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Control of a laminar separating boundary layer by induced stationary perturbations

A.V. Boiko [a], A.V. Dovgal [a,*], S. Hein [b]

[a] *Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, Novosibirsk, 630090, Russia*
[b] *Institute of Aerodynamics and Flow Technology DLR, Bunsenstrasse 10, 37073, Göttingen, Germany*

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Abstract

Wind-tunnel data on stationary streaky structures developing in a laminar flow behind a backward-facing step on a flat plate are presented. The streaks were generated in a controlled manner by a row of three-dimensional surface humps placed periodically in the span-wise direction close to the separation line. The mean flow distortion of the separation region created in this way was documented by hot-wire measurements. Details of the evolution of the stationary perturbations in the separation region as well as their effect upon the oscillatory flow component, which are of interest due to elaboration of prospective methods for control of low-speed aerodynamics, are elucidated.

Keywords: Laminar flow separation; Separation control; Hydrodynamic instability

1. Introduction

At present, a variety of approaches for control of flow separation are available either used in engineering applications or subject to experimental, theoretical and computational substantiation. Those employ different physical ideas and control principles for modification of mean and oscillatory flow characteristics promoting reattachment even up to complete elimination of separation or, contrary, to its initiation [1]. An approach to separation control which is in focus of research work in recent decades is flow manipulation by perturbations generated in the separation region by different kinds of actuators. Quite a lot of exploration results concerning this point have been obtained up until now, for references see, e.g., [2,3]. In that case a control effect is gained, basically, through coupling of the excited disturbances with those emerging due to natural separated flow instabilities. Thus, by forcing the separation in a time-periodic manner, one can significantly alter the unsteady flow component through modification of the separated layer transition and/or the dynamics of the large-scale coherent vortices induced by separation, as it is shown for mixing layers [4]. This, in turn, results in a rearrangement of the entire flow field normally appearing as a diminution of the separated flow region. In this version of separation control its effectiveness depends on amplitude and frequency of the induced perturbations as well as on a particular source of the oscillations and its arrangement (e.g., acoustic waves of

* Corresponding author.
E-mail addresses: boiko@itam.nsc.ru (A.V. Boiko), dovgal@itam.nsc.ru (A.V. Dovgal), stefan.hein@dlr.de (S. Hein).

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the free stream [5–7], alternating blowing/suction through the body surface or their combinations including zero-mass flux jets [8–11], periodic heating of the wall strips [12], and oscillatory mechanical devices [13,14]). At a proper selection of the above conditions a pronounced control result can be obtained, especially for laminar separating layers. Due to their high receptivity to external oscillations and the highly unstable nature, even small-amplitude excitation of properly scaled separated flow perturbations may have a large effect upon the flow pattern. A striking example is the suppression of the leading-edge separation on airfoils at near stalling conditions produced by external periodic forcing [15].

Another way to produce amplifying perturbations in shear layers comes from a non-modal transient growth of disturbances composed of non-orthogonal modes of perturbations even if the latter might be all damped according to linear stability theory (see, e.g., [16–20]). Practically, this growth mechanism is associated with origination of stationary and quasi-stationary stream-wise disturbances of the flow velocity known also as "streaky structures" or "streaks". In attached boundary layers the streaky structures which could be induced by the above mechanism were observed in a number of experimental studies both under natural wind-tunnel conditions [21] and through controlled excitation of the perturbations [22,23]. Similarly, the stream-wise disturbances evolving at laminar flow separation were examined in experiments [24,25]. As a result, it was found that under appropriate conditions of the streaks generation, both stationary [25] and unsteady [24] streaky structures amplify behind the point of separation. If so, one expects a pronounced effect of the induced perturbations upon the flow characteristics. Thus, the objective of the present study was to clarify the response of locally separating boundary layer to stationary disturbances subject to transient growth in the separation region.

In what follows, experimental procedure is described in Section 2. In Section 3 main base flow characteristics are given and the flow response to the stationary disturbances is elucidated. A similarity of some characteristics of the response to those of optimal disturbances is discussed. Conclusions are summarized in Section 4.

