TRANSITION EXPERIMENTS WITH STREAMWISE VORTICES IN SUBCRITICAL BOUNDARY LAYERS

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ABSTRACT

Experiments were conducted by affixing smooth hills, with a short gap, on a flat plate mounted in a low turbulence tunnel. Configurations with three gap-widths of the order of the hill height (also of the order of the incoming boundary layer) and a range of freestream speeds were examined. PIV and hotwire data were obtained. At the hill location the Reynolds number was always subcritical. Flow past the hill develops streamwise vorticity that develops into a pair of streamwise vortices with the common flow between them directed away from the plate. At low freestream speeds of about 2 m/s, the lift-up action of these vortices creates inflectional profiles but there is no transition. Above a threshold speed, which increases with gap width, transition was observed. Between the streamwise vortices a low speed streak forms, flow separates and then reattaches. A reverse flow index shows unsteady reattachment over an extended region and the concomitant rise in velocity fluctuations. A high shear layer appears, which then rolls up. The unsteady reattachment is in this roll-up region. There are similarities with recent studies of transition induced by freestream turbulence. Present results indicate the common feature of late stages of transition due to freestream turbulence or wall protrusions to be streak breakdown.

INTRODUCTION

Recent experiments, physical and numerical, have improved our understanding of the late stages of boundary layer transition. The late stages are marked by three-dimensionality, the presence of streamwise vortices, streaks, sinuous and varicose oscillations, and the appearance of spots leading to a complete breakdown. The late stages have similar sets of traits even though the origins are as varied as the slow, linear Tollmein-Schlicting instability of a weakly perturbed, boundary layer, to the rapid breakdown induced by freestream turbulence or protrusions on the wall. So, one class of studies have been of the ways in which these different origins eventually lead to transition. Our studies are of the later stage, of the developments that follow once streamwise vortices are present in the boundary layer. These are not studies of instabilities of a flat plate boundary layer, but of the late stages where the boundary layer has already become altered by the presence of streamwise vortices even though the associated cross flow velocities are quite small.

In our first study, isolated, streamwise vortices were created in a boundary layer by mounting a smooth hill over one-half the span of a flat plate mounted in a low-turbulence tunnel (Manu *et al.* (2009, 2010)). The arrangement had been used earlier by Hamilton & Abernathy (1994) to examine transition in a water table flow. Two types of hills were used: a steep profile 3 mm high, 30 mm wide, and a shallow profile 1.5mm high and 50 mm wide. Tunnel freestream speed ranged from 3.5 m/s to 7.5 m/s. Hills were mounted at subcritical locations where the Reynolds number based on momentum thickness was no more than 245, and hill heights were always less than the thickness of the undisturbed boundary layer. It was found that flow underwent transition only when the freestream speed was above a threshold. At lower speeds, a single streamwise vortex formed, wall-normal and spanwise velocity profiles became inflectional, the lift-up action of the streamwise vortices created streaks, but the perturbations decayed downstream rather than effect transition. At the higher speeds transition was observed, but the routes were different for the steep and shallow hills. With the shallow hill, the flow disturbed by the single vortex broke down continuously: hotwire signals were irregular a short distance downstream, and the level of the fluctuations continued to grow. With the steep hill, the signal showed a regular, near periodic fluctuation whose amplitude continued to grow for some distance downstream before becoming irregular. Fourier transform showed a strong peak, sidebands, and a harmonic. We concluded that the streamwise vortex formed by the steep hill was located away from the wall and underwent an oscillatory instability before breakdown; with the shallow hill the vortex was closer to the wall and broke down sooner. Thus we postulated the wall interaction of the streamwise vortex as a last stage of transition. The oscillations of the steep-hill vortex was a pre-cursor that lasted until this vortex came close enough to the wall for some interaction that results in breakdown. The present study with vortex pairs was conceived as a search for a possible wall-interaction, as an essential, last stage that commits the flow to transition.

