

Evolution of a Turbulent Wedge from a Streamwise Streak

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Abstract

A narrow streamwise low-speed streak is deliberately introduced into an otherwise extremely uniform Blasius boundary layer. The streak shares many of the characteristics of Klebanoff modes known to be responsible for bypass transition at moderate Free Stream Turbulence (FST) levels. However, for the low background disturbance level of the free stream ($u'/U_1 < 0.05\%$), the layer remains laminar to the end of the test section ($R_x \approx 1.4 \times 10^6$) and there is no evidence of bursting or other phenomena associated with breakdown to turbulence. A harmonic disturbance is used to excite a sinuous form of instability, which grows over a considerable streamwise distance before breakdown of the streak occurs, which leads to the formation of a turbulent wedge. Detailed measurements show that new streaks are formed on either side during the breakdown process. The characteristics of the wedge are examined over a considerable streamwise distance. A similar mechanism appears to be responsible for the spanwise growth of the wedge since a spanwise succession of new streaks is observed in the early stages of its development.

Introduction

The current experiment was motivated by observations during a series of flow quality improvements by Watmuff [6] in which the background unsteadiness, u'/U_1 , in a Blasius boundary layer was reduced by a factor of 30. The effectiveness of the improvements was judged by examining contours of hot-wire data in spanwise planes through the layer. The contours demonstrated a form of three-dimensionality in which locally concentrated regions of elevated background unsteadiness appeared to be correlated with small spanwise variations of the layer thickness. The characteristics of the unsteadiness (e.g. low frequency spectral content) in the concentrated regions were much the same as at other spanwise positions, where the u'/U_1 distribution was more uniform and the Blasius wall distance of the u'/U_1 maxima was $\eta \approx 2.3$. These characteristics have much in common with Klebanoff modes observed by Klebanoff [4], Kendall [2, 3] and Westin et al. [8] at elevated FST levels.

The most significant reductions in u'/U_1 were realised after painstaking improvements were made to the uniformity of the porosity of wind tunnel screens. Watmuff found that even almost immeasurably small Free Stream Nonuniformity (FSN) variations (e.g. $\Delta U/U_1 \approx 0.05\%$) appeared to be associated with local concentrations of elevated unsteadiness. During the final stages, further improvements to the screen system produced only a relatively minor reduction in the FST level, but the additional decrease in the FSN led to a three-fold reduction of u'/U_1 within the layer. The extraordinary sensitivity to weak FSN encouraged Watmuff to develop a means of deliberately embedding a streak with Klebanoff-mode-like characteristics into the boundary layer in order to perform detailed studies in a controlled manner.

Boiko et al. [1] demonstrated that the combination of vibrating ribbon generated Tollmien-Schlichting (TS) waves and grid generated Free Stream Turbulence (FST) leads to transition at lower Reynolds numbers than when the FST is present alone. These results prompted Watmuff [7] to use a vibrating ribbon to examine the interaction between the streak and TS waves. He found that the deformation of the mean flow associated with the streak is responsible for substantial phase and amplitude distortion of the TS waves. He used pseudo-flow visualization of hot-wire data to show that the breakdown of the distorted waves is more complex and that it occurs at a lower Reynolds number than the breakdown of the *K*-type secondary instability that was observed when the FSN is not present.

However, breakdown of the flow was not observed unless the wave amplitude was sufficiently large to reach a level for the onset of secondary instability when the FSN is not present. In this paper the stability of the streak alone is considered.

Introduction of streak into Blasius boundary layer

The base-flow consists of a highly spanwise uniform Blasius boundary layer. The development of the mean flow closely follows the Blasius similarity solution. The background unsteadiness levels are extremely low: in the free-stream, $u'/U_1 < 0.05\%$; and within the layer, $u'/U_1 < 0.08\%$. Vibrating ribbon experiments by Watmuff [7] demonstrate the growth of distortion-free Tollmien-Schlichting waves closely follow predictions from the linearized Parabolized Stability Equations (PSE) provided by Bertolotti [private communication].

