Propulsion and Power Research 2019;8(1):23–34

HOSTED BY

ELSEVIER

http://ppr.buaa.edu.cn/

Propulsion and Power Research

www.sciencedirect.com

REVIEW ARTICLE

On bypass transition in separation bubbles: a review

Zhiyin Yang

Department of Mechanical Engineering and the Built Environment, College of Engineering and Technology, University of Derby, Derby, UK

Received 15 January 2018; accepted 29 September 2018
Available online 14 January 2019

KEYWORDS

Transition;
Bypass transition;
Separated free shear layer;
Separation bubbles;
Free-stream turbulence

Abstract Transition from laminar flow to turbulent flow is of great practical interest as it occurs in many engineering flows and often plays a critical role in aerodynamics and heat transfer performance of those flow devices. There could be many routes through transition, depending on flow configuration, geometry and the way in which transition is initiated by a wide range of possible background disturbances such as free-stream turbulence, pressure gradient, acoustic noise, wall roughness and obstructions, periodic unsteady disturbance and so on. This paper presents a brief overview of wall bounded flow transition in general and focuses more on the transition process in the free shear layer of separation bubbles, demonstrating that at elevated free-stream turbulent intensity the so called bypass transition could occur in geometrically induced separation bubbles where the separation point is fixed.

Nomenclature

D	flat plate thickness (unit: m)
f	normalized frequency (unit: Hz)
k_{max}	maximum turbulent kinetic energy (unit: m^2/s^2)
U_0	free-stream velocity in the axial direction (unit: m/s)
x_R	mean separation bubble length (unit: m)
x	co-ordinate in the axial direction (unit: m)
y	co-ordinate in the vertical direction (unit: m)
z	co-ordinate in the spanwise direction (unit: m)
$\delta_1(x)$	boundary layer displacement thickness (unit: m)
DNS	direct numerical simulation
KH	Kelvin-Helmholtz
LES	large eddy simulation
POD	proper orthogonal decomposition
TS	Tollmien-Schlichting
2D	two-dimensional
3D	three-dimensional

E-mail address: Z.Yang@derby.ac.uk

Peer review under responsibility of National Laboratory for Aeronautics and Astronautics, China.

https://doi.org/10.1016/j.jppr.2018.12.004

1. Introduction

Transition from laminar flow to turbulent flow is hugely complex and remains one of unsolved problems in fluid dynamics despite enormous efforts by engineers, physicists and mathematicians for more than a century. Transition has drawn such attention and efforts since it can be found in many engineering flows and has a significant impact on the aerodynamics and heat transfer characteristics of those flow systems. Transition is so complex because it may take many different routes depending on flow configuration and geometry, and transition process is greatly influenced by the presence of many possible flow disturbances such as wall roughness or obstructions, free-stream turbulence, acoustic noise, pressure gradient, surface heating or cooling, suction or blowing of fluid from the wall and so on.

It is well known that Osborne Reynolds was the first person who systematically studied pipe flow transition experimentally in the late 19th century. William McFadden Orr and Arnold Sommerfeld were pioneers in the theoretical investigation of transition. They developed a method independently trying to explain the onset of turbulence and the method was named after them as the Orr-Sommerfeld approach (more commonly known as linear stability theory). Following the Orr-Sommerfeld approach active theoretical study of transition started in the early 20th century.

Numerical studies of transition, solving numerically a simplified, linearized version of the Navier-Stokes equations, started even before computers came into being. Nevertheless, it was not until the late 1980s proper numerical studies of transition using large-eddy simulation (LES) and direct numerical simulation (DNS) started to appear, with significant progress in the past two decades.

Traditionally for wall bounded flows, transition has been classified into the following three main categories:

1.1. *Natural transition*

This kind of transition occurs in an attached boundary layer under very low level flow disturbances, e.g., free-stream turbulent intensity less than 0.5%. The transition process is initiated by two-dimensional (2D) instability waves called Tollmien-Schlichting (TS) waves (primary instability), followed by a three-dimensional (3D) instability (secondary instability) leading to significant 3D flows with the formation of streamwise/spanwise vortices. The final stage of such transition process is called the breakdown stage, which involves the breakdown of those large scale vortices into smaller flow structures and the generation of turbulent spots which eventually merge to form a turbulent boundary layer [1–6]. Natural transition is the most extensively researched area compared with other two categories of transition (a significant amount of work had already been done by the first half of 20th century mainly based on linear stability theory and some experiments) and hence the transition process is relatively much better understood. There are several stages involved in the transition process:

i) Receptivity stage – how the disturbances are projected into growing eigenmodes, or how they enter or otherwise induce disturbances in a boundary layer.
ii) Primary instability – small disturbances are amplified due to a so called primary instability (2D TS waves) of the flow.
iii) Secondary instability – usually once a disturbance reaches a finite amplitude it often saturates and transforms the flow into a kind of new, possibly steady state. Very rarely the primary instability can lead the flow directly into a turbulent state and the new steady or quasi-steady flow becomes a base on which secondary instability can occur (3D flows develop). This secondary instability can be viewed as a new instability of a more complicated flow. The growth rate of disturbances is much larger than that of the primary instability stage.
iv) Breakdown stage – nonlinearities and possibly higher instabilities excite an increasing number of scales and frequencies in the flow. This stage is more rapid than both the linear stage and the secondary instability stage.

1.2. *Bypass transition*

For an attached boundary layer under sufficiently high flow disturbances, e.g., a boundary layer on a flat plate without pressure gradient under free-stream turbulent intensity larger than 1%, transition occurs more rapidly and the 2D instability stage of natural transition is bypassed. The term "bypass transition" was first given by Morkovin [7] to this type of transition. Bypass transition was initially regarded as a mystery as turbulent spots seemed to be generated very rapidly out of nowhere compared with natural transition. However, over the past two decades better understanding of bypass transition has been obtained through numerical simulations with stability analysis (especially DNS - direct numerical simulation) [8–16]. Despite different bypass transition mechanisms proposed a general accepted description of bypass transition may be summarized as follows:

i) At elevated free-stream turbulence levels, low-frequency disturbances penetrating into the laminar boundary layer may undergo an algebraic growth (called transient growth or nonmodal growth, with the later referring to the fact that this mode is not predicted as one of the eigenmodes of the solution of linearized theories based on the Orr-Sommerfeld and Squire equations), leading to the formation of elongated streamwise streaks. Those streaks are termed boundary layer streaks or Klebanoff distortions (or called Klebanoff modes) after P.S. Klebanoff who investigated this phenomenon first and described them as a periodic thickening/thinning of the boundary layer [17,18]. They are zones of forward and backward jet-like perturbations (high- and low-speed streaks) in the streamwise direction, alternating in the spanwise direction with a wavelength in the order of boundary layer thickness.

ii) A laminar boundary layer distorted by the streaks is susceptible to instabilities and the streaks grow downstream both in length and amplitude. Transition is usually initiated near the top of the boundary layer via an inflectional type of instability as a result of the interaction between the low-speed streaks lifted from the near wall region and high-frequency disturbances in the free-stream which is strongly damped by the laminar shear layer (called shear sheltering) and hence cannot penetrate into the boundary layer.
iii) Turbulent spots are generated initially and further downstream, those turbulent spots merge to form a fully turbulent boundary layer.