2. Experimental set-up and measurement technique

The experiments were performed in TUG, a low-turbulence wind tunnel of DLR, Göttingen, see Fig. 1. The facility is a wooden contoured wind tunnel with a closed test section, a 16:1 contraction nozzle and an open diffuser. The test section of the tunnel is 6.25 m long, 0.3 m wide and 1.5 m high. The operation velocities are in the range from 4 to 45 m/s.

The data were obtained for laminar boundary layer separation at a backward facing step on a flat plate surface. The acrylic plate was the same as in the experiments of [26,27] being 1500 mm wide, 1175 mm long, and 40 mm thick. It was installed vertically in the plane of symmetry of the test section. The elliptical leading edge of the plate with the axis-ratio 6:1 and a trailing-edge flap were designed to avoid flow separation in the upstream part of the model and to minimize background velocity perturbations in this region. The turbulence level over the plate under the conditions close to present experiment was documented in detail in [26,22]. It appeared to be independent of the downstream coordinate over the whole region of measurements and was characterized by certain anisotropy: $u' = 0.19$, $v' = 0.07$, and $w' = 0.06\%$ of U_0, so that $\mathrm{Tu} = \sqrt{(u'^2 + v'^2 + w'^2)/3} \approx 0.12\%$ of U_0 at low frequency cut off of 5 Hz.

The backward facing step was located 225 mm downstream of the leading edge of the plate at the downstream end of an acrylic plate cover of 100 mm length, 300 mm width, and 3.3 mm height. The stationary perturbations in the separation region were generated by roughness elements mounted on the model surface. A similar technique of the streaks excitation in a separating boundary layer was used earlier in experiments [25]. As a result, it was found that amplifying mean flow disturbances can be produced by a surface non-uniformity close to the line of separation. Taking into account these observations, in the present study several configurations of the roughness elements spaced periodically along the span of the model symmetrically to its center-plane were examined, see Fig. 1 and Table 1. An easily reproducible rectangular shape of the elements was taken with their height and width comparable to the step height. Thus, a sufficient spatial resolution of the perturbations during hot-wire measurements was ensured to clarify contribution of different stationary modes of velocity perturbations in the separated flow pattern.

In what follows, a coordinate system is used with x being the stream-wise distance measured from the step position, z is the span-wise coordinate with $z = 0$ in the centerplane of the model and y is normal to the wall with $y = 0$ at the base of the step.

Stream-wise mean and fluctuating velocity components were measured by a DISA constant-temperature hot-wire anemometer. Single-sensor miniature DISA probes designed for use in boundary layers with a sensitive length of