EXPERIMENTS

Hills were mounted on a flat plate in two, symmetrical ways to get a pair of counter-rotating vortices. Figure 1 shows a short-span hill and a short-gap hill. At the flat edges of the hills, streamwise vorticity forms as the spanwise vorticity in the incoming boundary layer is tilted, and also from the wall due to spanwise pressure gradients. These mechanisms by which streamwise vorticity is generated by the edge of the hill has been discussed in detail before (Manu *et al.* (2010)). Hills have a smooth Gaussian profile, and flow does not separate or shed, either upstream or downstream. Although the streamwise vorticity generated is positive and negative in different parts of the vicinity of the hill, a single vortex of about the size of the hill height is observed downstream of the hill edge. Downstream of the short-span hill, the common flow between the counter-rotating vortices is directed towards from the wall. Similarly, the common flow is away the wall beyond the short-gap hill. A simulation of the vicinity of the hill using a commercially available code (FLUENT) shows the streamwise vortex pair (Fig. 2).

Experiments were conducted for three values of hill-span or gap b of 2, 4 and 8 mm, termed small, medium and large, with the steep profile ($h = 3$ mm, width $c = 30$ mm), at freestream speeds U_0 of 1.8, 2.5, 3 and 3.5 m/s. The hills were mounted with their midplanes at 175 mm from the plate leading edge where the Reynolds number based on boundary layer thickness was only 346 at the highest speed. In all conditions, the short-span hill produced a pair of counter-rotating streamwise vortices with a common flow between them that was directed towards the plate. The action of these vortices is to bring higher speed fluid closer to the wall giving rise to fuller profiles. Overall, this stabilizing effect dominated, even though vortices would have lifted up fluid on the outside, so that transition was not observed even as far downstream as 500 mm of the short-span hill. So this configuration was not considered any further.

RESULTS

Transition was observed for all three gap widths for the short-gap configuration. The conditions in all the experiments are in Table 1. With $b = 2$ mm, transition was observed at all speeds considered ($U_0 > 1.8$); with $b = 4$ and 8 mm, transition was observed at 3.5 m/s only. These are all transitions at lower freestream speeds than that needed for the single vortex situation. Peak fluctuation levels, $u_{rms,max}$ are about 15 to 19% (see Fig. 8), which are higher than those for isolated vortices but are comparable to those in the simulations of streak instability (Brandt & Henningson (2002)). These peaks are attained within a distance c to $2c$ downstream of the hill for the small gap and by $4c$ for the large gap. In every case when transition occurred, a low speed streak formed downstream of the gap where the action of the vortex pair lifted up the fluid. There is no separation or shedding from the hill itself. Also, as had been observed before with the single vortex, both transitional and non-transitional flows exhibit inflectional profiles. So the ensuing transition is not due to the formation of inflection points.

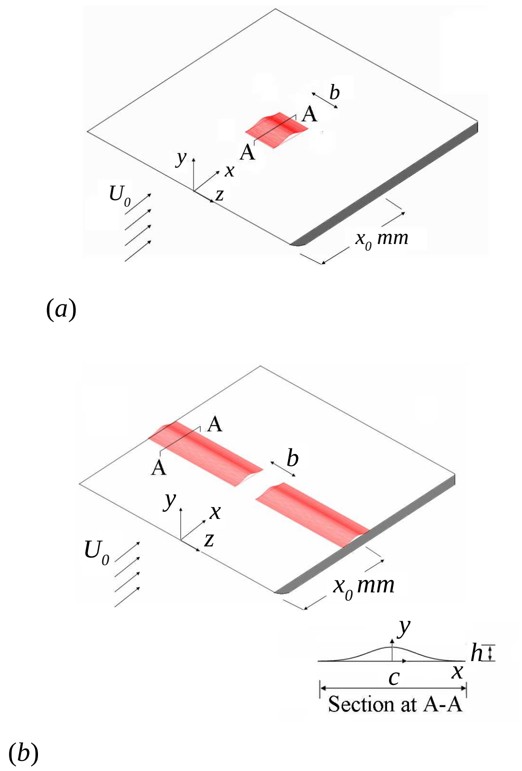


Figure 1. (*a*): Short-span and (*b*): short-gap hills.