1.3. Separated-flow transition

When a laminar boundary layer separates or when laminar flow separates at a blunt/sharp/rounded leading edge of a flat plate, transition may occur in the separated free shear layer of the flows. This is called separated-flow transition (or called separated boundary layer transition). It is worth noting that in some literature transition has been classified into four categories and the fourth one is called wake-induced transition [6,19–22] since in turbomachinery flows, the transition process is strongly influenced by impinging wakes coming from the preceding blade rows.

The use of a single category (separated-flow transition) to describe transition in a separated laminar shear layer is too general or too vague. It was argued by Walker [23] in the early 1990s that, similar to the bypass transition in an attached boundary layer, "bypass transition" could occur in separated shear layers too. Nevertheless specific studies on the topic of "bypass transition in separated shear flows" have been very scarce. Furthermore, separation can be induced in many different ways, e.g., boundary layer separation on a flat plate due to an adverse pressure gradient; separation induced geometrically, and also in some cases separated flows reattach to the surface to form a separation bubble while in other cases they never reattach again.

In the following two sections of this paper a discussion on the transition process in separation bubbles formed due to an adverse pressure gradient will be presented in Section 2. Section 3 will focus on the influence of free-stream turbulence levels on the transition process in separation bubbles induced geometrically where the separation point is fixed with a very short distance for the development of an attached boundary layer or no boundary layer development before the separation point at all.

2. Transition in separation bubbles induced by an adverse pressure gradient

An attached laminar boundary layer on a smooth, flat or slightly curved surface may separate due to the presence of an adverse pressure gradient and transition could occur in the separated free shear layer, which reattaches and develops into a turbulent layer. This can be found in external flows such as flows over wind turbine blades and aircraft wings, and in internal flows such as gas turbine engine flows. Generally speaking for wind turbines and flight applications the free-stream turbulent intensity is relatively low ($<$ 5%) while it is high for turbomachinery flows at about 5% to 10% in compressor/turbine regions and can be as high as 20% in the wakes [2,24].

2.1. Transition process under low free-stream turbulence

Under low levels of free-stream turbulent intensity it has been clearly demonstrated by many numerical and experimental studies [25–32] that the transition process starts in the separated free shear layer above the wall due to an inviscid instability mechanism - the Kelvin-Helmholtz (KH) instability. These initial 2D instability waves grow downstream with an amplification rate usually larger than that of TS waves. 3D motions develop further downstream via a secondary instability mechanism associated with distortion of coherent 2D spanwise vortices called the KH rolls. Streamwise vorticity forms as a results of those distorted KH rolls. Those large scale coherent structures breakdown to small scale structures, leading eventually to turbulence around the mean reattachment point. It is worth noting that although the KH instability usually plays a dominant role in the separated boundary layer transition process the TS instability may still be present, interacting with the KH instability and in some cases the TS instability mechanism may play a significant role in the breakdown to turbulence [33–37].

Even at low free-stream turbulence levels our understanding of the transition process in a separation bubble is relatively very limited compared with that for an attached boundary layer, and in the transition process described above only the first stage - the primary instability stage is well understood. The secondary instability mechanisms are reasonably well understood for attached boundary layer transition, such as K-type secondary instability, H-type secondary instability or O-type secondary instability but for separated flow transition there is no general consensus regarding the secondary instabilities at work despite many studies in the past two decades [27,38–42] with several possible instability mechanisms proposed, e.g., Jones et al. [41] carried out numerical studies on transition process of forced and unforced laminar separation bubbles on an aerofoil at incidence, identified that two possible secondary instabilities were active: elliptical instability in elliptic regions of fluid flow (spanwise vortex core regions) and hyperbolic instability in hyperbolic regions of fluid flow (regions between two consecutive spanwise vortices called Braid regions). Detailed review on secondary instability in separation bubbles is beyond the scope of this article.

2.2. Transition process under elevated free-stream turbulence

Many experimental and numerical studies have shown that free-stream turbulent intensity can have a big impact on separation bubbles, e.g., increasing the shear-layer entrainment rates, decreasing the mean separation bubble length and resulting in earlier transition to turbulence [24,43–47].

Haggmark [48] carried out an experimental study of a separation bubble developing on a flat plate under a grid generated turbulent intensity of 1.5%, and low-frequency, large-amplitude boundary layer streaks were observed in the boundary layer and in the separated free shear layer. In addition, there was no evidence of two-dimensional waves from the flow visualization in the experiment.

McAuliffe and Yaras [28] studied transition mechanisms in separation bubbles formed over a flat plate due to an adverse pressure gradient under low (0.1% at separation) and elevated (1.45% at separation) free-stream turbulence levels using DNS. They performed the simulations using the commercial finite volume CFD code: ANAYS CFX. The second-order central differencing scheme was selected for spatial discretization and second-order Euler backward differencing scheme was used for temporal discretization. Their main findings are that under the low free-stream turbulence level transition occurs through receptivity of the laminar separated free shear layer to small disturbances via the KH instability mechanism but at the elevated free-stream turbulence level the receptivity mechanism leading to separated free shear layer roll-up is bypassed as a result of the boundary layer streaks formed upstream of the separation due to high free-stream disturbances interacting with the separated free shear layer. Turbulent spots are generated through the interactions of the separated free shear layer with the streaks via a localized secondary instability, and the Strouhal number (based on local conditions) associated with this instability closely matches that of the KH instability.

Balzer and Fasel [24] employed DNS to investigate the effect of free-stream turbulence level on boundary layer separation. The temporal discretization scheme used was an explicit, fourth-order accurate Runge-Kutta method and the spatial derivatives were discretized using fourth-order accurate compact differences. One case without free-stream turbulence (unforced separation bubble) and three cases with different free-stream turbulent intensities: 0.05%, 0.5%, 2.5%, were studied and the elongated streamwise streaks (Klebanoff modes) were found in the laminar boundary layer even at the lowest free-stream turbulent intensity of 0.05% as shown in Figure 1. The regions where acceleration ($u'>0$) and deceleration ($u'<0$) associated with the Klebanoff mode can be clearly observed in this Figure. The amplitude of these streaks was significantly larger at higher levels of free-stream turbulent intensity, as shown in Figure 2 for the case at free-stream turbulent intensity of 2.5%. However, at free-stream turbulent intensity of 0.05% the Klebanoff modes are quite weak and are not connected directly with the turbulent flow region while for the case at free-stream turbulent intensity of 2.5% the streaks are directly connected to the turbulent flow structures in the region $12<x<13$. They also found that separation still occurred at the highest free-stream turbulence intensity case (2.5%) and turbulent spots were not observed upstream of the separation bubble.

