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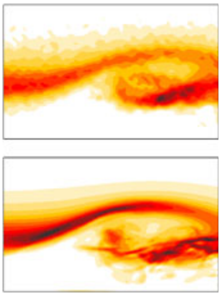
Instabilities in laminar separation bubbles



J.-C. Robinet[†]

DynFluid Laboratory, Arts et Métiers ParisTech, 151 Boulevard de l'Hôpital,
75013 Paris, France

Wall-bounded flows, in their transition from a laminar state to turbulence, pass through a set of particular stages characterized by different physical processes. Among wall-bounded flows, separated flows have a special place because their dynamics can either be noise amplifiers or oscillators. For several years Marxen and co-workers have been studying the evolution of two- and three-dimensional perturbations in the laminar part of a laminar separation bubble. In Marxen *et al.* (*J. Fluid Mech.*, vol. 728, 2013, p. 58) they study vortex formation and its evolution in laminar–turbulent transition in a forced separation bubble. By the combined use of numerical and experimental methods, different mechanisms of secondary instabilities have been highlighted: elliptic instability of vortex cores and hyperbolic instability responsible for three-dimensionality in the braid region. This work shows, for the first time in laminar separation bubbles, the first nonlinear stages of transition to turbulence of such a flow. However, since this type of flow is very sensitive to various environmental stresses, several scenarios for transition to turbulence remain to be explored.

Key words: boundary layer separation, nonlinear instability, vortex shedding

1. Introduction

Laminar separation bubbles (LSBs) can occur when a laminar boundary layer is subject to a sufficiently strong adverse pressure gradient and detaches from the wall. These are instances of so-called pressure-gradient-induced separation, to be contrasted with 'geometry-induced' separation, which is separation over a sharp corner. LSBs can be classified into two distinct families: short and long bubbles (Tani 1964). The bubble is said to be 'short' when the bubble length is of the order of $10^2\delta_s$–$10^3\delta_s$, where δ_s is the displacement thickness at separation, and the bubble is 'long' when its length is of order $10^4\delta_s$. A detailed classification of the different properties of these two types of separation bubble is given in Marxen & Henningson (2011). In some settings, a small change in governing parameter results in a significant modification to the topological and physical properties of separation bubble. A short laminar separation

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[†] Email address for correspondence: Jean-Christophe.Robinet@ensam.eu

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bubble becomes much longer because of the effect of mean flow deformation (Marxen & Rist 2010) and nonlinear pressure feedback, and becomes a long bubble. This phenomenon has been referred to as the ‘bursting’ of the bubble. Parameters governing bursting were initially identified by Gaster (1969).

In LSBs the separated shear layer becomes unstable due to the presence of an inflection point, and in such flow, laminar–turbulent transition usually occurs in the detached shear layer. Near the separation point, LSBs have both viscous Tollmien–Schlichting and inviscid Kelvin–Helmholtz characteristics, but downstream of the separation point, the dynamics are strongly dominated by the inflectional nature of the flow. Although the convective primary instability is initially two-dimensional and initiates the formation of large vortices in a laminar separation bubble, these vortices are rapidly distorted in the spanwise direction and quickly disintegrate downstream into small-scale turbulence. Several hypotheses have been advanced to explain this phenomenon. Early explanations addressed the free shear layer. During the process of primary vortex formation, consecutive spanwise vortices are connected by thin filaments of vorticity called braids, and the combination of several secondary instability mechanisms destabilizes the flow again, which becomes three-dimensional and quickly breaks up into small-scale vortices before a turbulent reattachment boundary layer develops. Until now, the physical nature of the secondary instability mechanisms for an LSB has been unclear. However, the numerical studies of Mashayek & Peltier (2012) for stratified free shear layers have provided some promising leads showing that a shear layer can be the seat of a combination of several secondary instabilities associated with vortex cores or braid regions. Marxen *et al.* explore this avenue in the case of short laminar separation bubbles.