A narrow low-speed streak (i.e. region of elevated thickness) is deliberately introduced into the Blasius boundary layer as a result of the interaction of a laminar wake with the leading edge of the flat plate. The wake is generated by stretching a fine wire across the full extent of the test section and it is aligned perpendicular to the freestream and to the leading edge. A range of wire diameters, at varying distances from the leading edge have been used by Watmuff [7] to produce streaks with different properties. For the results in this paper, the wire diameter, $d = 50.8 \mu\text{m}$ and it is located 184 mm upstream of the leading edge.

The wake profile is shown in figure 1(a) at a location 63.5 mm upstream of the leading edge. The measurements were obtained using a flattened total pressure tube which was connected directly to a high accuracy differential pressure transducer and a fixed total pressure tube was used as the reference pressure. The velocity defect compares very well with the theoretical distribution predicted using a linearized theory which is shown as a solid line. The unit Reynolds number for the experiments is $6.68 \times 10^5 \text{ m}^{-1}$ ($U_1 \approx 10 \text{ ms}^{-1}$), giving $R_d = 34$. Streamwise development of the spanwise variation of displacement thickness resulting from interaction of the wake with the leading edge is shown in figure 1(b) for 16 streamwise positions, ranging from $x = 0.3$ to 1.8 m. The results clearly demonstrate the narrow region of elevated thickness, i.e. the low-speed streak.

A rather surprising result is that the shape factor of the layer affected by the streak remains close to the Blasius value, $H=2.59$, despite the large spanwise thickness variation. Another feature that is not shown here, is that regions of elevated background unsteadiness occur on either side of the peak layer thickness, which share many of the characteristics of Klebanoff modes identified by Kendall [2, 3] that are observed at elevated Free Stream Turbulence (FST) levels. However, for the low background disturbance level of the free stream, the layer remains laminar to the end of the test section ($R_x \approx 1.4 \times 10^6$) and there is no evidence of bursting or other phenomena associated with breakdown to turbulence.

The advantage of using a steady free-stream disturbance in the current experiments is that the streak is almost single stationary, which allows its features to be examined in detail using a hot-wire probe, with 0.5 μm diameter and 0.5 mm long filaments.

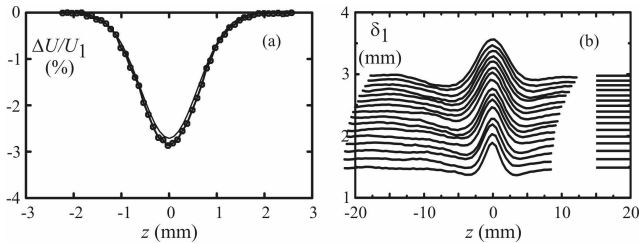


Figure 1. (a) Wake profile 63.5 mm upstream of leading edge. z -coord. relative to wire centreline. (b) Streamwise growth of spanwise variation of displacement thickness, δ_1 . z -coord. relative to the peak δ_1 values. Lines in range $15 < z < 20$ are Blasius values, i.e. $\delta_1 = 1.7208 (\nu x / U_1)^{1/2}$.

Excitation of the streak

It was discovered by experiment that a harmonic disturbance could be used to excite a sinuous form instability in the streak. The source of the disturbance is a 0.5 mm diameter hole in the test surface located beneath the streak at a point $x = 0.38$ m from the leading edge. The response of the streak was found to be remarkably sensitive to the excitation frequency. A nondimensional frequency, $F = 2\pi f \nu / U_1^2 = 185 \times 10^{-6}$ ($f \approx 265$ Hz) was found to introduce the strongest response. This is larger than the frequency corresponding to the Branch II of the neutral stability curve at this location, $f \approx 165$ Hz, so small amplitude disturbances should decay according to linear stability theory.