Their spectral analysis shows that a distinct peak is clearly observable for the case without freestream turbulence (top of Figure 3) which is associated with the inviscid shear layer instability (KH instability). This distinct peak at similar value is still observed when the free-stream turbulence intensity increases, even for the highest free-stream turbulence case although less pronounced as shown in Figure 3 (bottom). This indicates that the inviscid shear layer instability mechanism must still be present in all cases, which was further confirmed by their linear stability analysis that even for the highest free-stream turbulent intensity case (2.5%) the linear shear layer instability mechanism (KH instability) is not completely bypassed. Hence, they concluded that the transition to turbulence was due to both the primary shear-layer instability and the enhanced three-dimensional disturbance level, in particular the streamwise streaks caused by the free-stream turbulence. This is consistent with the results of a recent numerical study by Li and Yang [49] of a separated boundary layer transition on a flat plate with 3% free-stream turbulent intensity. It was found in the study by Li and Yang [49] that the boundary layer streaks (Klebanoff distortions or modes) were formed upstream the separation, similar to the previous studies just discussed above. Nevertheless the flow visualization reveals the existence of distorted KH rolls, indicating that the KH instability is also present. As a result of the interactions between the distorted KH rolls and the streaks, a portion of the KH roll merges with the streaks and develop into chaotic 3D structures

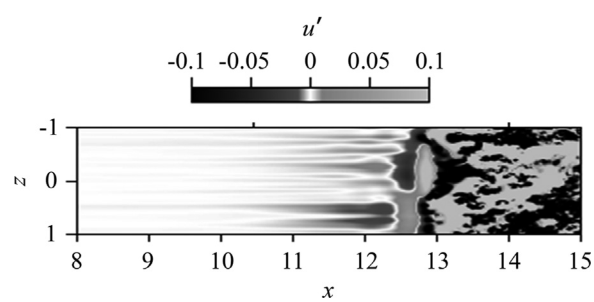

Figure 1 Contours of the streamwise velocity fluctuations in an x-z plane at $y=\delta_1(x)$ at free-stream turbulent intensity of 0.5% [24].

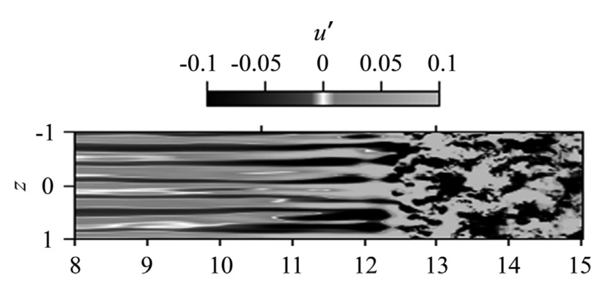

Figure 2 Contours of the streamwise velocity fluctuations in an x-z plane at $y=\delta_1(x)$ at free-stream turbulent intensity of 2.5% [24].

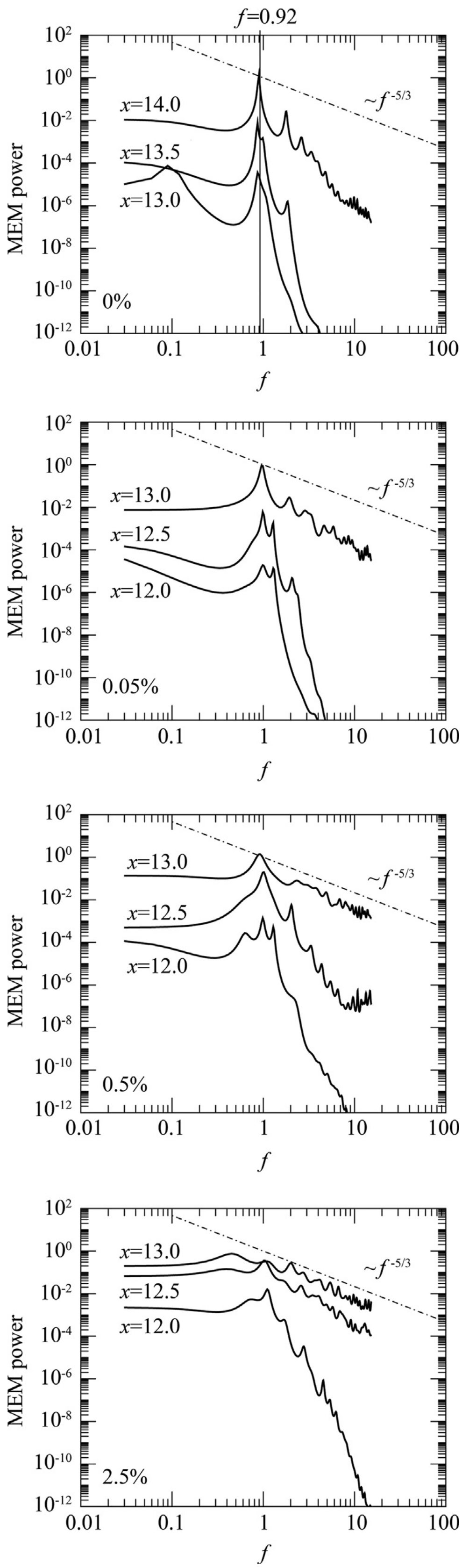

Figure 3 Spectral energy obtained using maximum entropy method at different free-stream turbulent intensities. From top to bottom: 0%; 0.05%; 0.5%; 2.5% [24].

rapidly downstream. Their further stability analysis confirmed the existence of the KH instability.

In a very recent experiment, Istvan and Yarusevych [47] studied the effects of free-stream turbulence on transition in a laminar separation bubble formed over the suction side of a NACA 0018 airfoil at two Reynolds numbers (80,000; 125,000). They performed both low and high-speed two-component PIV measurements to capture flow development in both streamwise and spanwise planes under four free-stream turbulence intensity levels (0.06%, 0.32%, 0.51%, 1.99%). Their results show that the shear layer rolls up into vortices just upstream of the mean transition location, leading to vortex shedding further downstream as shown in Figure 4. The location of shear layer roll-up is shifted upstream with increasing free-stream turbulence intensity level and for the highest free-stream turbulence intensity case the shear layer roll-up/vortex shedding is still clearly observed as shown in Figure 4(d), similar to that in the lower free-stream turbulence intensity cases. This indicates that the inviscid shear layer instability (KH instability) is still at work under the free-stream turbulence intensity of 1.99%. Nevertheless they demonstrated from the proper orthogonal decomposition (POD) analysis that for the highest free-stream turbulence intensity case, the streamwise streaks propagating from the boundary layer upstream of the bubble play an important role in the transition process since the streaks contribute more to the overall energy of velocity fluctuations than spanwise rollers.

The influence of free-stream turbulence on transition in a compressor cascade was carefully studied by Zaki et al. [50] and five cases were considered, one without turbulence and four with different turbulent intensities at inlet: 3.25%, 6.5%, 8.0% and 10%. The transition process found on the pressure surface is very different from that on the suction surface as separation only occurs for the case without turbulence at inlet and for all other cases flow remains attached. This is because under those free-stream turbulence levels the boundary layer transitions to turbulence upstream of the laminar separation location, ensuring that the flow remains attached. Other studies have also demonstrated that separation could be prevented completely or suppressed periodically because wake initiated transition before the boundary layer could separate [51,52]. Zaki et al. [50] showed that streaks were formed and amplified upstream of transition at the inlet turbulent intensity of 3.25% (decaying to about 2.5% at the blade leading edge). They found, however, that the breakdown of those streaks did not follow the conventional bypass mechanism as an inner instability was observed similar to those found in the secondary instability of classical TS waves. Nevertheless they further demonstrated that at higher inlet turbulent intensities bypass transition via the secondary instability of streaks became dominant. However, on the suction surface laminar separation persists and is modulated by the boundary layer streaks formed upstream of the separation location at the inlet turbulent intensity of 3.25%. The KH instability is still