2. Overview

From a combined numerical/experimental investigation of laminar separation bubbles, Marxen, Lang & Rist (2013) have analysed the three-dimensional nature of the vortex formation and breakup process. The configuration considered here is pressure-induced laminar separation on a semi-infinite flat plate, where the LSB is generated by an adverse pressure gradient via the streamwise velocity u or a displacement body at the upper boundary in numerical simulations and experiments, respectively. Here, the LSB can be classified as a short bubble (see figure 1). The study is restricted to the case of a forced LSB in which the vortex forms as a result of a convective shear-layer instability of a two-dimensional wave. Disturbances are triggered via blowing/suction at the wall, which has been specifically adapted to match the experimentally observed forcing. Modes $(1, 0)$ and $(1, \pm 1)$ are forced here. The notation (h, k) is used to specify modes, with h and k denoting frequency or spanwise wavenumber coefficients, respectively. Downstream from the disturbance location, a nonlinear interaction of the primary disturbances $(1, \pm 1)$ rapidly generates a streamwise vortex system $(0, 2)$. At the beginning of the vortex formation region, the fundamental mode $(1, 0)$ is the largest instability and plays a central role in initiating the vortex process, and is responsible for the reattachment of the flow in the mean. At this stage, the flow is mainly two-dimensional and slightly modulated in the spanwise direction. The next step in the dynamics is characterized, firstly, by the nonlinear interaction between the modes $(1, 0)$ and $(0, 2)$, generating modes $(1, \pm 2)$, and secondly by the existence of a secondary instability of the primary mode, further enhancing modes $(1, \pm 2)$. This instability is active in the vortex formation region. The secondary instability occurs both for the fundamental mode $(1, \pm 1)$

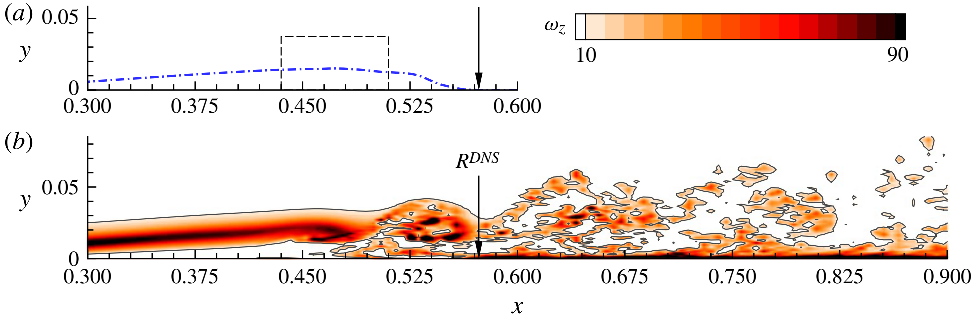

FIGURE 1. Contours of the instantaneous spanwise averaged spanwise vorticity $\overline{\omega}_z$ from direct numerical simulation (*b*) together with mean dividing streamline $\overline{\psi} = 0$ (-·-, *a*). The vortex formation region studied is marked by the dashed box in (*a*).

and also for the (unforced) subharmonic mode $(1/2, \pm 1)$. The vortex is elliptically deformed by a strain field and is subject to so-called elliptic instability, resulting in the deformation of the vortex core, along the vortex axis. In the braid region, an 'hyperbolic' instability cycle is identified where the perturbation resulting in the formation of intense longitudinal vorticity is intensified. Three-dimensional small-scale vorticity is created: for example, the mode $(1, \pm 4)$ is very active in the braid region, followed by high-frequency modes $(2, 0)$ and $(2, \pm 2)$ when the fundamental modes saturate. The box in figure 2(*b*) can be regarded as the active zone for the elliptic instability and the arrow in figure 2(*d*) marks the active zone for the hyperbolic instability. All these mechanisms generate significant three-dimensional effects in the flow and the dislocation of large vortex structures to small-scale vortices. Finally, the flow becomes turbulent, the resulting turbulent shear layer eventually reattaches downstream, and thus a closed bubble is formed.