For small disturbance amplitudes, the magnitude of the instability was found to grow and then decay with streamwise distance. However, for moderate disturbance amplitudes, the streamwise growth of the instability reached a threshold leading to breakdown of the streak. The streamwise distance between the source and the breakdown of the streak is dependent on the magnitude of the disturbance. Selection of the disturbance magnitude for detailed study was a compromise between using smaller amplitudes (to minimize the initial nonlinearity) and larger amplitudes (to limit the distance between the source and the breakdown and minimize phase jitter in the measurements).

When the streak is not present (wire removed from test section), measurements have demonstrated that a low amplitude harmonic disturbance at $F = 60 \times 10^{-6}$ generates a 3D TS wave pattern that closely match the pattern calculated by Mack & Herbert [5] using the Parabolized Stability Equations. Similar measurements have been performed using the larger amplitude disturbance at nondimensional frequency of $F = 185 \times 10^{-6}$, corresponding to the parameters for the streak study, but without the presence of the streak. The results are not shown here, but they demonstrate that the disturbance has larger amplitude and is of a more complex form than the 3D Ts wave pattern of Mack & Herbert. However, the disturbance remains confined in the spanwise direction. The magnitude of the disturbance, $u''/U_1 \approx 3\%$, but the amplitude

decays with streamwise distance. When the streak is excited by the harmonic disturbance the phase-averaged velocity fluctuations reach an amplitude of $u''/U_1 \approx \pm 25\%$ at the point of breakdown, given by $x=0.63$ m, i.e. about 0.25 m from the source of the disturbance.

Form and growth, and breakdown of streak instability

Detailed 64-interval phase-averaged measurements have been made with a single hot-wire to investigate the spatial form of the streak instability during the growth period and the final breakdown process. Contours of the total phase-averaged streamwise velocity, $\bar{U} + u_\phi$, in two cross-stream planes are shown in figure 2(a-b). Spanwise meandering of the outer region of the streak is evident in the results, as shown for the two phase intervals in each plane. A more complete depiction of the streak instability can be made by using pseudo-flow visualization, i.e. the use of phase as the streamwise coordinate. Pseudo-flow contours of $\bar{U} + u_\phi$ and the phase-averaged unsteadiness, u''_ϕ are shown in planes parallel to wall in figures 3(a-b). The velocity contours possess a local kink that is associated with a region of elevated phase-averaged unsteadiness. This region reveals the onset of randomness of instability with streamwise distance. Two localized regions of elevated unsteadiness appear in the contours in figure 3(b) which suggest that additional kinks may form with streamwise growth.

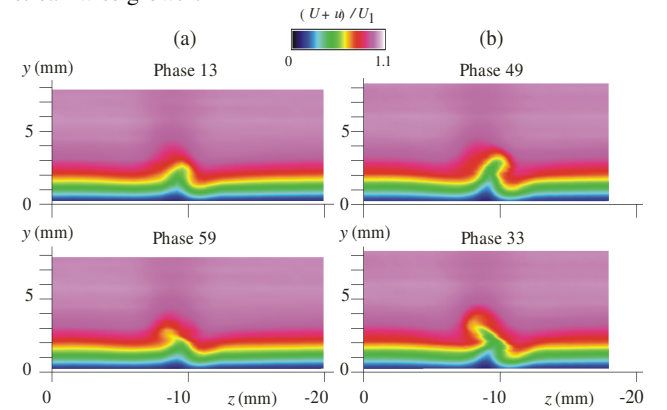


Figure 2. Total phase-averaged velocity, $(\bar{U} + u_\phi)/U_1$, in cross-stream planes (a) $x=0.52$ m, $\phi=13$ & $\phi=59$ (b) $x=0.58$ m, $\phi=49$ & $\phi=33$.