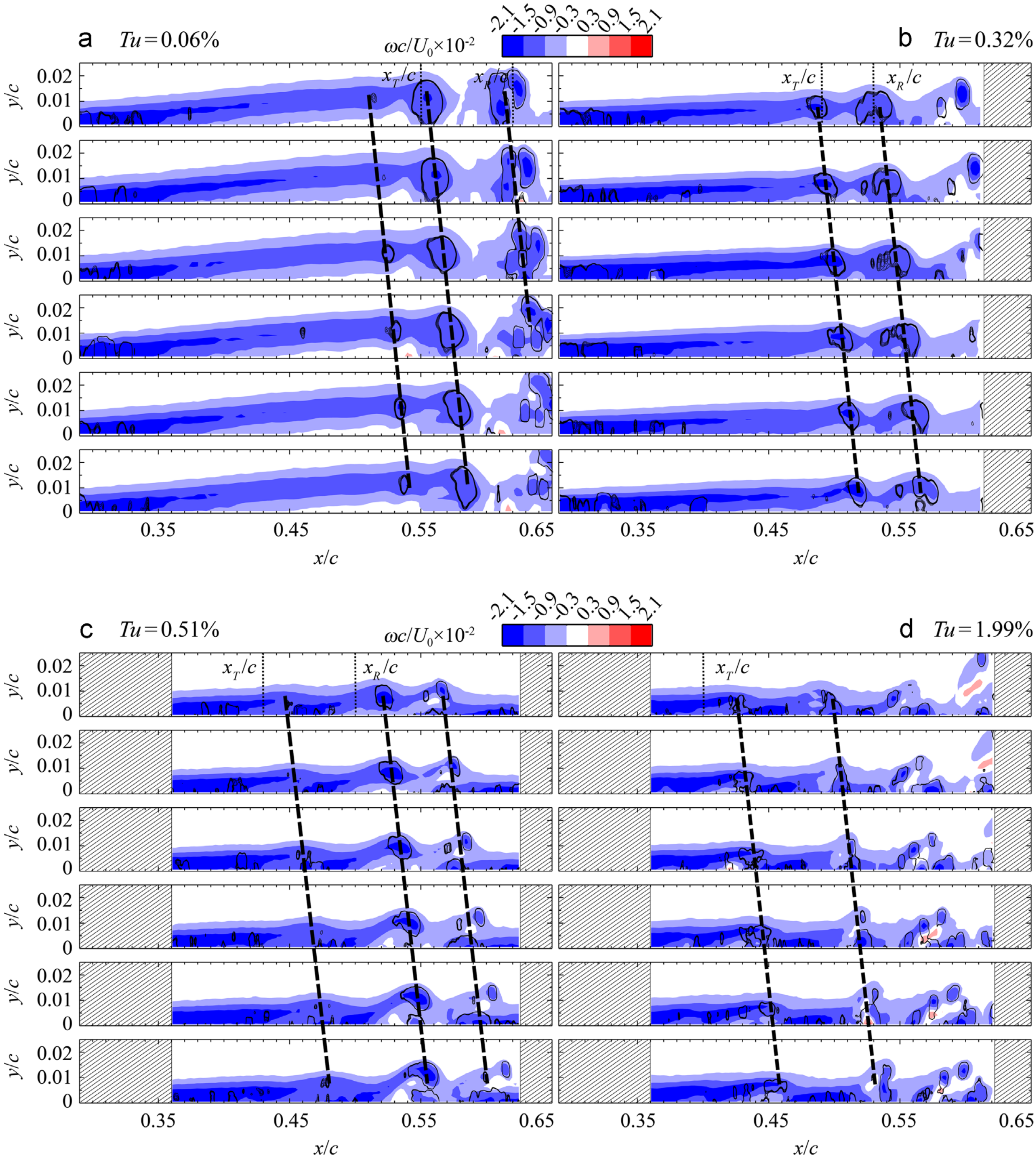

Figure 4 Contours of instantaneous spanwise vorticity, dashed lines trace the approximate centers of spanwise vortices and consecutive images are separated by 0.33 ms [47].

present and their flow visualization shows that once the KH rolls are formed, they are quickly destabilized and breakdown to turbulence. It is also noted that those KH rolls are not 2D but highly distorted in the span, very similar to the findings by Li and Yang [49]. At the next higher level of inlet turbulent intensity of 6.5% (decaying to about 4% at the blade leading edge) their averaged results indicate laminar separation and subsequent turbulent reattachment. However, they pointed out that this was misleading as the instantaneous flow fields showed the formation of turbulence spots in some regions where the boundary layer remained attached as shown in Figure 5. It can be seen from Figure 5(a) and (b) that at those two instances flow separation occurs across the whole span whereas at the other two instances, as shown in Figure 5(c) and (d), flow separation happens only at certain spanwise region and in the rest of the region flow remains attached.

When the inlet turbulent intensity was further increased to 8% and 10% (decaying to about 5.5% and 6.3% at the blade leading edge) they showed that a combination of

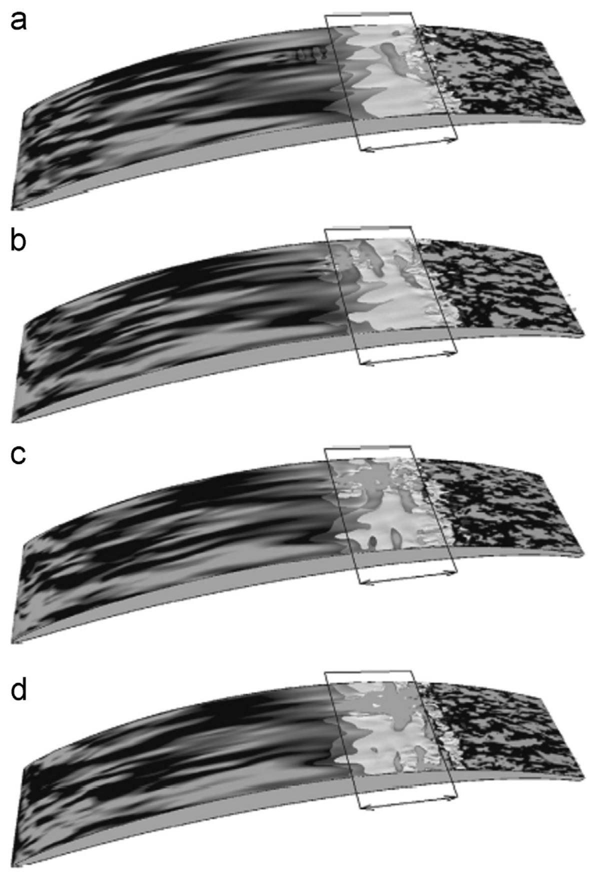

Figure 5 Contours of the tangential velocity fluctuations at four instances, with the instantaneous separation surface (white region) superimposed. The mean separation length is shown by dark lines [50].

mean flow distortion and transition to turbulence caused the boundary layer to remain attached and the transition was dominated by the bypass mechanism of an attached boundary layer.

In a recent experimental study using time-resolved PIV instrumentation by Simoni et al. [46], the effects of free-stream turbulence intensity level on the structure and dynamic properties of a laminar separation bubble has been investigated at three Reynolds numbers. The bubble was formed on a flat plate due to an adverse pressure gradient typical of ultra-high-lift turbine blade profiles. They performed measurements in the midspan plane for three Reynolds numbers (40,000; 75,000; 90,000) and three free-stream turbulence intensity levels at the plate leading edge (0.65%, 1.2% and 2.87%). Their results show that the separation bubble decreases with increasing Reynolds number and free-stream turbulence intensity, especially at the highest Reynolds number (90,000) and free-stream turbulence intensity (2.87%) the bubble could not be detected from the mean streamwise velocity contours as shown in Figure 6. They carried out detailed spectral analysis and identified a peak frequency of vortex shedding associated with the inviscid shear layer instability (KH instability) for all cases apart from the case at the highest Reynolds number (90,000) and free-stream turbulence intensity (2.87%). It was further confirmed through their proper orthogonal decomposition (POD) analysis that there was, indeed, no vortex shedding for the highest Reynolds number and free-stream turbulence intensity case as shown in Figure 7. It can be seen clearly from this Figure that for all the cases, apart from the highest Reynolds number and free-stream turbulence intensity case, POD modes are present which are representative of vortex shedding process. All those evidence confirms what is shown in Figure 6 that the separation bubble is indeed eliminated when the free-stream turbulence intensity is increased to 2.87% at the Reynolds number of 90,000.

