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Local structure of boundary layer transition in experiments with a single streamwise vortex

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ABSTRACT

Transition induced by an isolated streamwise vortex embedded in a flat plate boundary layer was studied experimentally. The vortex was created by a gentle hill with a Gaussian profile that spanned on half of the width of a flat plate mounted in a low turbulence wind tunnel. PIV and hot-wire anemometry data were taken. Transition occurs as a non-inclined shear layer breaks up into a sequence of vortices, close to the boundary layer edge. The passing frequency of these vortices scales with square of the freestream velocity, similar to that in single-roughness induced transition. Quadrant analysis of streamwise and wall-normal velocity fluctuations show large ejection events in the outer layer.

1. Introduction

Streamwise vortices near the wall are a common feature in many observations of boundary layer transition. A streamwise vortex will cause fluid to be carried closer to the wall and away from it so that the boundary layer flow is distorted into alternate high-speed and low-speed streaks, respectively. There have been many theoretical, fully numerical and experimental studies of transition beginning from embedded streamwise vortices, or streaks, or together. Several of the later studies have identified streak instability as a late stage, and have examined several aspects. A broad division into transition due to freestream turbulence (FST), surface roughness and surface excitation like blowing/-suction for fast or bypass transition can be considered.

A recent view of boundary layer transition induced by FST is that the origin is from low frequency modes that penetrate the boundary layer, forming elongated high-speed and low-speed streamwise streaks. Subsequently, these low-speed streaks rise towards the edge of the boundary layer where they break-up on interacting with high frequency freestream disturbances, and develop into turbulent spots [13,37,18]. The presence and development of streaks in boundary layer transition had been the subject of earlier studies also [14,31], for example.

Another view, following from a different set of studies, is that streaks acquire sinuous or varicose modulations from instabilities of their spanwise or wall-normal, inflectional profiles, respectively. Such waviness of streaks has been observed in the experiments of Asai et al. [3], Matsubara and Alfredsson [24], Mans et al. [22], and in the simulations of Schlatter et al. [7]. After examining these two views, Zaki and Durbin [32] concluded that such secondary instability of streaks is a precursor to spot formation, common to both sets of studies, and attributed the description in Zaki and Durbin [37] to have followed from two-dimensional visualizations. In both sets of studies, a low-speed streak moves away from the wall and starts oscillating before shedding vortices near the boundary layer edge, leading to flow randomization in the late stages of transition.

Streak instability can come about in different ways. Liu et al. [18] found that Tollmien–Schlichting waves can cause streaks to break down. Brandt and de Lange [6] set up a high-speed streak to follow a low-speed streak in a boundary layer simulation and found that the direct collision initiated streak breakdown. When the high-speed streak was offset spanwise, it would slide alongside and initiate breakdown. No additional forcing (such as freestream eddies) by FST was needed. Nolan and Walsh [26] found that such streak interactions were naturally set up due to FST (levels were between 2% and 4.2%), and noted their subsequent evolution into spots. Though the high levels were needed for streaks to form, the breakdown was not correlated to FST. So additional forcing was not needed, in agreement with Brandt and de Lange [6]. In this natural flow they also found the direct collision (symmetric case) to be the more common situation.

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Nomenclature

a	hill width parameter, mm
c	hill width (chord), mm
f	frequency, Hz
R_{uu}	correlation function of fluctuating streamwise velocity
R_{vv}	correlation function of fluctuating wall-normal velocity
U_0	freestream velocity, m/s
U	mean streamwise velocity component, m/s
V	mean wall-normal velocity component, m/s
W	mean spanwise velocity component, m/s
U_c	phase velocity, m/s
u	instantaneous streamwise velocity component, m/s
v	instantaneous wall-normal velocity component, m/s
w	instantaneous spanwise velocity component, m/s
u'	fluctuating streamwise velocity component, m/s
v'	fluctuating wall-normal velocity component, m/s
w'	fluctuating spanwise velocity component, m/s
u_{rms}	root-mean-square of streamwise velocity fluctuations, m/s
v_{rms}	root-mean-square of wall-normal velocity fluctuations, m/s
w_{rms}	root-mean-square of spanwise velocity fluctuations, m/s
x	streamwise coordinate, mm
y	wall-normal coordinate, mm
z	spanwise coordinate, mm
x_0	streamwise distance from plate leading edge to middle of the hill, mm
δ	boundary layer thickness, mm
δ^*	displacement thickness, mm
δ_0	δ at x_0, mm
Ω_z	instantaneous spanwise vorticity, m^2/s
Re	Reynolds number

