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SINUOUS STREAK INSTABILITY AND BREAKDOWN IN A BLASIUS BOUNDARY LAYER

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ABSTRACT

A narrow low-speed streamwise streak is deliberately introduced into an otherwise extremely spanwise 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 ($R_x = 1.4 \times 10^6$) 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 [1] 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 $\eta = 2.3$. These characteristics have much in common with Klebanoff modes observed by Klebanoff [2], Kendall [3, 4], and Westin et al. [5] at elevated FST levels.

The most significant reductions in u/U_1 were realized 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. $u/U_1 \approx 0.05\%$) appeared to be associated with local concentrations of elevated unsteadiness in the layer. 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. [6] demonstrated that the combination of vibrating ribbon generated Tollmien-Schlichting (TS) waves and grid generated Free Stream Turbulence (FST) leads to transition at

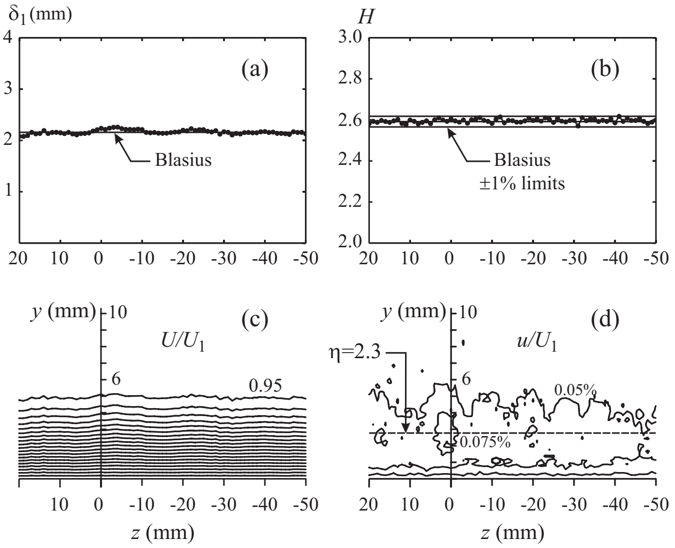

FIGURE 1. Spanwise uniformity of base-flow Blasius boundary layer for $R = 837.51$ ($x = 1.05$ m): (a) Displacement thickness, δ_1; (b) Shape factor, H, and contours of (c) Mean velocity, U/U_1; (d) Background unsteadiness, u/U_1. Grid: (Ny,Nz) = (31,71), *i.e.* 71 hot-wire profiles. Profile spacing, $\delta z = 0.5$ mm (length of hot-wire filament).

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.

1 PROPERTIES OF BASE-FLOW 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, $u/U_1 < 0.05\%$. The spanwise uniformity of the base-flow boundary layer at the position $x = 1.05$ m, i.e. $R(= R_x{}^{1/2}) = 837.5$, is shown in Figs. 1(a-d).The displacement thickness, δ_1, is within $\pm 1.5\%$ of the theoretical Blasius value, except in the range $0 > z > -10$ mm, where δ_1 increases to be about 3 % larger than the Blasius value. The shape factor, H, is uniform to within $\pm 1\%$ and the smaller variations are considered to be random errors introduced by hot-wire calibration drift or by small uncertainties in the wall distance. The contours in figure Figs. 1(d) demonstrate the low overall background unsteadiness level within the boundary layer, *i.e.* $u/U_1 < 0.08\%$. (Note that hot-wire signals are unfiltered and no allowance has been made for electronic noise). 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]. All of these observations demonstrate the high quality of the Blasius boundary and the suitability of the flow for controlled transition investigations.