Previous studies have demonstrated that under elevated free-stream turbulence transition is more rapid and a kind of "bypass transition" has been mentioned in a few studies. However, "bypass transition" here means that the receptivity stage of disturbances enter the separated shear layer, leading to the shear layer roll-up being bypassed [28]. Whereas bypass transition in an attached boundary layer means that the dominant linear instability mechanism, TS Waves, is bypassed. There is no evidence so far that in the separated boundary layer transition under elevated free-stream turbulence the linear shear layer instability mechanism, the KH instability, is bypassed. Several studies have confirmed the existence of the KH instability up to 3% free-stream turbulent intensity and a few studies demonstrated that separation is suppressed at much higher free-stream turbulent intensities and/or at higher Reynolds numbers. Hence it is not really meaningful to say that KH instability is bypassed as separated shear layer does not exist anymore in such a case.

3. Transition in separation bubbles induced geometrically

This section focuses on the transition process in separation bubbles induced geometrically. The main distinct

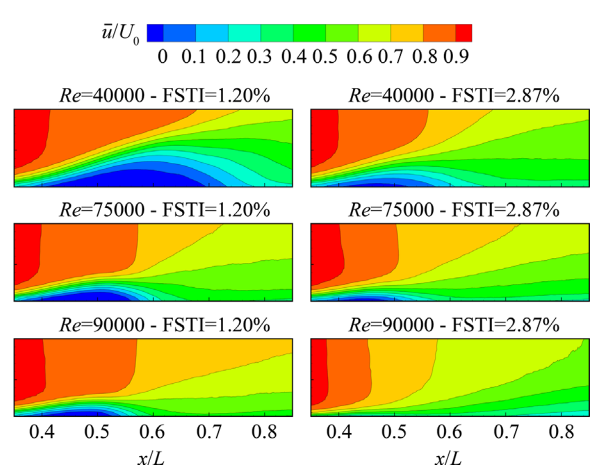

Figure 6 Contours of mean normalized streamwise velocity for different Reynolds numbers at two free-stream turbulence intensity levels (1.2%, 2.87%) [46].

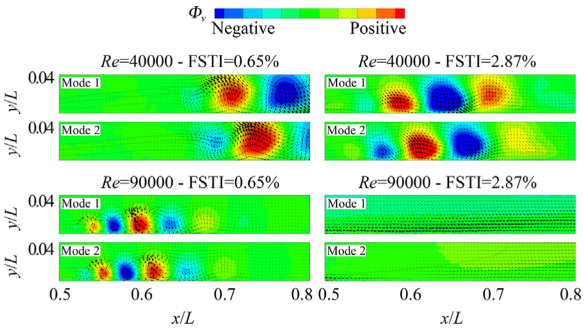

Figure 7 POD modes and iso-contour lines [46].

feature of those separation bubbles is that the separation point is usually fixed with a very short distance for the development of an attached boundary layer or no boundary layer development before the separation point at all, e.g., separation bubbles on a flat plate with a blunt/rounded leading edge [53–56]. As a result of this transition can only occur in the separated shear layer. Under low free-stream turbulence it has been demonstrated in many studies [57–65] that the transition process is initiated via the KH instability mechanism, more or less the same as in the cases discussed in the previous section. However, the transition process could be quite different under elevated free-stream turbulence as there is virtually no attached boundary layer developing before separation.

The literature on the transition process in separation bubbles induced geometrically under elevated free-stream turbulence is scarce. Experiments were carried out for a transitional separation bubble on a flat plat with a semi-circular leading edge with different flow conditions under different free-stream turbulence levels, denoted as the T3L test case of the ERCOFTAC Special Interest Group on transition [53,66] but unfortunately few detailed numerical simulations have been performed on this test case.

A transitional separated–attached flow over a flat plate with a blunt leading edge under 2% free-stream turbulent intensity was studied numerically using the large eddy simulation (LES) by Yang and Abdalla [67,68]. The governing equations were discretized on a staggered grid using the finite volume method and the sub-grid stresses were approximated by a dynamic sub-grid-scale model. The explicit second order Adams–Bashforth scheme was used for temporal discretization and the spatial discretization scheme was the second order central differencing, which is widely used in LES owing to its non-dissipative and conservative properties. They found that the mean bubble length was reduced by about 14% compared with the case without free-stream turbulence [61]. The free-stream disturbances produced more chaotic motion in the separated free shear layer, resulting in an early breakdown of the boundary layer as can be seen in Figure 8, showing a snapshot of instantaneous spanwise vorticity for the case without free-stream turbulence and the 2% free-stream turbulent intensity case. Nevertheless their flow visualization showed that the KH rolls were still visible, indicating the presence of the KH instability. This was further confirmed by the existence of the characteristic peak in the spectra as shown in Figure 9, equivalent to the characteristic KH value identified in the case without free-stream turbulence [61].

Langari and Yang [69] carried out a detailed LES study of a transitional separated boundary layer over a flat plate with a semi-circular leading edge under two free-stream turbulence levels (0.2% and 5.6% above the leading edge). The simulations were performed using an in-house finite volume LES code with multi-block curvilinear structured co-located grid. Rhie-Chow pressure smoothing was used to get rid of the pressure-velocity decoupling problem. The seconder order central differencing scheme was employed for spatial discretization and a single stage backwards Euler scheme was used for temporal discretization. The sub-grid stresses were modeled using a dynamic sub-grid-scale model. They demonstrated that for the low free-stream turbulence case the free shear layer formed in the separation bubble was inviscidly unstable via the Kelvin-Helmholtz instability mechanism, consistent with many previous studies discussed above.

For the higher free-stream turbulence case their results clearly demonstrate that the attached thin boundary layer, formed from the leading edge and developed over a very short distance before it reaches the separation point, is receptive to the free-stream turbulence disturbances and a small amount of turbulent kinetic energy is generated in the boundary layer which initially decays due to the acceleration of flow along the semi-circular surface from leading edge point to the separation location. However, after the separation at $x/D = 0.5$ (where D is the flat plate thickness, x is measured from the leading edge) turbulent kinetic energy is generated very rapidly for the elevated free-stream turbulence case, reaching the peak value at about $x/D = 1$ while for the low free-stream turbulence case the peak value is located at about $x/D = 3.25$ as shown in Figure 10, which presents the growth of maximum turbulent kinetic energy (the spanwise averaged peak value of k

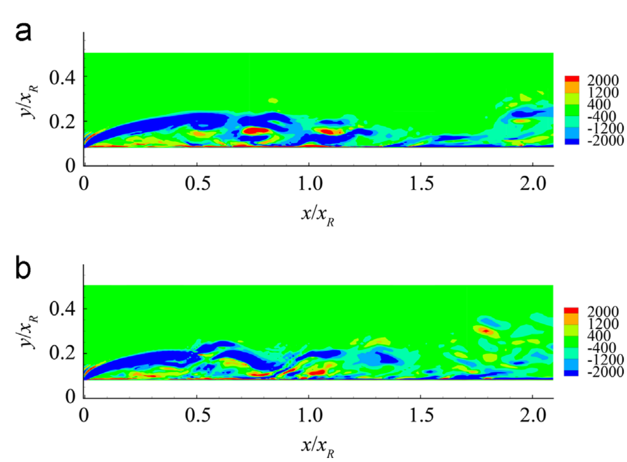

Figure 8 Instantaneous spanwise vorticity: (a) zero free-stream turbulence case and (b) 2% free-stream turbulent intensity case [67].