Another by-pass route is that due to surface roughness. Small protrusions are often present in practice, unavoidably or by design, and it is useful to understand their effect on transition, especially for design. Counter-rotating streamwise vortices appear immediately downstream of surface roughness elements, wrapped around them and sometimes shedding from them, depending on the shape [1,38]. Unsteady vortex shedding can also occur from a high shear layer (a shear layer in the upper part of the boundary layer) formed in the wake of the roughness element itself [15]. Effects of an array of cylindrical roughness elements on transition were clarified by an experiment [10] and its simulation [30]. Ergin and White [10] observed fluctuations at the flanks of low-speed streaks which had formed in the wake of the roughness elements. These fluctuations spread across the streak. The simulation showed streamwise vorticity at the spanwise edge of the wake (lowspeed streak) immediately downstream of the roughness element. It was absent for a short distance downstream and then reappeared (see Fig. 27 in Rizzetta and Visbal [30])—the transient growth sequence discussed in Schlatter et al. [32]. Optimal perturbations for transient growth are streamwise vortices which themselves decay while they inducing the growth of streaks. Then, wall-normal vorticity at the flanks of streaks tilt to become quasi-streamwise vortices. The importance of receptivity to the transient growth process has been highlighted by Denissen and White [9] who found that the sub-optimal streaks produced by surface roughness can undergo transition faster than the optimal streaks. In other experiments [11], though the streaks formed initially are not optimal, they evolve towards optimality downstream.

Though not necessary, it is reasonable to expect the late stages of transition to have common features. One way to determine this is to examine each type of flow, say FST-induced or roughness-induced transition, and identify commonalities. Here we take a different approach: noting that streamwise vortices have been described in, perhaps, all reports of boundary layer transition, natural and by-pass, we employed a configuration that gives rise to a single, steady streamwise vortex, embedded in a subcritical flat plate boundary layer. Measurements of the downstream development effected by the presence of this vortex were taken to determine commonalities. Transition, when it occurs, is not due to FST, since turbulence levels were quite low, or due to typical roughness elements that generate pairs of streamwise vortices, which may also shed from the element. The configuration provides a steady streamwise vortex, which undergoes instability, becomes unsteady and then breaks down. We examined flow structure, frequencies in the transition region, and Reynolds stress events.

The experimental configuration to set up the single streamwise vortex is due to Hamilton and Abernathy [12]. They had created isolated streamwise vortices by the side of a half-span hill mounted on a water table. The hill height was less than the upstream water depth. Their primary result was that inflectional profiles were not sufficient for transition. It was an important demonstration because, in prior studies with flows that underwent transition, inflections in upstream profiles were supposed to have provoked the transition. Recently, this work was extended to flat plate boundary layers [23]. There are no other studies with isolated streamwise vortices. Asai et al. [3] created an embedded, single streak but then forced it with blowing and suction through ports, thereby introducing streamwise vortices as well.

Here we present analyses of the transition process for the steep hill case (mean slope of 1:10) from Manu et al. [23]. Transition occurred only when the freestream velocity exceeded a threshold, even though, in every case, the streamwise vortices made the boundary layer velocity profiles inflectional. Our analyses show that there are some similarities with the roughness -induced-transition studied by Klebanoff et al. [15] such as the breakup of a shear layer near the outer edge of the boundary layer into successive vortices, and the scaling of the vortex passing frequency with square of the free-stream speed. There are also important differences in frequency scaling, Reynolds stress and ejection/sweep events obtained by quadrant analyses.

2. Description of experiments

The experiments were carried out in an open-circuit, low-speed wind tunnel with a square test section of size 500 mm × 500 mm × 3000 mm. The settling chamber ahead of the 14:1 contraction had a smooth entry section with honeycomb and screens (4 screens; 8 mesh wires/cm). The short diffuser was isolated from the rest of the tunnel by a flexible rubber band to minimize the transmission of vibrations to the test section. A speed controller regulated a 5 KW DC motor, which drove the fan at the diffuser end. The maximum tunnel speed was 22 m/s, and the free-stream turbulence level was about 0.1% for air speed below 15 m/s. The test section had a divergence of about 1/487 over 3 m on both side walls to correct for the sidewall boundary layer growth. A flat plate that was placed horizontally in the mid-plane of the test section had a super-ellipse-shaped leading edge. Many constant pressure experiments have been performed in this facility, and flow uniformity measurements have been reported before [4].