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Numerical investigation of the interaction between laminar to turbulent transition and the wake of an airfoil

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ABSTRACT

The objective of this work is to investigate numerically the different physical mechanisms of the transition to turbulence of a separated boundary-layer flow over an airfoil at low angle of attack. In this study, the spectral elements code Nek5000 is used to simulate the flow over a SD7003 wing section at an angle of attack of $\alpha = 4°$. Several laminar cases are first studied from $Re = 2000$ to $Re = 10000$, and a gradual increase of the Reynolds number is then performed in order to investigate one transitional case at $Re = 20000$. Computations are compared with measurements where the instability mechanisms in the separated zone and near wake zone have been analyzed. The mechanism of transition is investigated, where the DMD (Dynamic Mode Decomposition) is used in order to extract the main physical modes of the flow and to highlight the interaction between the transition and the wake flow. The results suggest that the transition process appears to be physically independent of the wake flow, while the LSB shedding process is locked-in with the von Kármán instability and acts as a sub-harmonic.

1. Introduction

In both hydrodynamic and aerodynamic communities, the question of transition to turbulence over wing sections has been largely addressed and investigated, mostly because of its crucial role in the design of lifting bodies. In many cases, a good knowledge of the boundary-layer flow regime around the body is required, particularly when modifications of the boundary-layer flow around or on the body occurs, as is the case for transitional flows. A characterization of the transition region combined with a good understanding of the physical process leading to turbulence is then a key in the prediction of the body's performances. It is also of crucial importance for the evaluation of the noise and of the structural vibrations due to flow unsteadiness. In the hydrodynamic field, it has been shown that the control surfaces of Autonomous Underwater Vehicles (AUV) can operate at transitional regimes due to their relatively small scales, with moderate to high Reynolds numbers ($5 \cdot 10^5 < Re < 3 \cdot 10^6$). At smaller scale, transition on Micro Air Vehicles has been largely studied because it can take place on more than 50% of the wing, thus having a direct key role in the flight [1].

Transition on lifting bodies is often triggered by a laminar separation and reversed flow due to an adverse pressure gradient. The development of the turbulent flow, which causes a momentum transfer in the wall normal direction, allows the flow to reattach, forming a so called laminar separation bubble (LSB). Downstream of the LSB, the flow is usually highly unsteady and is subject to several complex mechanisms resulting in transition to turbulence.

At first, the reattachment point is subjected to a low frequency oscillation in the shear layer (known as *flapping*), and is responsible for the first destabilization of the LSB. In the mean time, it has been shown that primary instabilities (Kelvin–Helmholtz vortex and/or Tollmien–Schlichting waves) are responsible for a partial detachment of the LSB yielding to LSB vortex shedding. The physical process leading to the breakdown of coherent structures into smaller scales triggering turbulence is then usually caused by secondary instabilities.

In regard to recent works on laminar-turbulent transition, it appears that some efforts are still to be done in (i) the characterization of the transitional region and its direct effect on pressure distribution hydro/aerodynamic loading (*i.e.* global effects) and (ii) the understanding of the physical mechanisms that lead to turbulence, including the instability mechanisms and the unsteadiness of the vortex flow that convects downstream of the transitional region and later in the wake.

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1.1. Previous works of separation induced transition on flat plates

Many studies have been dedicated to the issue of laminar separation, in particular for aerodynamic applications on flat plates and lifting bodies. The characterization of laminar separation bubbles has been given a special interest, from the pioneering experimental works of Gaster [2] or Tani [3] to recent numerical studies involving direct numerical simulations (DNS). A synthesis of knowledge on the dynamics of LSB can be found in [4].

Simplified geometries where transition is caused by the application of an adverse pressure gradient, such as flat plates [5,6], or by the geometry itself [7], have led to significant improvements in the understanding of the LSB behavior and instability mechanisms. Major reasons are the relative control of laminar separation and the good knowledge of the physical time scales that allow convective perturbations forcing inside the transition region.

The following literature review will concern flat plate with adverse pressure gradient, as it is the closest case to airfoil, and also the most studied.

Direct numerical simulations performed by Alam and Sandham [8] show that complex and multi-scaled structures can exist in the LSB wake. Moreover, the presence of vortex shedding of the bubble has been characterized by Pauley et al. [9]. They found that the frequency of the vortex shedding from the bubble could be made non-dimensional using a Strouhal number St_θ based on the momentum thickness θ_{sep} and the external velocity $(v_{\text{ext}})_{\text{sep}}$ at laminar separation.