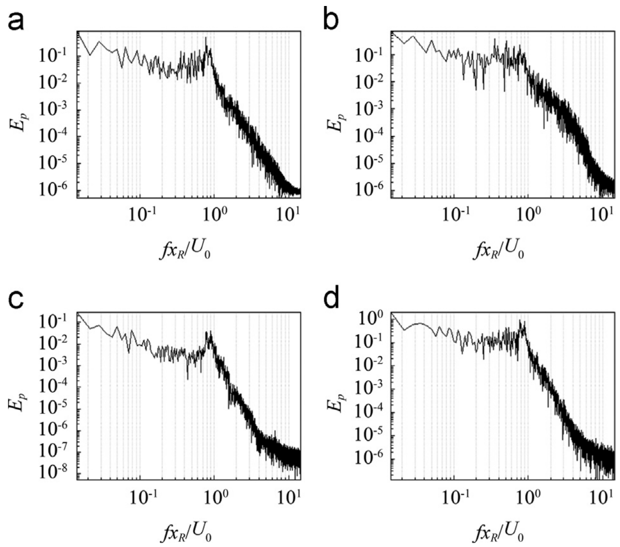

Figure 9 The pressure spectra at $x/x_R = 0.75$ and at (a) $y/x_R = 0.01$, (b) $y/x_R = 0.05$, (c) $y/x_R = 0.13$, and (d) $y/x_R = 0.2$ [68].

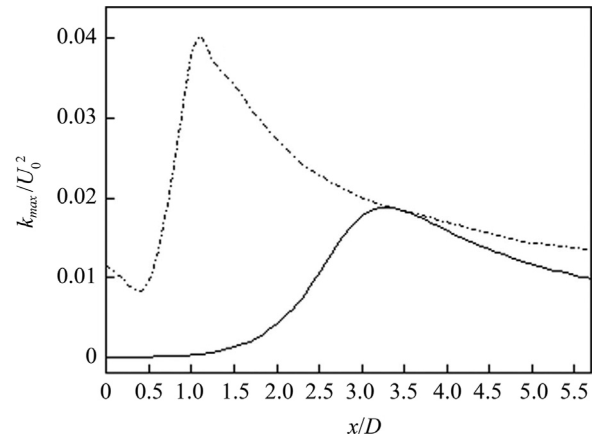

Figure 10 Development of the maximum turbulent kinetic energy: low free-stream turbulence case (solid line), elevated free-stream turbulence case (dashed line) [69].

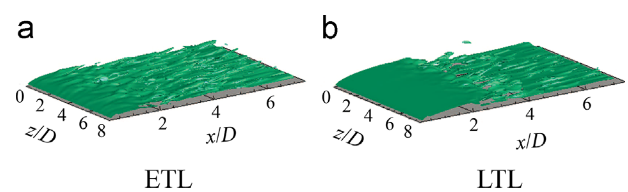

Figure 11 Isosurfaces of instantaneous spanwise vorticity: (a) elevated free-stream turbulence case and (b) low free-stream turbulence case [69].

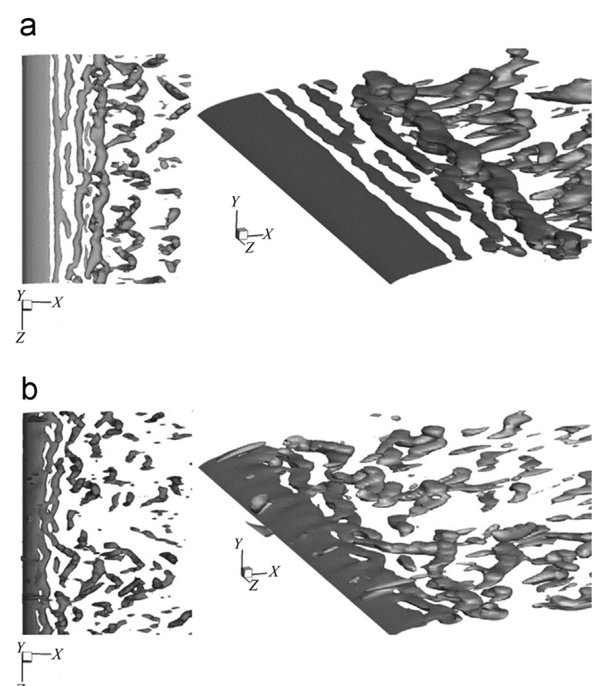

Figure 12 Top and perspective views of the Q-criterion isosurfaces: (a) low free-stream turbulence case and (b) elevated free-stream turbulence case [69].

profile along the wall normal direction in the boundary layer and the separated free shear layer). The rapid generation of turbulent kinetic energy after the separation leads to earlier transition and breakdown to turbulent flow as can be seen in Figure 11, which shows isosurfaces of instantaneous spanwise vorticity for both the very low and elevated free-stream turbulence cases.

Their instability analysis shows that the criterion for the KH instability to occur is not satisfied anymore, which strongly suggests that the KH instability is bypassed. This is further confirmed by their flow visualization as shown in Figure 12 that the early stage of transition process is very different for the elevated free-stream turbulence case (5.6%) compared against the low free-stream turbulence case (0.2%). For the low free-stream turbulence case the spanwise oriented 2D KH rolls are clearly visible at the early stage of the bubble and become distorted/deformed downstream due to 3D motion setting in as a result of a possible secondary instability. However, for the elevated free-stream turbulence case those spanwise oriented 2D KH rolls are not visible anymore and spanwise irregularity appears at the early stage of the bubble in the separated shear layer leading to the formation 3D structures very rapidly, bypassing the 2D KH rolls stage, leading to a much earlier breakdown to turbulence. They conclude, hence, that a “bypass transition” occurs as the KH instability stage is bypassed under the free-stream turbulence intensity of 5.6%, similar to the “bypass transition” process in attached boundary layers where TS instability stage is bypassed.

4. Conclusions

This paper presents a very brief overview of wall bounded flow transition which has been conventionally classified into three main categories: natural transition, bypass transition and separated-flow transition. Our current understanding of those three main categories of transition is briefly summarized and separated-flow (or separated boundary layer) transition is the least understood in comparison with natural transition and bypass transition in attached boundary layers.