2 INTRODUCTION OF STREAK INTO LAYER

Watmuff [7] showed that narrow low-speed streaks (*i.e.* regions of elevated layer thickness) can be 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

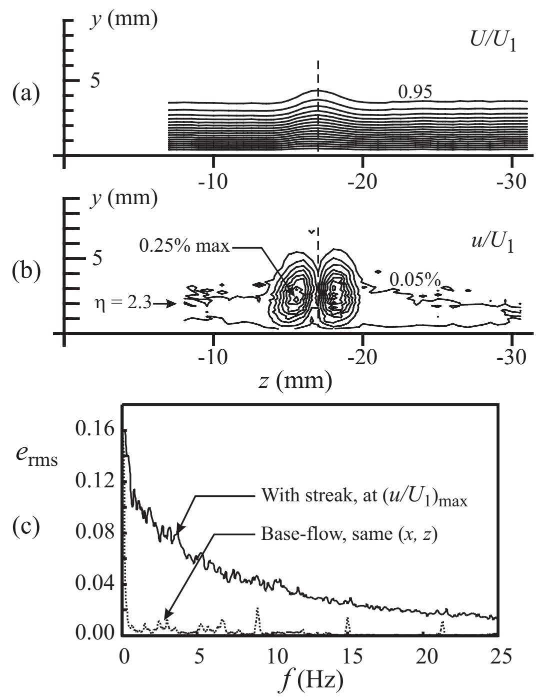

FIGURE 2. Streak characteristics generated by interaction of wake from $d = 25.4\,\mu$m wire with leading edge. Spanwise contours in plane $R = 641$ ($x = 0.615$ m): (a) Mean flow, U/U_1, CI = 0.05; (b) Unsteadiness, u/U_1, CI = 0.025 %. (CI is Contour Increment). From 51 hot-wire profiles, spaced $\delta z = 0.5$ mm (c) Power spectra in layer; with and without streak.

to the leading edge. A range of wire diameters, at varying distances from the leading edge were used to produce streaks with a range of characteristics.

The result of the interaction of the laminar wake from a $d = 25.4\,\mu$m ($R_d = 17$) wire with the leading edge is shown in Fig. 2. The interaction leads to a form of three-dimensionality in which there is a narrow region of elevated thickness (the streak) and a pair of locally concentrated regions of elevated background unsteadiness on either side. Contours of a similar but weaker form were observed before and at each stage during the flow quality improvements. The characteristics of u/U_1 also have much in common with Klebanoff modes appearing at elevated FST levels (see Klebanoff [2], Kendall [3, 4], and Westin et al. [5]). For example, the two maxima in the background unsteadiness contours are located at the Blasius wall distance of $\eta \approx 2.3$. Also, the elevated background unsteadiness occurs at low frequencies, as shown in the power spectrum in Fig. 2(c). The frequency corresponding to the lower branch of the neutral stability curve at this streamwise position is $f \approx 50$ Hz. It is clear that most of the unsteadiness in the streak occurs at frequencies much lower than those predicted from classical linear stability theory.

For the low background disturbance level of the free stream, the layer remains laminar to the end of the test section ($R_x = 1.4\times10^6$) and there is no evidence of bursting or other phenomena associated with breakdown to turbulence. 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 local increase in layer thickness of about 25% of the Blasius value.

For the results in this paper, the wire diameter, $d = 50.8\,\mu$m and it is located 184 mm upstream of the leading edge. The wake profile was measured at a location 63.5 mm upstream of the leading edge and is shown in figure Fig. 3(a). 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. It is evident that the measured velocity distribution compares very well with the Gaussian profile predicted from simple linear theory. The unit Reynolds number for the experiments is $6.68\times10^5\text{m}^{-1}$ ($U_1 \approx 10\text{ms}^{-1}$), giving $R_d = 34$.