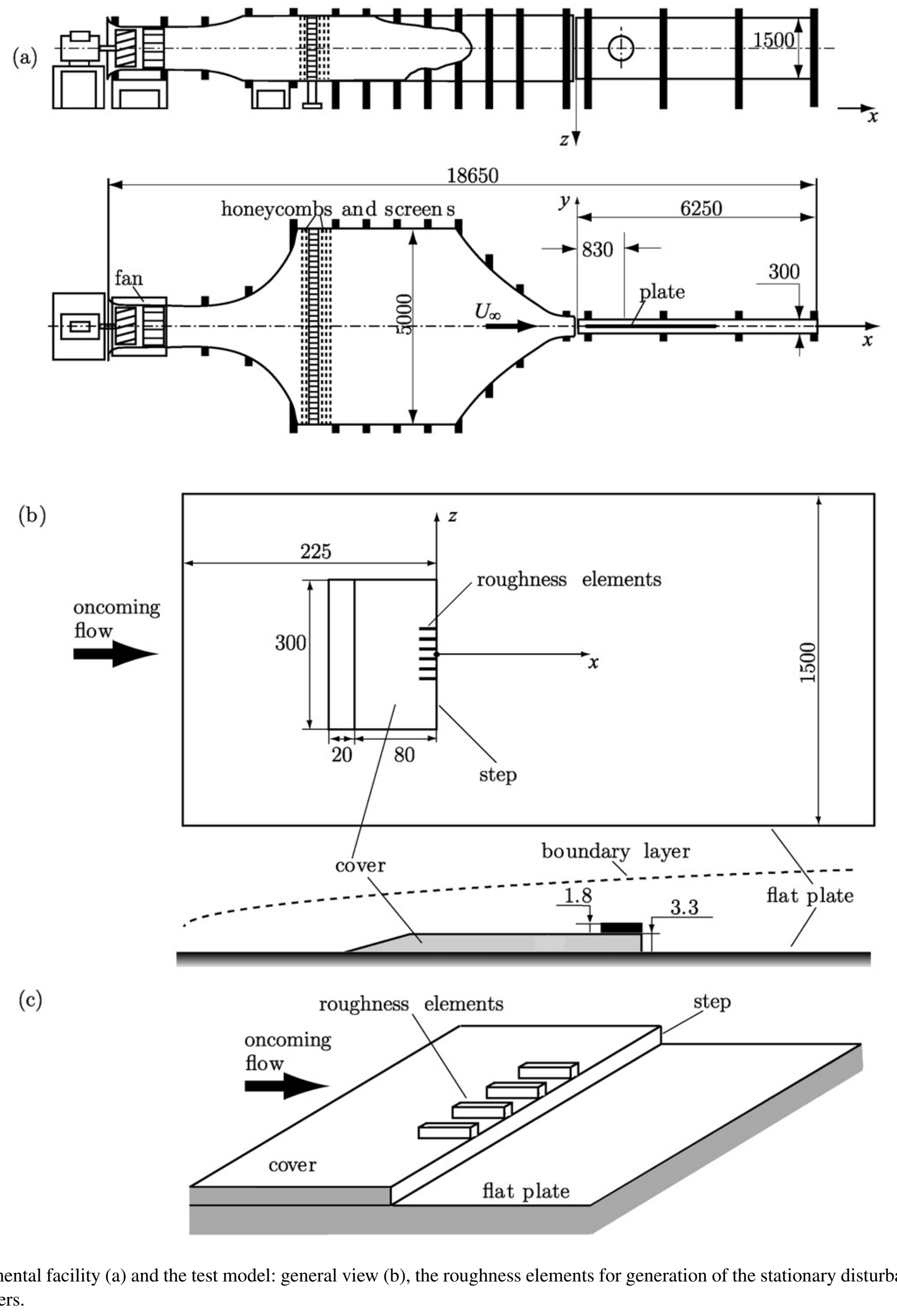

Fig. 1. Experimental facility (a) and the test model: general view (b), the roughness elements for generation of the stationary disturbances (c). Sizes are in millimeters.

about 0.5 mm were operated at 80% overheat ratio. Anemometer signals were digitized by a 12-digit A/D converter. To improve the dynamic range of the measuring system and resolution of the samples, an analog signal conditioner was used which subtracted a fixed constant voltage from the anemometer signal. The samples were linearized and processed with a personal computer in a MATLAB environment. Because stationary velocity fluctuations were the main objective of the present study, 256 Hz sampling rate was used that is sufficient to resolve the laminar and early transitional events in the separation bubble under investigation.

Table 1
Configurations of the roughness elements disturbing the separation bubble

No.	Roughness dimensions, mm (width × height × length)	No. of roughness elements	Span-wise spacing λ, mm
1	2.0 × 1.8 × 10.0	6	5
2	2.0 × 1.8 × 10.0	6	10
3	2.0 × 1.8 × 10.0	6	15
4	2.0 × 1.8 × 10.0	4	20
5	4.0 × 1.8 × 10.0	6	10
6	4.0 × 1.8 × 10.0	6	15