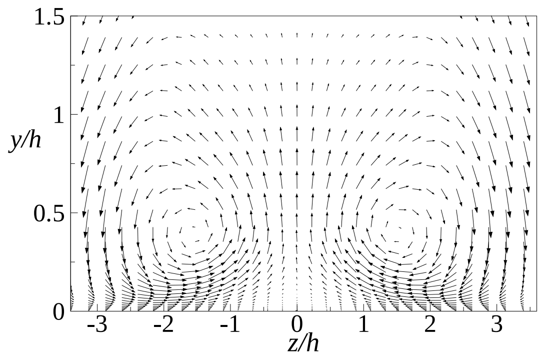


Figure 2. Crossflow vectors from a simulation with a short-gap hill. $U_0 = 3.5$ m/s, $b = 4$, $(x - x_0)/((c/2) = 1.5$.

Figure 3 shows the development of the wall-normal profiles at three stations along the mid-span for a non-transitional case. Although the flow separates, and the profile is inflectional, there is just a slow relaxation and no transition. Figure 4 shows two transitional cases with the smallest gap at a low and a high freestream speed. Flow separation (reverse flow) can be seen in the PIV data on a wall parallel plane in Fig. 5. Growth of fluctuations along two wedges can be seen in Fig. 6.

The present study was to determine what wall interactions may precede final breakdown. With the small gap, steady separation from the plate was observed just downstream of the hill (profile at $(x - x_0)/(c/2) = 2$ in Fig. 4(*a*)); further downstream, unsteady separation bubbles were present, but this is not evident in the mean velocity profiles. The profiles at $(x - x_0)/(c/2) = 9$ in Fig. 4 sug-

Table 1. Conditions in short-gap hill experiments. State of flow: T-transitional, NT-non-transitional

Case	b mm	U_0 m/s	h/δ_0	Re_{δ_0}	State of flow
SG0	2	1.8	0.5	248	T
SG1	2	2.5	0.58	292	T
SG2	2	3	0.63	320	T
SG3	2	3.5	0.69	346	T
MG0	4	1.8	0.5	248	NT
MG1	4	2.5	0.58	292	NT
MG2	4	3	0.63	320	NT
MG3	4	3.5	0.69	346	T
LG0	8	1.8	0.5	248	NT
LG1	8	2.5	0.58	292	NT
LG2	8	3	0.63	320	NT
LG3	8	3.5	0.69	346	T

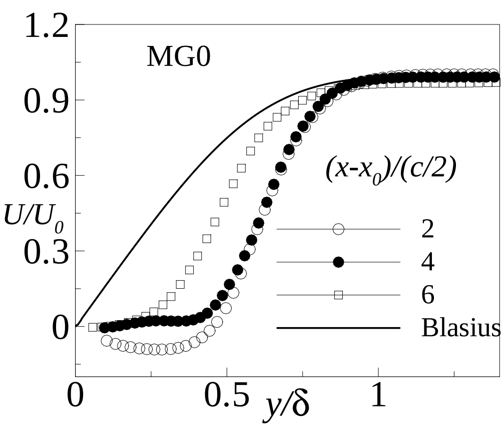
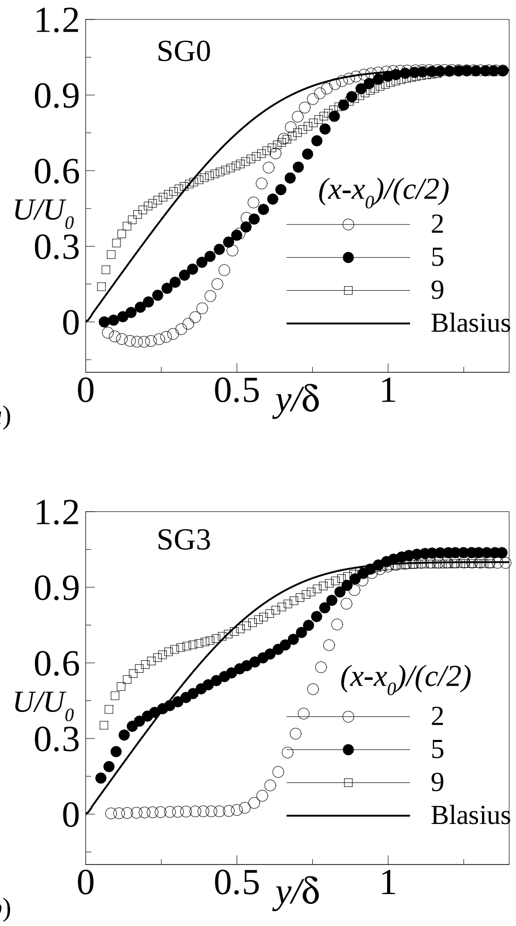