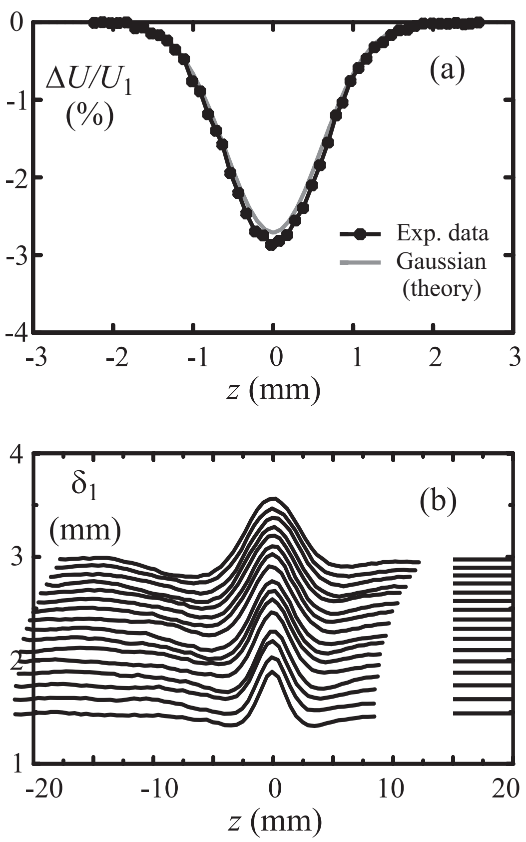

FIGURE 3. Undisturbed streak characteristics in current experiment: (a) Wake profile from $d = 50.8\,\mu$m wire used to generate streak, measured 63.5 mm upstream of leading edge. (b) Streamwise growth of spanwise variation of displacement thickness. Lines in range $15 < z < 20$ are Blasius values, *i.e.* $\delta_1 = 1.7208(\nu x/U_1)^{1/2}$. ($z$-coord. relative to wire centreline and peak δ_1 values).

The advantage of using a steady free-stream disturbance in the current experiments is that the streak is almost stationary, which allows its features to be examined in detail. A custom-made miniature hot-wire probe has been used for these measurements with a filament of diameter $d = 2.5\,\mu$m and length of 0.5 mm.

Watmuff [7] evaluated the shape factor, H, from detailed velocity profile measurements at $x = 1.05$ m ($R = 837.5$). He found the spanwise uniformity of the shape factor to be almost unaffected by the local increase in layer thickness introduced by the streak. Assuming independence of the Blasius shape factor from the streak occurs at other streamwise positions, then the spanwise variation of displacement thickness can be estimated by measuring U/U_1 along just a single spanwise profile at fixed wall distance.

The Blasius wall distance, $\eta(z)$, can be determined from each U/U_1 measurement by interpolation of the known Blasius solution. The displacement thickness variation is simply calculated using, $\delta_1(z) = 1.7208 y_p/\eta(z)$, where y_p is the distance of the hot-wire filament from the test surface. The basis of the method for the determination of the spanwise δ_1 variation from a single spanwise profile is the assumption of spanwise uniformity of the shape factor, H, which has not been determined at these positions. Nevertheless, comparison of cursory test results obtained at $x = 1.05$m indicated that δ_1 estimated from the spanwise profiles, compared surprisingly well with the value of δ_1 obtained by integration of the mean-velocity profiles. Overall, the δ_1 estimates were found to be within about $\pm5\%$ of the val-

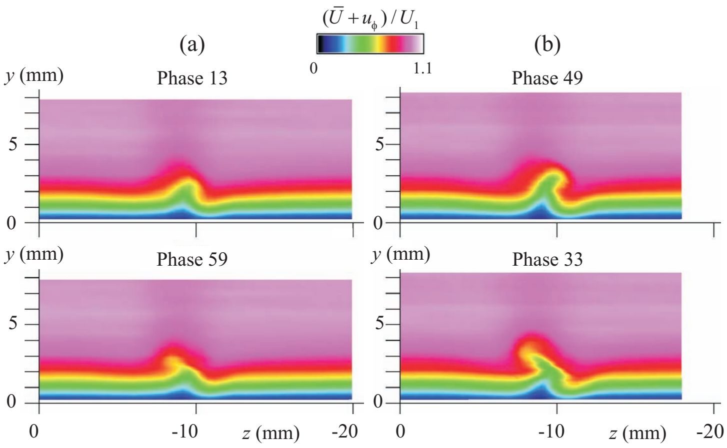

FIGURE 4. Contours of the total phase–averaged streamwise velocity, $(\overline{U}+u_\phi)/U_1$ in cross-stream planes (a) x=0.52 m, ϕ =13 & ϕ =59 (b) x=0.58 m, ϕ =49 & ϕ =33.

ues obtained by integration of the mean-velocity profiles.