The hot-wire probes were calibrated in the external flow with a Prandtl tube positioned close to the probe. A modified King's law (see, e.g., [28], and reference therein for details):

$$U = k_1(E^2 - E_0^2)^{1/n} + k_2(E - E_0)^{1/2}, \tag{1}$$

was used, where U is the stream-wise velocity to be determined, E is anemometer voltage, E_0 is the same at zero flow velocity, k_1 and k_2 are adjustable constants and n is the one to be determined for the best fit to the calibration data. Normally the value of $1/n$ is close to 0.5. The second term in the right-hand side of Eq. (1) accounts for the contribution of free convection at low velocities and corrects the hot-wire measurements at such conditions. The calibration was performed in the range from 0.9 to 6.0 m/s periodically. About 10 velocity measurements uniformly distributed in the velocity range of interest were used in each calibration. Relative error between the velocities obtained with the Prandtl tube and the hot wire was maintained less than 1%. The drift of the calibration curves was within this error as well.

For the probe positioning a multi-axis traversing mechanism controlled by a personal computer was used which allowed one to perform measurements with relative spatial accuracy of 12.5 μm in planes parallel to the model surface and 7.5 μm normal to the wall. The traversing mechanism was designed so that only a hot-wire holder is located inside the test section. Hot-wire readings were collected across the boundary layer and the separation bubble with a spacing of 0.2 to 0.3 mm in the near-wall region and of 0.5 to 1.0 mm in the external part of the shear layer. The testing area ranged from 5 mm upstream of the step up to 60 mm downstream of it. Measurements along the span of the model were carried out in its central part and covered two span-wise periods between the roughness elements.

3. Results and discussion

3.1. The base flow

All of the experimental runs were performed at a constant external flow velocity at the stream-wise position of the backward-facing step of $U_0 = 5.0$ m/s corresponding to the Reynolds number $Re = U_0 h/\nu = 1060$, where h is the step height and ν is air kinematic viscosity.

In the absence of roughness elements mounted on the model surface the laminar boundary layer separated at the step. Hot-wire data obtained at different span-wise positions close to the separation point indicated that the flow was quite uniform along the span of the model both in respect of its mean and oscillatory characteristics. At $x = -5$ mm the displacement (δ^*) and momentum (ϑ) thickness of the pre-separated boundary layer were 1.26 ± 0.03 and 0.50 ± 0.01 mm, respectively. The value of shape-factor $H = \delta^*/\vartheta = 2.52 \pm 0.02$ is somewhat different from the Blasius one ($H = 2.59$) due to the effects of the pressure gradient in the leading-edge region and the plate cover upon the near-wall layer. The maximum amplitude of background disturbances measured at $x = -5$ mm with low frequencies cut off at 5 Hz did not exceed 0.28% of U_0.

The mean flow in the separation region is illustrated in Fig. 2(a) by normal-to-wall velocity distributions $U(y)$ measured at different stream-wise distances downstream of the step. In each section the y-coordinate is normalized by δ^* at $x = -5$ mm and mean velocity is normalized by U_0, the latter deviated less than 2% through the x-range of measurements. Near the surface at $y < 1$ mm the data are not shown because in this region the measuring technique cannot provide quantitative data on the flow due to almost zero mean velocity and the presence of the backward flow component. However, this is not crucial for the present subject, as far as the perturbed flow behind the step