Figure 3. Wall-normal profiles of streamwise velocity for the non-transitional case MG0

gest attached flows, but there is intermittent reverse flow. To understand such situations better, a separation index, or reverse flow index, was used to determine the fraction of time that reverse flow exists at a location in the PIV data. For measurements in a longitudinal plane (z, constant), this index was defined as $S(x,y) = \sum_i s(x,y,i)/N$ where

$$s(x,y,i) = \begin{cases} 1, & (u(x,y,i) < 0) \\ 0, & (u(x,y,i) \geq 0) \end{cases},$$

and N is the number total of PIV frames. $S(x,y)$ is zero where flow is always attached, and takes on values between 0 and 1 where there is reverse flow some of the time. Fig-



(a)

(b)

Figure 4. Wall-normal profiles of streamwise velocity for transitional cases SG0 & SG3.

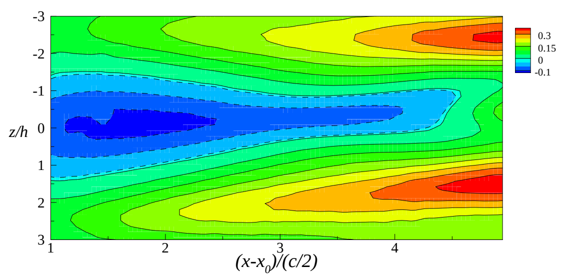


Figure 5. Contours of mean streamwise velocity component U/U_0 on $y = 0.67h$ for case SG0.

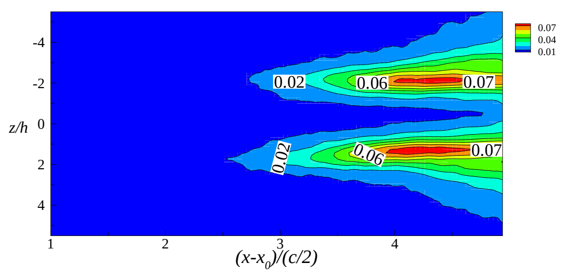


Figure 6. Rms of streamwise velocity component fluctuations on $y = 0.67h$ for case SG0.