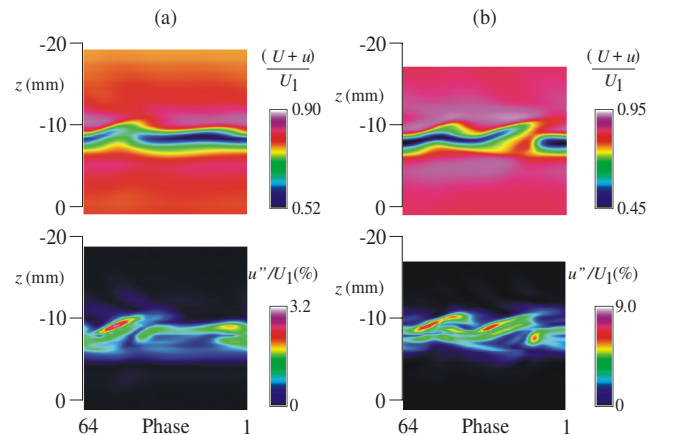


Figure 3. Pseudo-flow contours of $(\bar{U} + u_\phi)/U_1$ and u''_ϕ/U_1 at fixed wall distance. (a) $x = 0.52$ m, $y = 2.2$ mm (b) $x = 0.58$ m, $y = 2.6$ mm.

True spatial contours representing the final stages of growth and the ultimate breakdown of the streak are shown in figures 4(a-c). The sinuous shape of the streak remains much the same while the phase-averaged unsteadiness level increases in the region corresponding to the pseudo-flow contours in figures 3(a-b). Washout of the contours of the total phase-averaged streamwise velocity is evident in figure 4(a) in the vicinity of the streak centreline for $x > 0.6$ m. (Note that the streak is located about 10 mm away from the centreline of the test plate.) This region also corresponds with an increase in the phase-averaged unsteadiness level as shown in figure 4(b). These features demonstrate the onset of randomness associated with the instability as the streak undergoes breakdown to turbulence. Also visible in figure 4(b) are two regions with elevated phase-averaged unsteadiness levels that appear on either side of the centreline of the streak for $0.65 < x < 0.70$ m. The breakdown on the centreline and the formation of two regions of highly unsteady flow on either side of the streak are most clearly evident in the contours of the broadband unsteadiness shown in figure 4(c).

The sudden appearance of the two concentrated regions of highly unsteady flow on either side of the streak centreline is consistent with the notion that streak is responsible for introducing a new pair of streaks on either side via some instability mechanism. It is likely that the sinuous shape of the streak is responsible for introducing cross-flow velocity perturbations. Hence a plausible mechanism responsible for the appearance of the new streaks is cross-flow instability.

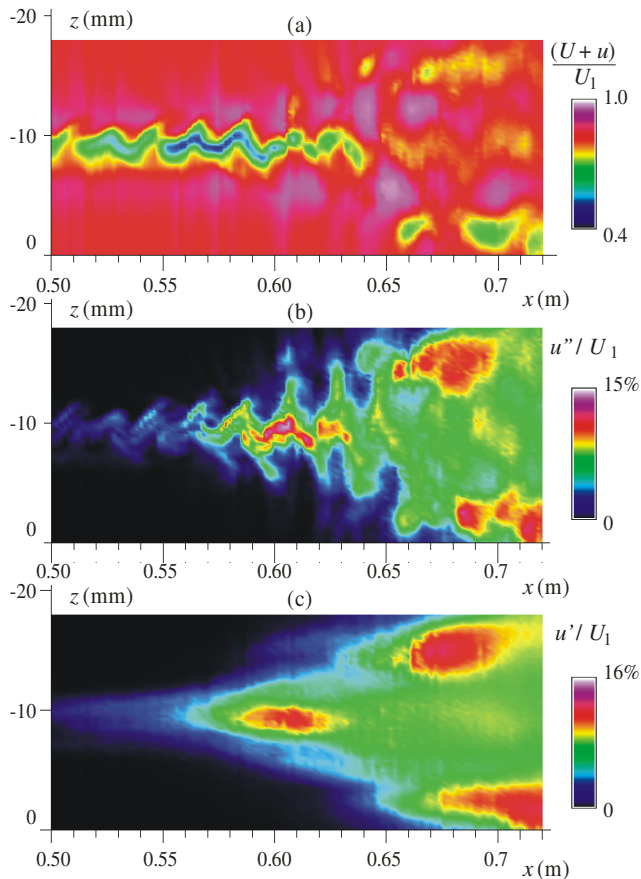


Figure 4. True spatial contours in plane, $y=2$ mm (a) $(\bar{U} + u_\phi)/U_1$, $\phi=21$. (b) u''/U_1 , $\phi = 21$. (c) Broadband unsteadiness, \bar{u}'/U_1 .