To understand the physical mechanisms in the transition region, Marxen and Henningson [10] have studied the flow on a flat plate submitted to convective perturbations with large amplitudes. In particular, the authors state that, depending on the length of the bubble (short or long, see Gaster [2]), two distinct behaviors can be observed. The short bubbles are governed by mean flow deformation (MFD), where an algorithmic relationship between the forcing amplitude and the bubble length is observed. For long bubbles, a bursting phenomenon is observed which plays a key role in the turbulent reattachment. Later, the same authors have associated secondary instabilities to be responsible for (i) the deformation of the Kelvin–Helmholtz vortex associated to an elliptic instability in the core of the vortex, and (ii) for the breakdown of the vortex into smaller structures associated with a hyperbolic instability in the braid region between two vortices [6]. Finally, it has been shown that the characteristics of the transitional region highly depend on the flow conditions. Walters and Leylek [11] have demonstrated that under different turbulence intensity levels and inflows, the LSB and transition point can change significantly. In this context, Abu-Ghannam and Shaw [12] have successfully developed an experimental relationship to predict boundary layer transition based on the effect of turbulence, pressure gradient and flow history on flat plates geometries. This experimental correlation is often used to model transition, see [13].

1.2. Previous works of separation induced transition on wing section

Depending on the application considered, the physics of the flow on wing geometries can be modified by the curvature of the wing, the angle of attack and by complex dynamics and/or transient effects that are directly taken from operating conditions. Hence, the characteristics of the LSB are directly dependent on its position along the chord. It has been shown both experimentally [14] and numerically [15] that the transitional region appears near the trailing edge for low to moderate angles of attack, and moves toward the leading edge as the angle of attack increases. Moreover, the length of the bubble is inversely related to the adverse pressure gradient. Consequently, the effect of transition may be very different if the laminar separation bubble is located near the leading or trailing edge [16]. It also has to be noted that most studies on lifting bodies investigate natural transition compared to forced transition for flat plates studies [10]. As a consequence, the transition mechanisms and the corresponding coherent structures can be different.

For low angles of attack and/or low Reynolds numbers, the transition region is larger and located closer to the trailing edge, which leads to large effect on aerodynamic performances, a low characteristic frequency of vortex shedding of LSB and strong interactions with the wake flow. An innovative experimental study by Hain et al. [17] uses a time-resolved particle image velocimetry (TR-PIV) system to determine the dominant frequencies of the transition process and of the flapping of the bubble along a SD7003 airfoil at $Re = 66000$. The authors identify dominant structures which lead to large magnitudes in the frequency spectrum. The same physics on the SD7003 geometry was investigated for Reynolds numbers between $20\,000 < Re < 66\,000$, and for different angles of attack using experimental [18–21] and numerical methods [22,23]. At $Re = 20\,000$, transition is observed near the trailing edge and a vortex associated with a Kelvin–Helmholtz instability is convected into the foil's wake at a characteristic frequency $0.0095 \leq St_\theta \leq 0.011$ [18]. However, the vortical flow in the wake has not been investigated. For $Re = 66\,000$, transition is stronger and a burst phenomenon is associated with a fast transition to turbulence [18,22] even if Kelvin–Helmholtz instabilities are still observed. Recently, Jones et al. [24] performed a numerical analysis of a LSB in the case of an airfoil at $\alpha = 5°$ and a low Reynolds number $Re_c = 50\,000$. The authors investigated the instability mechanisms leading to the breakdown to turbulence. As Marxen and Henningson [10] stated for the case of a flat plate, this breakdown is linked to the combination of two absolute instabilities: an elliptic instability and a mode-B or hyperbolic instability. An important conclusion was that, in the absence of convectively driven transition within the shear layer, an absolute instability can take place and makes the influence of free stream turbulence weaker.

At high angles of attack and/or high Reynolds numbers, transition is located at the leading edge and is characterized by a short laminar separation bubble. Transition occurs brutally in a very high pressure gradient region and its behavior is characterized by high frequency oscillations of the laminar separation bubble shedding [16]. Moreover, it has been shown that at higher angles of attack, the laminar separation was not able to reattach, and that the bubble may help the destabilization of the boundary-layer flow at the leading edge potentially causing stall to occur, as shown numerically by Shelton et al. [25] and Genç [26]. Genç et al. [14] also showed that as the Reynolds number increases, the stall characteristic is strongly modified and the mild stall occurs whereas the abrupt stall occurs at lower Reynolds numbers. They also highlighted that the stall angle decreases with decreasing Reynolds number, which induces the short bubble burst at higher angles of attack, and causes long bubble to occur. This has been validated by the computations of Karasu et al. [15], who show the importance to take into account for the transition in the numerical model

1.3. Objective and structure of the paper

Studies on airfoils show a transition by Laminar Separation Bubbles for which mechanisms associated with flapping of the shear layer and primary instability have been demonstrated. It appears however that further comparisons with flat plate studies are still necessary and could bring new elements in the understanding of the physics of transition. On the one hand, investigations on flat plate geometries have indeed led to detailed analysis of the instability mechanisms responsible for transition to turbulence. On the