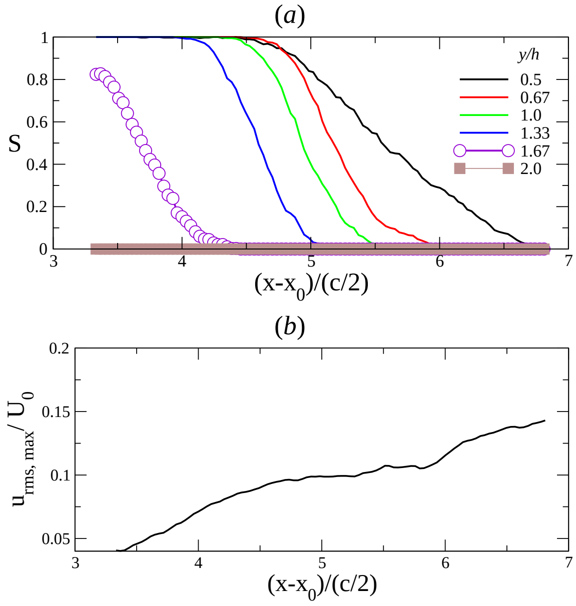


Figure 7. Separation index (*a*), and fluctuations (*b*), for short-gap hill at freestream speed $U_0 = 1.8$ m/s.

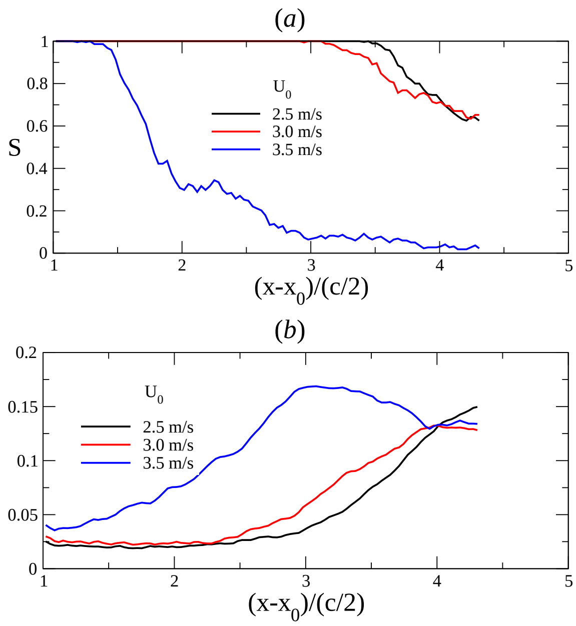


Figure 8. As in Fig. 7 at higher speeds $U_0 = 2.5$, 3.0, 3.5 m/s (cases SG1, SG2, SG3).

ure 7(*a*) shows the variation of S along lines at a fixed distance y from the wall, $z = 0$, at $U_0 = 1.8$ m/s (Case SG0). Figure 7(*b*) shows the corresponding growth of fluctuations. The curves are similar for $0.5 < y/h < 1.33$. All show the extended, unsteady reattachment and the concomitant rise in fluctuations. Figure 8 shows separation index and growth of fluctuations at the higher speeds with the same hill. Note the growth of fluctuations coinciding with unsteady reattachment. With the medium gap hill, the transition moved further downstream. Figure 9 shows the separation to be fairly rapid, and for fluctuation levels to remain very small, both at the onset of separation and over much of the steadily separated region. Again, fluctuation levels grow in the reattachment region.

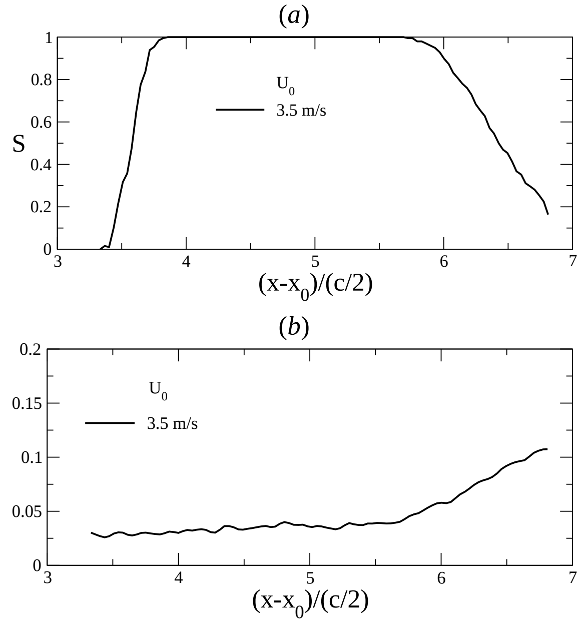


Figure 9. As in Fig. 2, for medium-gap hill at $U_0 = 3.5$ m/s.