Separated-flow transition has been classified further into two sub-groups in this paper: separation induced by an adverse pressure gradient and separation induced geometrically. For the first sub-group an attached boundary layer develops over a certain distance before it separates whereas there is hardly any distance for an attached boundary layer to develop before separation for the second sub-group. It has been demonstrated that for the first sub-group under low free-stream turbulence the dominant primary instability is the KH instability but the TS instability may be present too, interacting with the KH instability. Under elevated free-stream turbulence some researchers used the terminology "bypass transition" to describe the transition process but "bypass" here does not mean that the KH instability stage is bypassed as the KH instability is still present under free-stream turbulent intensity up to 3%. Nevertheless, one study clearly shows when the free-stream turbulent intensity is further increased to about 5.5% at a compressor blade leading edge the separation on the suction surface is suppressed completely and the transition is dominated by the bypass mechanism of an attached boundary layer. This finding is supported by several other studies, confirming that separation is indeed suppressed under sufficiently high free-stream turbulence and the usual bypass transition occurs in an attached boundary layer, not in a separated free shear layer. Therefore it is not really meaningful anymore to say that the KH instability is bypassed as the separated shear layer does not exist at all in such a case.

For the second sub-group under low free-stream turbulence many studies have clearly demonstrated that the KH instability is the dominant mechanism. Furthermore, there is strong evidence showing that the KH instability stage is indeed bypassed under sufficiently high free-stream turbulent intensity. Therefore bypass transition does occur for the second sub-group when the free-stream turbulent intensity is sufficiently high, which is fundamentally different from the situation in the first sub-group as the separation is completely eliminated under sufficiently high free-stream turbulence intensity.

Acknowledgements

The author gratefully acknowledges that some of the Figures presented in this paper are from the Ph.D studies by I.E. Abdalla and M. Langari under the author's supervision.

References

[1] H. Schlichting, Boundary-Layer Theory, McGraw-Hill, New York, 1979.
[2] R.E. Mayle, The role of laminar-turbulent transition in gas turbine engines, J. Turbomach. 113 (1991) 509–537.
[3] F. Ducros, P. Comte, M. Lesieur, Large-eddy simulation of transition to turbulence in a boundary layer developing spatially over a flat plate, J. Fluid Mech. 326 (1996) 1–36.
[4] M. langari, Z. Yang, On transition process in separated-reattached flows, Adv. Appl. Fluid Mech. 8 (2010) 157–181.
[5] T. Sayadi, P. Moin, Large eddy simulation of controlled transition to turbulence, Phys. Fluids 24 (2012) (114103-1-17).
[6] E. Dick, S. Kubacki, Transition models for turbomachinery boundary layer flows: a review, Int. J. Turbomach. Propuls. Power 2 (2017) (4-1-45).
[7] M.V. Morkovin, On the many faces of transition, in: C.S. Wells (Eds.), Viscous Drag Reduction, in: Proceedings of the Symposium on Viscous Drag Reduction, Dallas, USA, 24-25, September 1968, pp. 1–31.
[8] P.R. Voke, Z. Yang, Numerical study of bypass transition, Phys. Fluids 7 (1995) 2256–2264.
[9] P. Andersson, L. Brandt, A. Bottaro, D.S. Henningson, On the breakdown of boundary layer streaks, J. Fluid Mech. 428 (2001) 29–60.
[10] R.G. Jacobs, P.A. Durbin, Simulations of bypass transition, J. Fluid Mech. 428 (2001) 185–212.
[11] T.A. Zaki, P.A. Durbin, Mode interaction and the bypass route to transition, J. Fluid Mech. 531 (2005) 85-111.
[12] P.A. Durbin, X. Wu, Transition beneath vortical disturbances, Annu. Rev. Fluid Mech. 39 (2007) 107–128.
[13] P. Schlatter, L. Brandt, H.C. de Lange, D.S. Henningson, On streak breakdown in bypass transition, Phys. Fluids 20 (2008) 101505.
[14] J.J. Wang, C. Pan, P.F. Zhang, On the instability and reproduction mechanism of a laminar streak, J. Turbul. 10 (2009) N26.
[15] M.J.P. Hack, T.A. Zaki, Streak instabilities in boundary layers beneath free-stream turbulence, J. Fluid Mech. 741 (2014) 280–315.
[16] Z.Q. Xu, Q.J. Zhao, Q.Z. Lin, J.Z. Xu, Large eddy simulation on the effect of free-stream turbulence on bypass transition, Int. J. Heat Fluid Flow 54 (2015) 131–142.
[17] P.S. Klebanoff, K.D. Tidstrom, Evolution of amplified waves leading to transition in a boundary layer with zero pressure gradient, NASA TN D 195, 1959.
[18] P.S. Klebanoff, Effect of freestream turbulence on the laminar boundary layer, Bull. Am. Phys. Soc. 16 (1971) 1323–1334.
[19] U. Orth, Unsteady boundary-layer transition in flow periodically disturbed by wakes, ASME J. Turbomach. 115 (1993) 707–713.
[20] X. Wu, R.G. Jacobs, J.C.R. Hunt, P.A. Durbin, Simulation of boundary layer transition induced by periodically passing wakes, J. Fluid Mech. 398 (1999) 109–153.
[21] M.T. Schobeiri, K. Read, J. Lewalle, Effect of unsteady wake passing frequency on boundary layer transition, experimental investigation and wavelet analysis, J. Fluids Eng. 125 (2003) 251–266.
[22] J.G. Wissink, T.A. Zaki, W. Rodi, P.A. Durbin, The effect of wake turbulence intensity on transition in a compressor cascade, Flow Turbul. Combust. 93 (2014) 555–576.
[23] G.J. Walker, The role of laminar-turbulent transition in gas turbine engines: a discussion, J. Turbomach. 115 (1993) 207–216.
[24] W. Balzer, H.F. Fasel, Numerical investigation of the role of free-stream turbulence in boundary-layer separation, J. Fluid Mech. 801 (2016) 289–321.
[25] P.R. Spalart, M.K.H. Strelets, Mechanisms of transition and heat transfer in a separation bubble, J. Fluid Mech. 403 (2000) 329–349.