Using this approximate technique, the streamwise development of the spanwise variation of displacement thickness resulting from interaction of the wake with the leading edge is shown in Fig. 3(b) for 16 streamwise positions, ranging from $x = 0.3$ to $x = 1.8$m. The results clearly demonstrate the narrow region of elevated thickness, i.e. the low-speed streak.

3 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 1.0 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, $F = 2\pi f\nu/{u_1}^2 = 185\times10^{-6}$ ($f \approx 265$ 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 = 165 Hz, so small amplitude disturbances at this frequency 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 initial 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 $F = 60\times10^{-6}$ generates a 3D TS wave pattern that closely match the pattern calculated by Mack & Herbert [8] using the Parabolized Stability Equations. Similar measurements have been performed using the larger amplitude disturbance at nondimensional frequency of $F = 185\times10^{-6}$, 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 $u/U_1 \approx \pm25\%$ at the point of breakdown, given by x=0.63 m, i.e. about 0.25 m from the source of the disturbance.

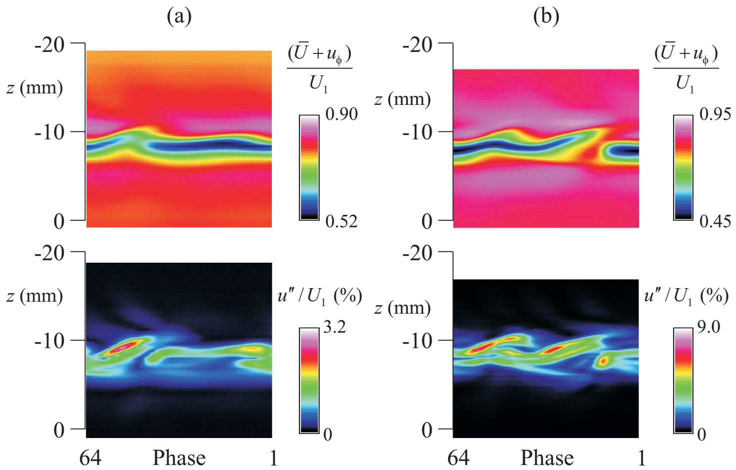

FIGURE 5. Pseudo-flow contours of $(\overline{U}+u_\phi)/U_1$ and $u''/U_1(\%)$ at fixed wall distance. (a) x = 0.52 m, y = 2.2 mm (b) x = 0.58 m, y = 2.6 mm.

4 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, $(\overline{U}+u_\phi)/U_1$, in two cross-stream planes are shown in Fig. 4(a-b). The spanwise meandering of the outer region of the streak is clearly 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