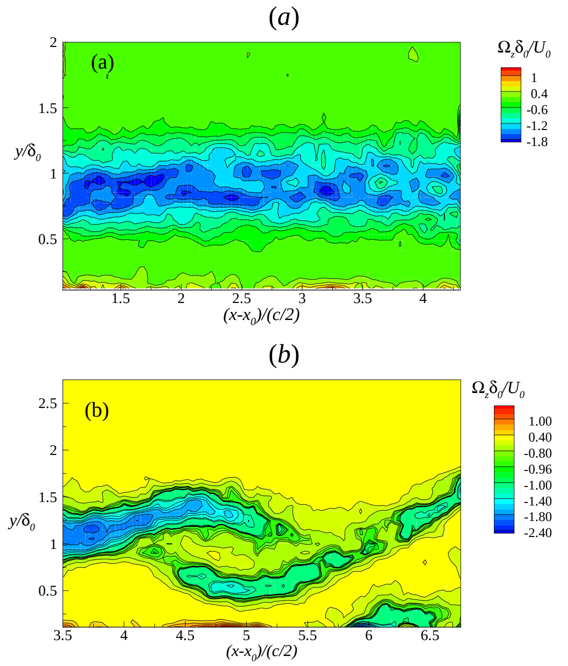


Figure 10. Spanwise vorticity, short-gap hill at $U_0 = 1.8$ m/s.

DISCUSSION AND CONCLUSIONS

The variation of the separation index and the corresponding growth of fluctuations suggest that the last stage of transition is in the reattachment region. Separation has, perhaps, facilitated this stage. Remarkably, there is a close resemblance to the processes detected in simulations of transition due to free-stream turbulence. Durbin & Wu (2007) deduced from their simulations that long wavelength perturbations due to freestream turbulence penetrate the boundary layer, then get lifted up towards the edge of the boundary layer where the breakdown occurs by interacting with short wavelength perturbations from the freestream. In the present situation, the action of the streamwise vortices creates an internal shear layer which lies close to the edge of the boundary layer and undergoes a similar breakdown. Figure 10(*a*) shows the appearance of the internal layer—just a larger value of boundary layer vorticity; not a vortex sheet. Close to the wall there is a layer of spanwise vorticity of the opposite sign. Downstream, the high shear layer rolls up (Fig. 10(*b*)), and the vorticity near the wall is also of the same sign where the reverse flow region has ended. By comparison with Fig. 7 we observe that the growth of fluctuations begins where this roll-up occurs.

The role of wall interaction appears to be no more than that the separation also lifts up an internal shear layer on which the breakdown is initiated. At a lower speed, without separation, no such breakdown follows. Although the continuous-mode-transition mechanism discussed in Durbin & Wu (2007) is facilitated by freestream perturbations that act after a streak has been lifted up to the edge of the boundary layer, a subsequent study showed that a Tollmien-Schlicting wave (stable mode, beyond upper branch) can also destabilize these streaks(Liu *et al.* (2008)). In our study freestream turbulence levels are quite low and there is no unsteady forcing. The cause of the breakdown seems to be roll-up of the high shear layer, which is formed only when the freestream speed exceeds a threshold and in turn effects the strength of the induced streamwise vortices. Roll-up dynamics provides a continuous perturbation and the effect is seen as an extended termination of the reverse flow region.

The transition route examined here, and in our previous study, is induced by streamwise vortices. Such vortices are seen in the late stages of transition, whether induced by freestream disturbances, wall protrusions, or in natural transition. The similarities between the present observations and those of transition induced by freestream turbulence as discussed by Durbin & Wu (2007) and Schlatter *et al.* (2008) suggest that streak breakdown in one form or another is the common process, and not just with freestream turbulence.

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