Features of turbulent wedge

The contours in figures 4(a-c) demonstrate that the randomness associated with the breakdown of the streak precludes the use of phase-averaged data to examine the flow structure further downstream. However, broadband hot-wire measurements are useful for examining the structure of the turbulent wedge that develops downstream of the breakdown.

Contours of the temporal mean streamwise velocity are shown in figure 5. A smaller fixed wall distance of the measurement grid ($y=0.5$ mm) has been used for these results compared to the grid used to produce figure 4 ($y=2.0$ mm) since the central portion of the flow is fully turbulent. The grid is wedge-shaped to avoid time consuming measurements in the regions of inactive flow.

A series of streamwise streaks are clearly evident in the mean flow contours at this early stage of development. The streaks persist in the mean flow for considerable streamwise distance, despite the fully turbulent characteristics of the central region of the wedge. The innermost pair of streaks, located at $x = 0.7$ m, are the result of the growth and breakdown of the instability shown in figure 4. Another pair of streaks can be seen to form at successive spanwise positions near the border of the wedge as it develops with streamwise distance.

The overall features of the wedge are shown in the contours of the mean flow, and broadband turbulence intensity in the expanded view of the entire measurement grid in figure 6. The spreading rate of the wedge is shown by the half-angle of 8° , which is close to that observed in previous studies of roughness generated turbulent wedges. Contours of these quantities are also shown in a streamwise sequence of cross-stream planes in figure 7 and the streaks are clearly visible in the mean velocity distribution in the planes located at $x=0.8$ and 0.9 m. The maximum turbulence levels are experienced near the wall in the central region, and profiles (not shown) are similar to those observed in a turbulent boundary layer. However the distribution near the edge is spread over a larger wall distance and profiles (not shown) have a secondary maximum.

It is plausible that the spanwise growth of the wedge is the result of the formation of a spanwise succession of streaks, where the formation of each in turn is the result of an instability introduced by the streak immediately preceding it upstream. Streaks are not observed in the mean flow contours near the border of the wedge further downstream. However this does not preclude the preceding notion that the spanwise growth of the wedge is the result of a succession of streaks. Any randomness in the streak formation process will lead to increased randomness in the formation of downstream streaks because of their successive dependency on the streaks forming upstream. Increased randomness associated with the location of successive streaks would result in a smearing of data thereby causing washout of the streaks in the contours.

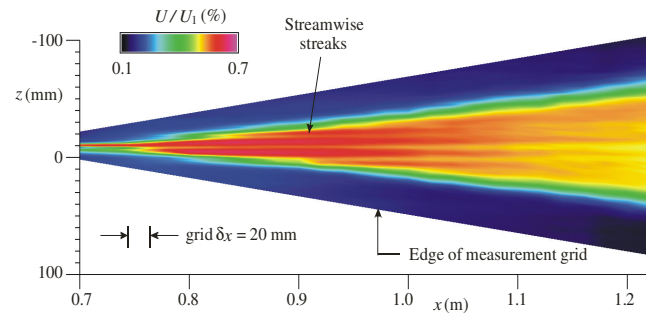


Figure 5. Contours of \bar{U}/U_1 , in plane, $y = 0.5$ mm.