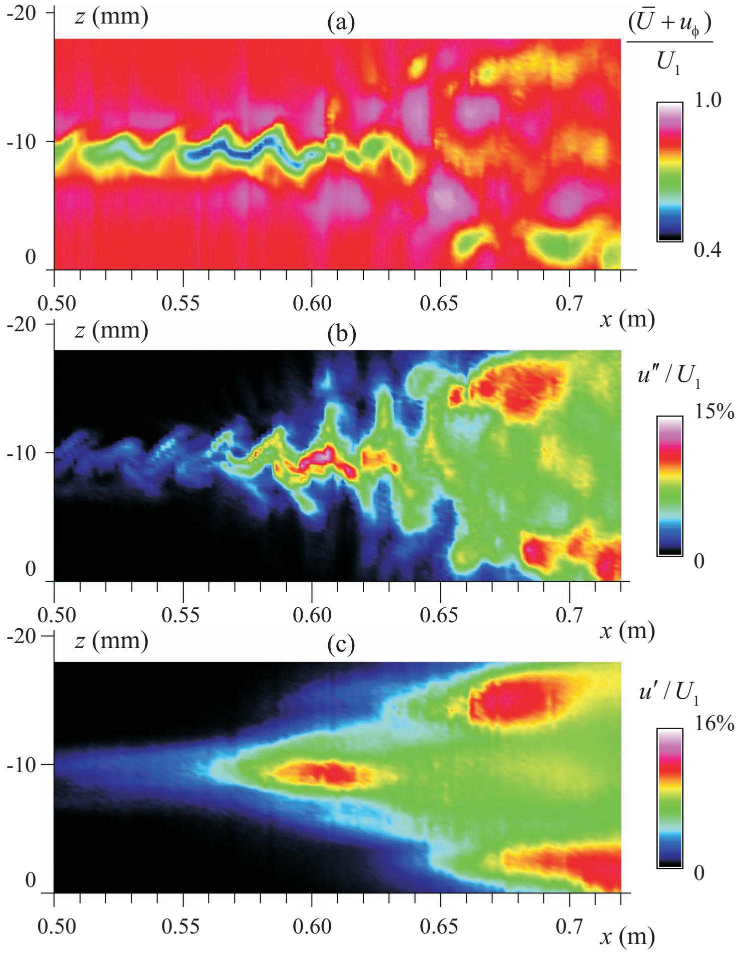

FIGURE 6. True spatial contours in plane, $y = 2$ mm: (a) Total phase-averaged velocity, $(\overline{U}+u_\phi)/U_1$; ϕ =21. (b) Random unsteadiness at constant phase, u''/U_1, ϕ = 21; and (c) Broadband unsteadiness, u'/U_1.

as the streamwise coordinate. Pseudo-flow contours of the total phase–averaged velocity, $(\overline{U}+u_\phi)/U_1$, and the phase-averaged random unsteadiness at constant phase, u''_ϕ/U_1, are shown in planes parallel to wall in Fig. 5(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 Fig. 5(b) which suggest that additional kinks may form with streamwise growth.

True spatial contours representing the final stages of growth and the ultimate breakdown of the streak are shown in figures Fig. 6(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 Figs. 5(a-b). Washout of the contours of the total phase-averaged streamwise velocity is evident in Fig. 6(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 Fig. 6(b). These features demonstrate the onset of randomness associated with the instability as the streak undergoes breakdown to turbulence. Also visible in Fig. 6(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 Fig. 6(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.

5 FEATURES OF TURBULENT WEDGE

The contours in Figs. 6(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

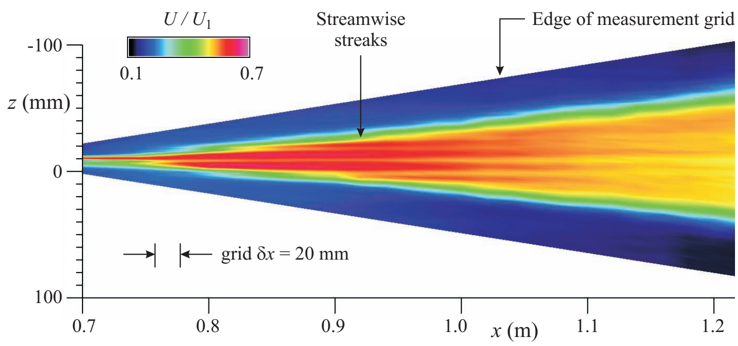

FIGURE 7. Contours of U/U_1, in plane, $y = 0.5$ mm.