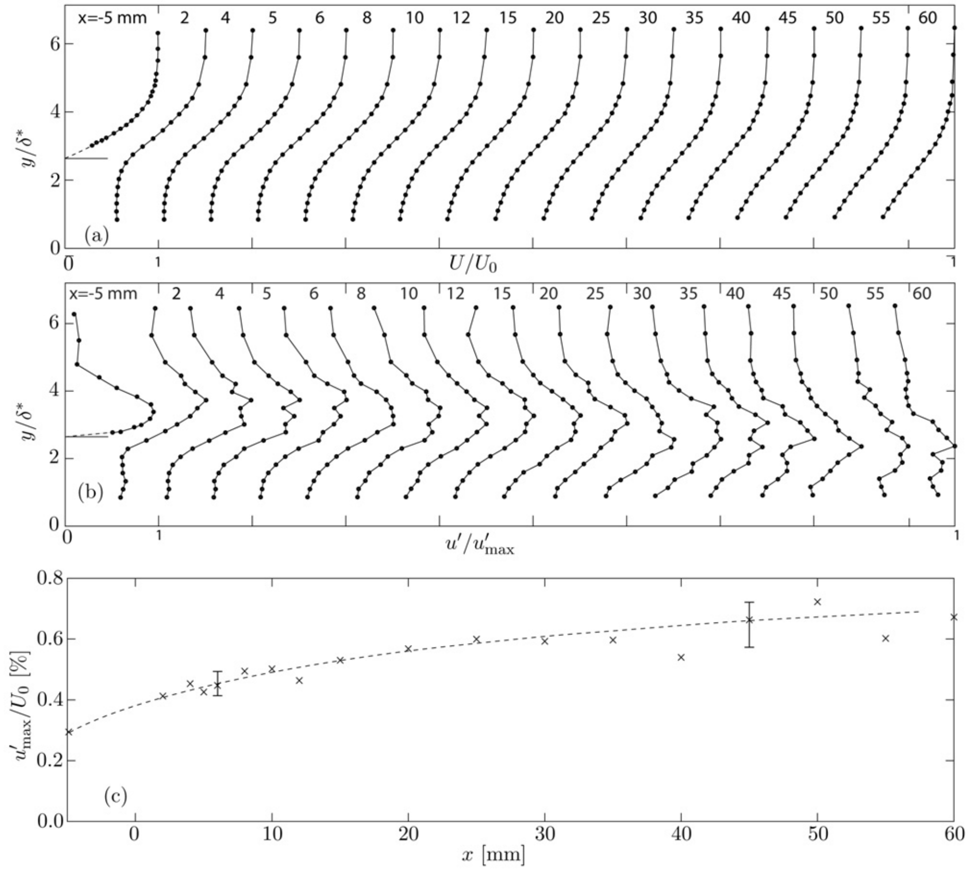

Fig. 2. Mean velocity profiles (a), r.m.s. profiles (b) in the two-dimensional separation bubble and corresponding stream-wise variation of the maximum r.m.s. amplitude $u'_{\max}$ of natural stream-wise velocity perturbations (c) from $x = -5$ to 60 mm. Wall-normal coordinate y is normalized by value of δ^* at $x = -5$ mm.

is dominated by disturbances evolving in the shear layer at the edge of the separation bubble. In this flow region the hot-wire method is quite reliable for determination of the velocity characteristics, as it comes from comparison of numerous wind-tunnel data on instability of such bubbles with numerical results [29–32]. As the stream-wise coordinate increases, the velocity distributions gradually change from the separated profile with a "dead-air" region close to the wall ($x = 2$ mm) to that of the reattaching boundary layer ($x = 60$ mm). This makes estimation for the length of reattachment as 15 to 20 step height which is in a fairly good agreement with previous experimental results on laminar boundary-layer separation at a backward-facing step in the same range of Reynolds number, see e.g. [33].

Similarly, in Fig. 2(b) wall-normal distributions of background stream-wise velocity perturbations evolving behind the step are presented. They are normalized by their local maximum amplitude $u'_{\max}$. At the small enough Reynolds numbers and low level of environmental disturbances of the present experimental facility, laminar flow is observed in the whole separation bubble. The natural flow perturbations slightly grow in the stream-wise direction so that their amplitude varies from 0.4% of U_0 just behind the step ($x = 2$ mm) up to about 0.7% of U_0 at the downstream end of the measurement region ($x = 60$ mm) as indicated in Fig. 2(c). These values are well below the intensity of disturbances usually found in boundary layers approaching the transition to turbulence and in turbulent flows.

A typical power spectrum of velocity fluctuations u'_f measured at the position of their maximum amplitude is shown in Fig. 3. The spectral data indicate some contribution of the low-frequency oscillations to the flow pattern without pronounced disturbances at higher frequencies of about 100 Hz (i.e. about $St = f\vartheta/U_0 \sim 0.01$, ϑ is the momentum-loss thickness), where one could expect a wave packet of the linear separated-layer instability behind a backward-facing step of the height comparable with the boundary-layer thickness [34].