3. Future research

Many questions, however, remain unanswered. The receptivity of a separated boundary layer is highly dependent on parameters such as the Reynolds or Mach numbers. For example, is the knowledge gained still valid for other flow regimes? Moreover, these flows, generally highly selective noise amplifiers, have dynamics largely driven by different upstream or environmental forcing. The sensitivity of these flows remains unclear (Alizard, Cherubini & Robinet 2009). Under certain configurations laminar separation bubbles may be the seat of self-sustained low-frequency oscillations, referred to as flapping. The physical origin of this flapping is unclear. Several scenarios are possible. Cherubini, Robinet & De Palma (2010) have shown that when an LSB is large enough the modes associated with the shear layer can interact non-normally and nonlinearly to generate self-sustained low-frequency oscillations. Other scenarios are possible, for instance synchronization of flow through a hydrodynamic and/or pressure feedback mechanism (such as the Rossiter mechanism, observed in open cavities) can force the flow at low frequency and enhance a collective interaction mechanism. Moreover, in an LSB where curvature effects are important, convective or global instabilities, both related to centrifugal mechanisms, are also possible. Although we are beginning to understand the bursting (Marxen & Henningson 2011), it is necessary to continue the investigation. The dynamics of a long laminar separation bubble is much less well understood. From the dynamics point

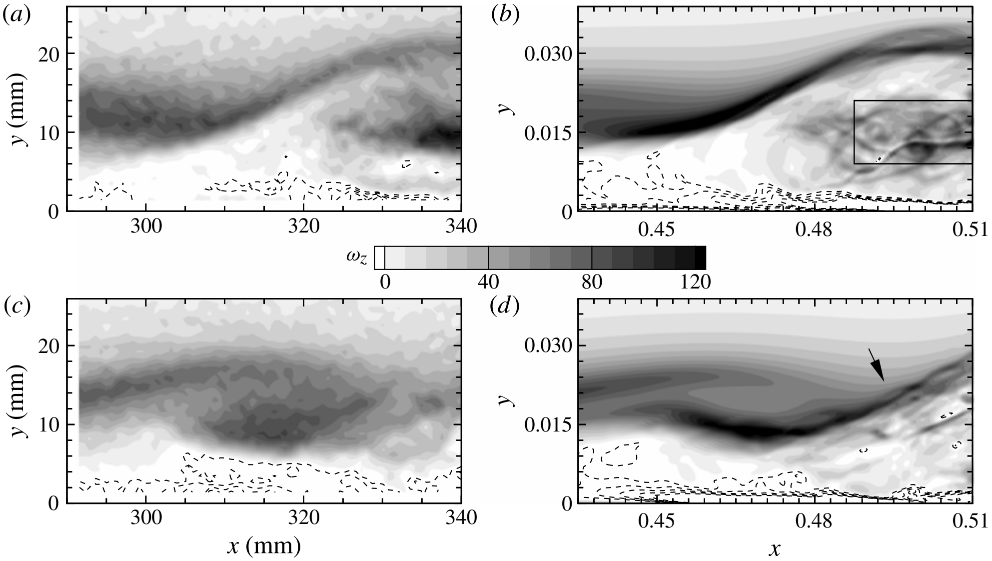

FIGURE 2. Contours (levels: $\overline{\omega}_z = 40 \ldots 120$, $\Delta = 8$) of the spanwise vorticity at $z = 0$ for (*a,b*) $t/T_0 = 0$ and (*c,d*) $t/T_0 = 0.4$. Comparison of phase-averaged ($T_{aver} > 20T_0$) results from (*a,c*) particle image velocimetry and (*b,d*) direct numerical simulation. Negative contours given as dashed lines only.

of view, what is happening in a fully turbulent separation bubble (TSB)? It is likely that the TSB also develop instabilities resulting in coherent structures. However, the physical mechanisms at work in these flows are much less well known. For example, a TSB may have self-sustained low-frequency oscillations. Are the mechanisms at work comparable to those observed in an LSB? What is the influence of upstream turbulence on the dynamics of the bubble? In the future it will be necessary to provide some answers to all these questions.

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