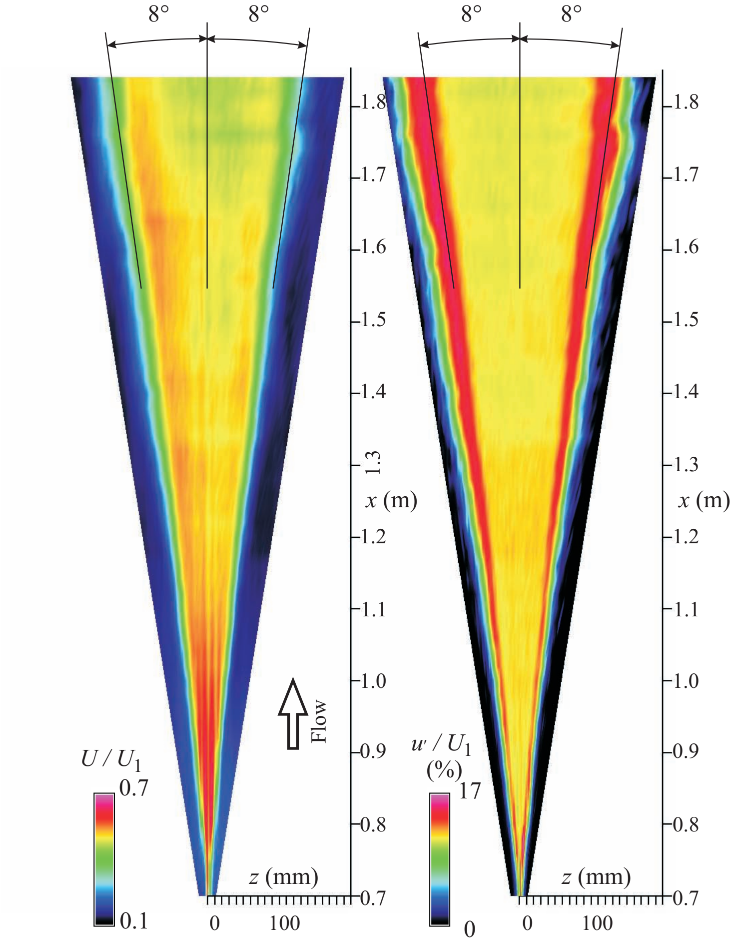

FIGURE 8. Contours of $\overline{U}/U_1$, broadband turbulence intensity, u'/U_1, in the plane, y = 0.5 mm. Grid: (Nx, Nz) = (56, 73); 4088 data points.

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.

6 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

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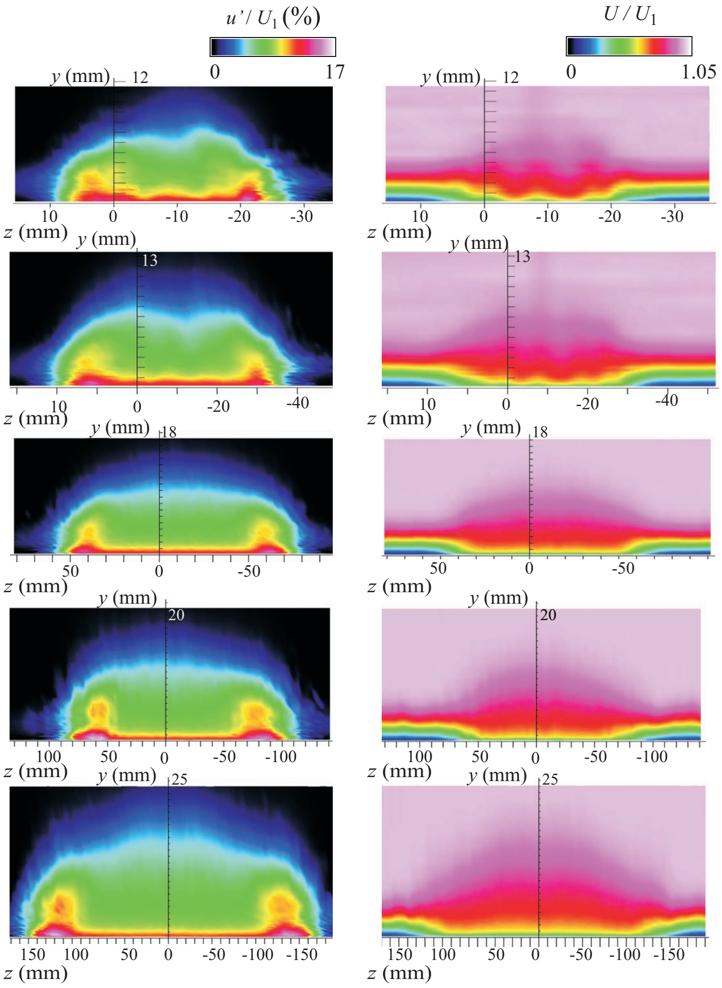

FIGURE 9. Streamwise development of $\overline{U}/U_1$, and u'/U_1 contours in cross-stream planes. From top to bottom: x = 0.8, 0.9, 1.2, 1.5 and 1.8 m.

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