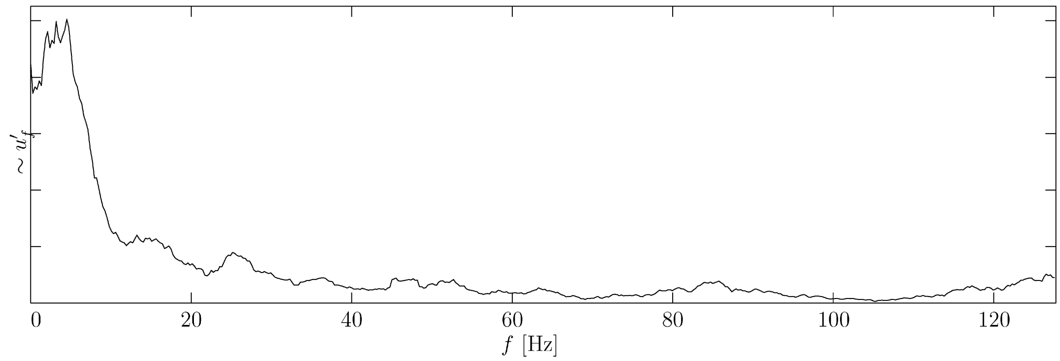

Fig. 3. Power spectrum (periodogram) of natural stream-wise velocity perturbations in the separated flow at $x = 50$ mm.

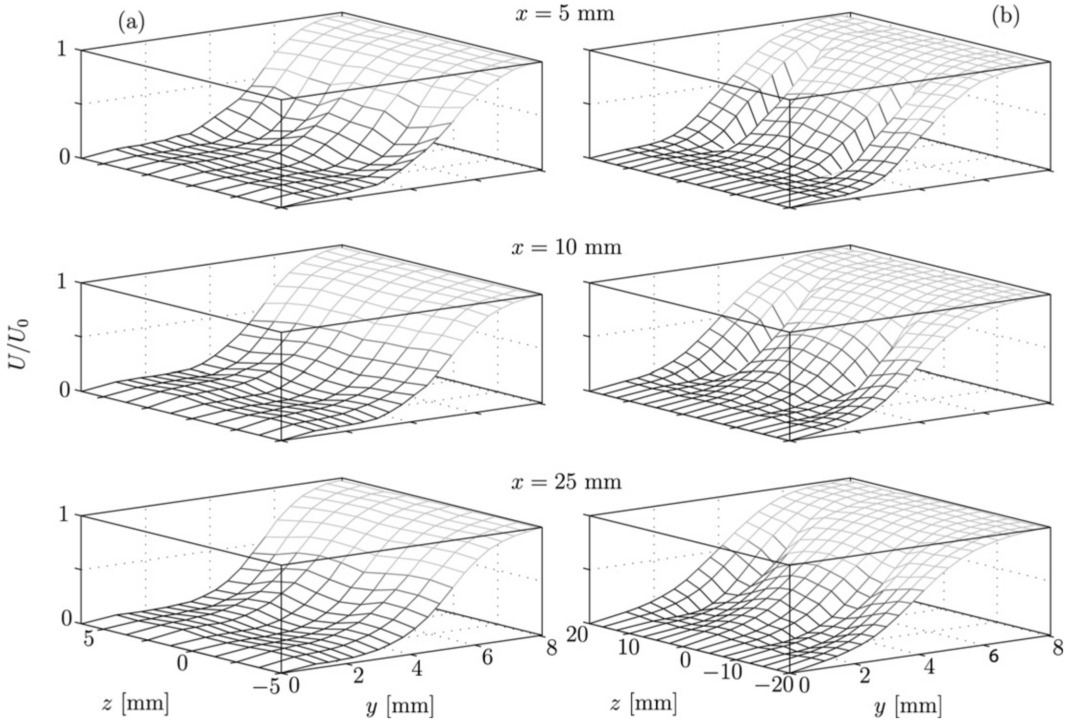

Fig. 4. Mean velocity profiles in the separation bubble over two span-wise periods of the stationary disturbances for 5 mm (a) and 20 mm (b) spacings between the roughness elements at $x = 5$, 10 and 25 mm.

