature of cellular separation, the present study provides a framework for more consistent identification of stall cells and a foundation for future investigations into their underlying physical mechanisms.

Data availability

The data that supports the findings of this study are available within the article [and its supplementary material].

Author declarations

Conflict of Interest: The authors have no conflicts to disclose.

Appendix A

Control line position sensitivity analysis

We consider three different wall-normal heights ($h^* = h/c = 0.025, 0.050$ and 0.075) and three chordwise positions ($x^* = 0.25, 0.5$ and 0.75), as illustrated in Figure 10. The side and top views illustrate lines at different wall-normal heights ($h^* = 0.025, 0.050$ and 0.075) and at three chordwise positions ($x^* = 0.25, 0.5$ and 0.75). As the wall-normal distance increases, the streamwise velocity approaches the free-stream value. To capture the time-resolved behavior of stall cells and their spatio-temporal evolution, the analysis must focus on a location that preserves the essential flow features.

For the analysis of the instantaneous flow, the streamwise velocity is visualized at $x^* = 0.5$ and $h^* = 0.025$, as this location is sufficiently close to the airfoil surface without significantly suffering from the reduction of tracer numbers at the wall, and the mid chord location ensures that the sampling line passes through the stall cell most of the time in each experiment. Selecting a point further from the surface (e.g., $h^* = 0.050$ or 0.075) would obscure key reversed-flow features in the data. A similar constraint applies to the chordwise location: moving it significantly upstream or downstream would result in the loss of important instantaneous flow structures.

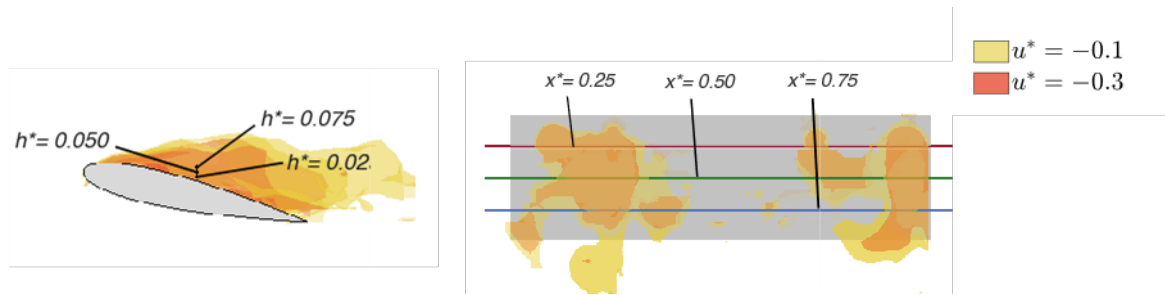


Figure 10 Cross-sectional and top view of u^* isosurfaces at $\alpha = 15^\circ$ and $Re = 1.7 \times 10^5$ for a single timestep.

To assess the sensitivity of the observed flow features to the wall-normal sampling location, y - t diagrams of the streamwise velocity are compared at different values of h^* for the case $\alpha = 15^\circ$ and $Re = 1.7 \times 10^5$, as shown in Figure 11. The overall flow topology remains qualitatively unchanged across the considered wall-normal heights, with stall cells clearly identifiable at all locations, indicating that their presence is not dependent on the specific choice of h^* . Nevertheless, increasing h^* leads to a progressive recovery of the freestream velocity and a corresponding reduction in the spatial and temporal extent of the separated flow region. This trend is consistent

with the increased distance from the airfoil surface, where reversed-flow signatures associated with stall cells are strongest.

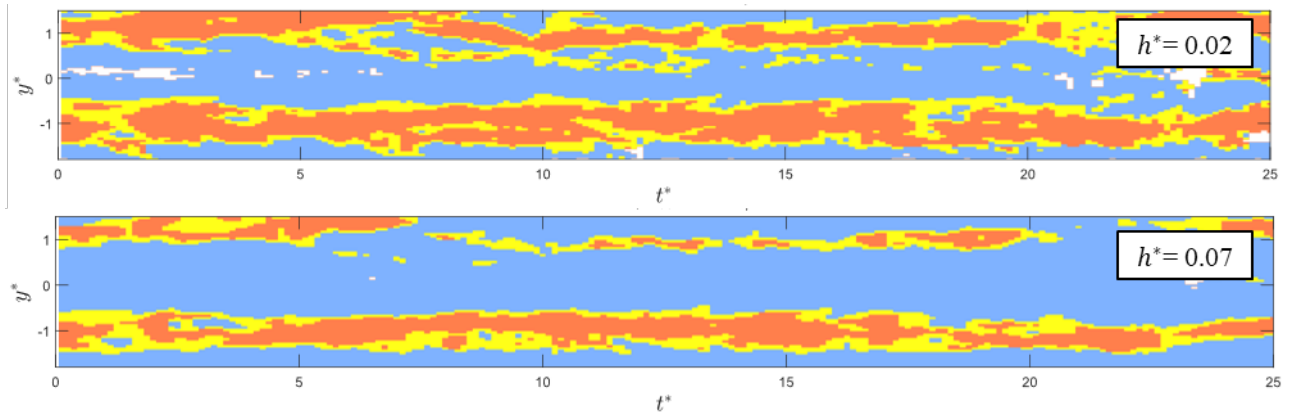


Figure 11 Streamwise velocity contours over time for $\alpha = 15^\circ$ and $Re = 1.7 \times 10^5$.

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