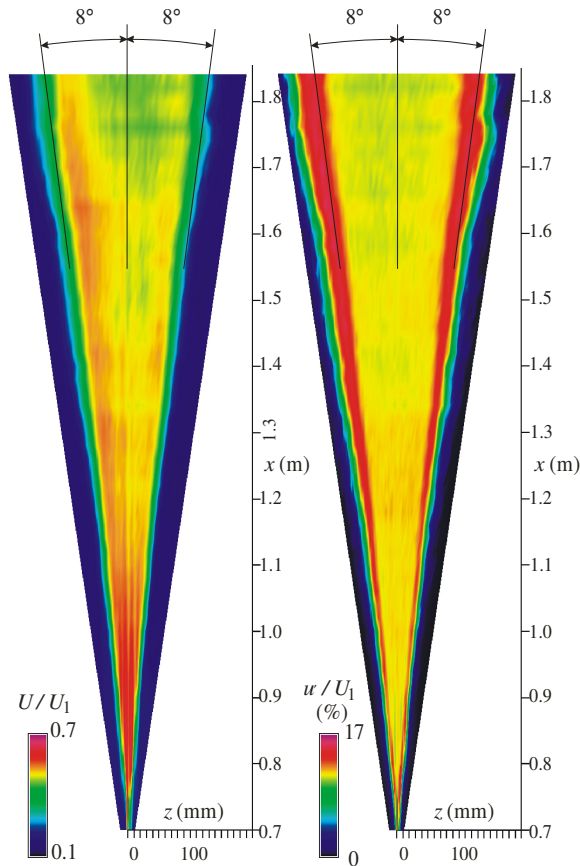


Figure 6. Contours of \bar{U}/U_1 , broadband turbulence intensity, \bar{u}'/U_1 , in the plane, $y = 0.5$ mm. Grid: $(N_x, N_z) = (56, 73)$; 4088 data points.

Conclusions

The breakdown process resulting from excitation of the steady streak leads to the formation of new streaks on either side. A similar mechanism also appears to be responsible for the spanwise growth of the wedge since a spanwise succession of new streaks is observed in the early stages of its development. A plausible mechanism that is common to both the breakdown of the streak and growth of the wedge is cross-flow instability.

Acknowledgments

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References

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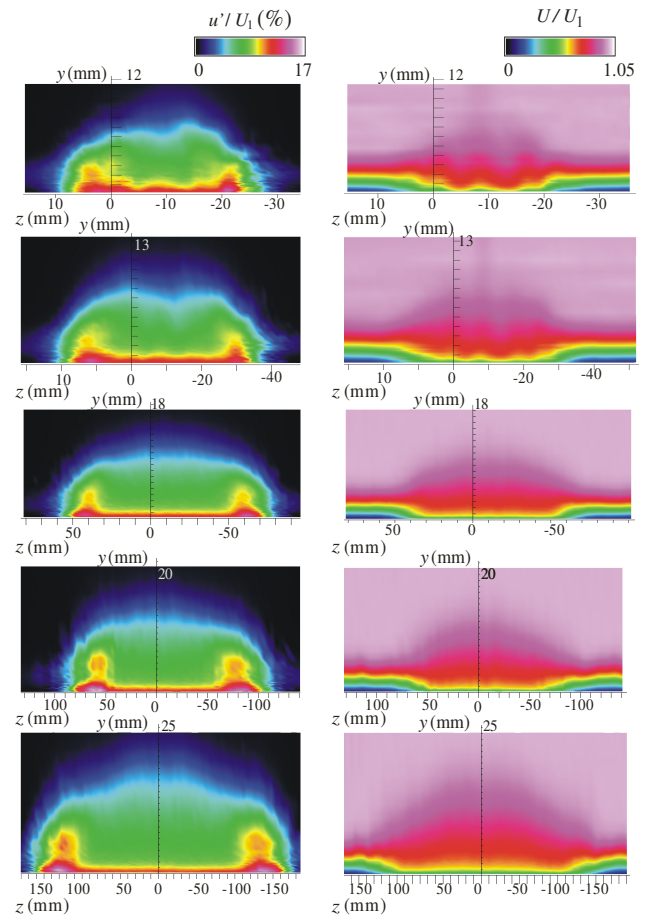


Figure 7. Streamwise development of \bar{U}/U_1 and \bar{u}'/U_1 contours in cross-stream planes. From top to bottom: $x = 0.8, 0.9, 1.2, 1.5$ and 1.8 m.

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