3.2. Controlled flow separation

The effect of stationary disturbances upon the mean flow in the separation region is illustrated in Fig. 4 for two configurations of the roughness elements differing by their span-wise spacing. In all of the experimental regimes under investigation the Reynolds number based on the roughness height and its tip velocity in the undisturbed boundary layer was about 490. One can see that in both cases the flow patterns are well correlated with the position of the streaks generators. However, a quite different stream-wise evolution of the disturbances is observed due to variation of the transverse spacing between the elements which is clearly visible in the perturbation contours; see Fig. 5. For the 5 mm spacing the disturbance induced by the roughness elements initially decays, then, starts to grow with a reversal of its amplitude distribution across the separation bubble and, finally, gets smaller in the last stream-wise section. The transformation of the local stream-wise velocity deficit to velocity excess behind a roughness element, as an indication of the transient growth of perturbations, has been found previously in laminar wakes behind small

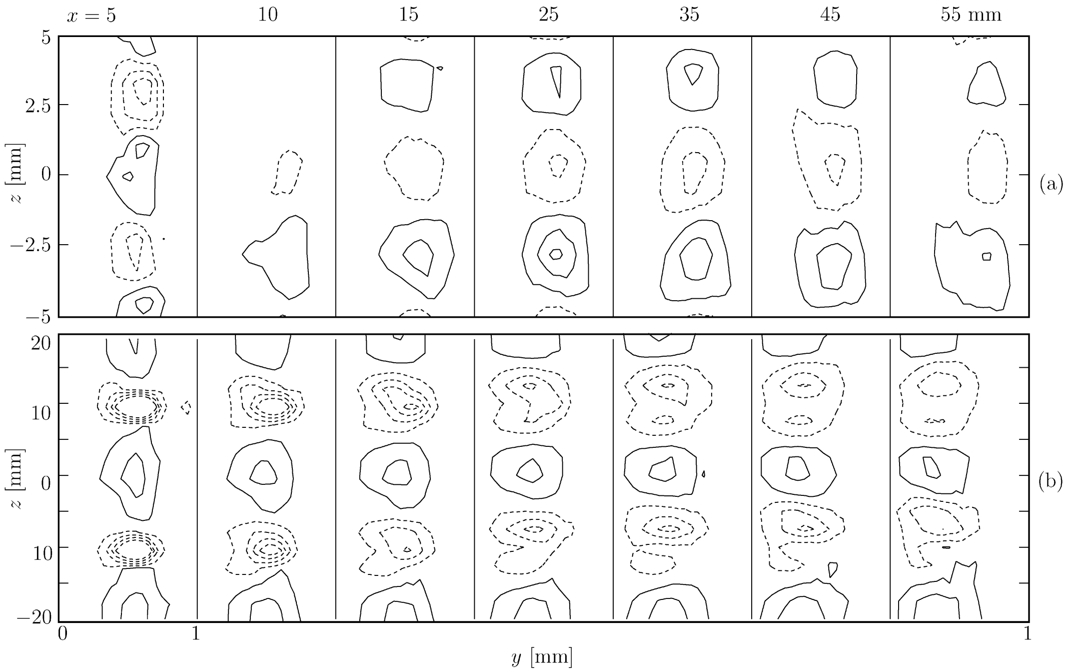

Fig. 5. Equidistant contours of the stationary mean velocity perturbations in y–z planes for 5 mm (top) and 20 mm (bottom) spacing between the roughness elements from $x = 5$ to 55 mm. *Solid* and *dashed* lines show positive and negative deviations respectively of local velocity from its values averaged along z-coordinate with step 3% of U_0.