[26] S. Burgmann, J. Dannemann, W. Schroder, Time-resolved and volumetric PIV measurements of a transitional separation bubble on an SD7003 airfoil, Exp. Fluids 44 (2008) 609–622.
[27] B.R. McAuliffe, M.I. Yaras, Passive manipulation of separation-bubble transition using surface modifications, J. Fluids Eng. 131 (2009) 021201.
[28] B.R. McAuliffe, M.I. Yaras, Transition mechanisms in separation bubbles under low- and elevated-freestream turbulence, J. Turbomach. 132 (2010) 011004.
[29] F. Satta, D. Simoni, M. Ubaldi, P. Zunino, F. Bertini, Experimental investigation of separation and transition processes on a high- lift low-pressure turbine profile under steady and unsteady inflow at low Reynolds number, J. Therm. Sci. 19 (2010) 26–33.
[30] J. Dahnert, C. Lyko, D. Peitsch, Transition mechanisms in laminar separated flow under simulated low pressure turbine aerofoil conditions, J. Turbomach. 135 (2012) 011007.
[31] Z. Yang, Numerical study of instabilities in separated-reattached flows, Int. J. Comput. Methods Exp. Meas. 1 (2013) 116–131.
[32] J. Serna, B.J. Lazaro, on the laminar region and the initial stages of transition in transitional separation bubbles, Eur. J. Mech. B/Fluids 49 (2015) 171–183.
[33] M. Lang, U. Rist, S. Wagner, Investigations on controlled transition development in a laminar separation bubble by means of LDA and PIV, Exp. Fluids 36 (2004) 43–52.
[34] R.J. Volino, D.G. Bohl, Separated flow transition mechanism and prediction with high and low free stream turbulence under low pressure turbine conditions, in: Proceedings of ASME Turbo ExpoPower for Land, Sea, and Air, Vienna, Austria, Paper No. GT2004-53360, June 14–17, 2004.
[35] S.K. Roberts, M.I. Yaras, Large-eddy simulation of transition in a separation bubble, J. Fluids Eng. 128 (2006) 232–238.
[36] B.R. McAuliffe, M.I. Yaras, Numerical study of instability mechanisms leading to transition in separation bubbles, J. Turbomach. 130 (2008) 1–8.
[37] O. Marxen, M. Lang, U. Rist, Discrete linear local eigenmodes in a separating laminar boundary layer, J. Fluid Mech. 711 (2012) 1–26.
[38] U. Maucher, U. Rist, S. Wagner, Transitional structures in a laminar separation bubble, in: W. Nitsche, H. Heinemann, R. Hilbig (Eds.), New Results in Numerical and Experimental Fluid Mechanics II, Vieweg, 1999, pp. 307–314.
[39] U. Maucher, U. Rist, S. Wagner, Secondary disturbance amplification and transition in laminar separation bubbles, in: H. Fasel, W. Saric (Eds.), Laminar-Turbulent Transition, Springer, Berlin, 2000, pp. 657–662.
[40] O. Marxen, M. Lang, U. Rist, S. Wagner, A combined experimental/numerical study of unsteady phenomena in a laminar separation bubble, Flow Turbul. Combust. 71 (2003) 133–146.
[41] L.E. Jones, R. Sandberg, N.D. Sandham, Direct numerical simulations of forced and unforced separation bubbles on an airfoil at incidence, J. Fluid Mech. 602 (2008) 175–207.
[42] D. Simoni, M. Ubaldi, P. Zunino, Experimental investigation of flow instabilities in a laminar separation bubble, J. Therm. Sci. 23 (2014) 203–214.
[43] S. Lardeau, M. Leschziner, T.A. Zaki, Large eddy simulation of transitional separated flow over a flat plate and a compressor blade, Flow Turbul. Combust. 88 (2012) 19–44.
[44] D.A. Olson, A.W. Katz, A.M. Naguib, M.M. Koochesfahani, D.P. Rizzetta, M.R. Visbal, On the challenges in experimental characterization of flow separation over airfoils at low Reynolds number, Exp. Fluids 54 (2013) 1470–1480.
[45] D. Lengani, D. Simoni, Recognition of coherent structures in the boundary layer of a low-pressure-turbine blade for different freestream turbulence intensity levels, Int. J. Heat Fluid Flow 54 (2015) 1–13.
[46] D. Simoni, D. Lengani, M. Ubaldi, P. Zunino, M. Dellacasagrande, Inspection of the dynamic properties of laminar separation bubbles: free-stream turbulence intensity effects for different Reynolds numbers, Exp. Fluids 58 (2017) (66-1-14).
[47] M.S. Istvan, S. Yarusevych, Effects of free-stream turbulence intensity on transition in a laminar separation bubble formed over an airfoil, Exp. Fluids 59 (2018) (52-1-21).
[48] C. Haggmark, Investigations of disturbances developing in a laminar separation bubble flow (Ph.D. thesis), Royal Institute of Technology, Stockholm, 1987.
[49] H. Li, Z. Yang, Numerical study of separated boundary layer transition under pressure gradient, in: Proceedings of the 12th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, Malaga, Spain, July 2016, pp. 1759–1764.
[50] T.A. Zaki, J.G. Wissink, W. Rodi, P.A. Durbin, Direct numerical simulations of transition in a compressor cascade: the influence of free-stream turbulence, J. Fluid Mech. 665 (2010) 57–98.
[51] Y. Dong, N.A. Cumpsty, Compressor blade boundary layer, part 2: measurements with incident wakes, J. Turbomach. 112 (1990) 231–241.
[52] J.G. Wissink, DNS of separating, low Reynolds number flow in a turbine cascade with incoming wakes, Int. J. Heat Fluid Flow 24 (2003) 626–635.
[53] A. Palikaras, K. Yakinthos, A. Goulas, Transition on a flat plate with a semi-circular leading edge under uniform and positive shear free-stream flow, Int. J. Heat Fluid Flow 23 (2002) 455–470.
[54] E. Lamballais, J. Silvestrini, S. Laizet, Direct numerical simulation of flow separation behind a rounded leading edge: study of curvature effects, Int. J. Heat Fluid Flow 31 (2010) 295–306.
[55] Z. Yang, A comparative study of separated boundary layer transition on a flat plate with a blunt/semi-circular leading edge, in: Proceedings of the 2nd International Conference on Fluid Mechanics, Heat & Mass Transfer, Corfu Island, Greece, July, 2011, pp. 191–195.
[56] Z. Yang, Numerical study of transition process in a separated boundary layer on a flat plate with two different leading edges, WSEAS Trans. Appl. Theor. Mech. 7 (2012) 49–58.
[57] E. Malkiel, R.E. Mayle, Transition in a separation bubble, J. Turbomach. 118 (1996) 752–759.
[58] Z. Yang, P.R. Voke, On early stage instability of separated boundary layer transition, in: C. Dopazo (Ed.), Advances in Turbulence VIII., CIMNE, Spain, 2000, pp. 145–148.
[59] Z. Yang, P.R. Voke, Large-eddy simulation of boundary layer separation and transition at a change of surface curvature, J. Fluid Mech. 439 (2001) 305–333.
[60] Z. Yang, Large-scale structures at various stages of separated boundary layer transition, Int. J. Numer. Methods Fluids 40 (2002) 723–733.
[61] I.E. Abdalla, Z. Yang, Numerical study of the instability mechanism in transitional separating-reattaching flow, Int. J. Heat Fluid Flow 25 (2004) 593–605.
[62] I.E. Abdalla, Z. Yang, Numerical study of a separated-reattached flow on a blunt plate, AIAA J. 43 (2005) 2465–2474.

[63] I.E. Abdalla, M.J. Cook, Z. Yang, Numerical study of transitional separated-reattached flow over surface-mounted obstacles using large-eddy simulation, Int. J. Numer. Methods Fluids 54 (2007) 175–206.
[64] I.E. Abdalla, Z. Yang, M.J. Cook, Computational analysis and flow structure of a transitional separated-reattached flow over a surface mounted obstacle and a forward-facing step, Int. J. Comput. Fluid Dyn. 23 (2009) 25–57.
[65] H. Gu, J. Yang, M. Liu, Study on the instability in separating-reattaching flow over a surface-mounted rib, Int. J. Comput. Fluid Dyn. 31 (2017) 109–121.
[66] Z. Vlahostergios, K. Yakinthos, A. Goulas, Experience gained using second-moment closure modeling for transitional flows due to boundary layer separation, Flow Turbul. Combust. 79 (2007) 361–387.
[67] Z. Yang, I.E. Abdalla, Effects of free-stream turbulence on large-scale coherent structures of separated boundary layer transition, Int. J. Numer. Methods Fluids 49 (2005) 331–348.
[68] Z. Yang, I.E. Abdalla, Effects of free-stream turbulence on a transitional separated-reattached flow over a flat plate with a sharp leading edge, Int. J. Heat Fluid Flow 30 (2009) 1026–1035.
[69] M. langari, Z. Yang, Numerical study of the primary instability in a separated boundary layer transition under elevated free-stream turbulence, Phys. Fluids 25 (2013) 074106.