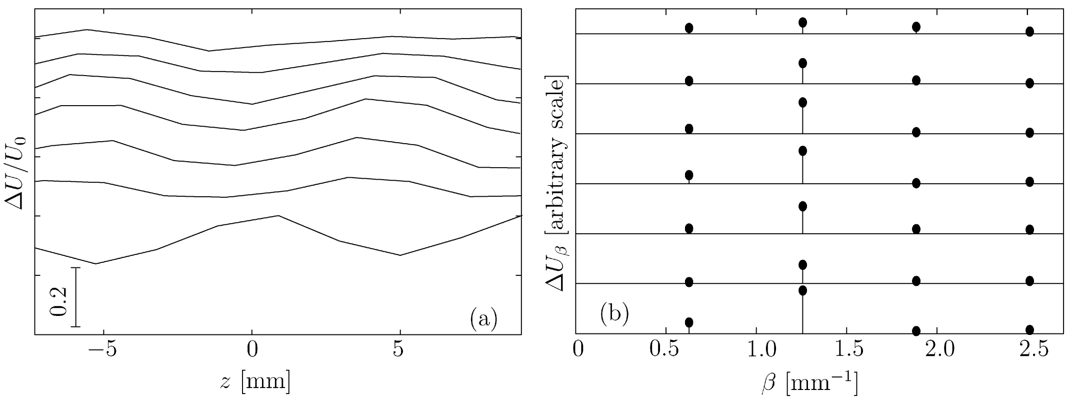

Fig. 6. Separated flow perturbation induced by the roughness elements with 5 mm span-wise spacing at $x = 5$, 10, 15, 25, 35, 45 and 55 mm (from *bottom* to *top*). Mean velocity distributions along z-coordinate at the maximum flow disturbance (a) and the corresponding wave-number spectra (b).

three-dimensional obstacles or shallow bumps inside the Blasius boundary layer in a series of experimental studies [35–39]. On the other hand, the mean flow distortion created by the roughness elements spaced with 20 mm periodicity decays monotonically (especially its negative part) in the flow direction. These features are obviously due to different conditions of the streaks generation, that is, the initial wave-number spectra of the induced stationary perturbations.

To obtain more details on the development of streaky structures in the separation region, a Fourier decomposition of recorded span-wise velocity distributions ΔU in a spectrum ΔU_β of span-wise wave numbers β was performed. The results of spectral analysis are illustrated in Figs. 6 and 7. These together with the similar data obtained for other roughness configurations made it possible to trace the evolution of spectral components of the stationary disturbances in the separation region, thus, comparing their contribution to the perturbed flow pattern.

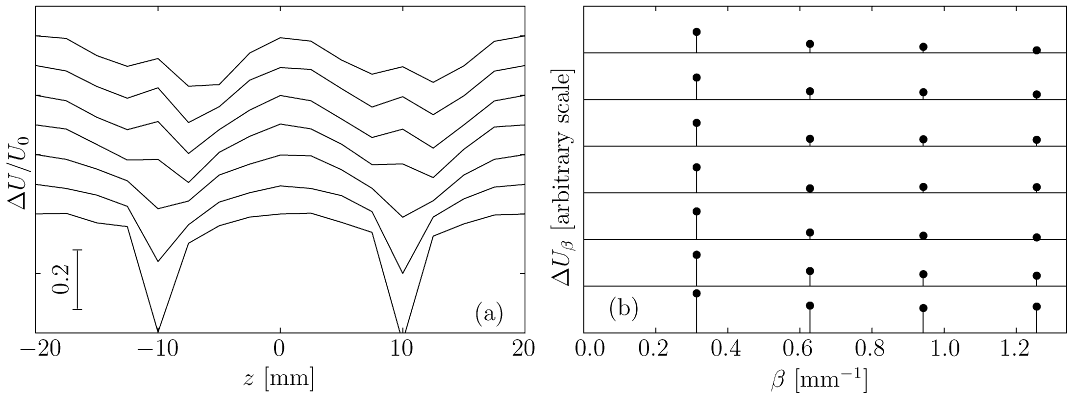

Fig. 7. Separated flow perturbation induced by the roughness elements with 20 mm span-wise spacing. For legend see caption of Fig. 6.

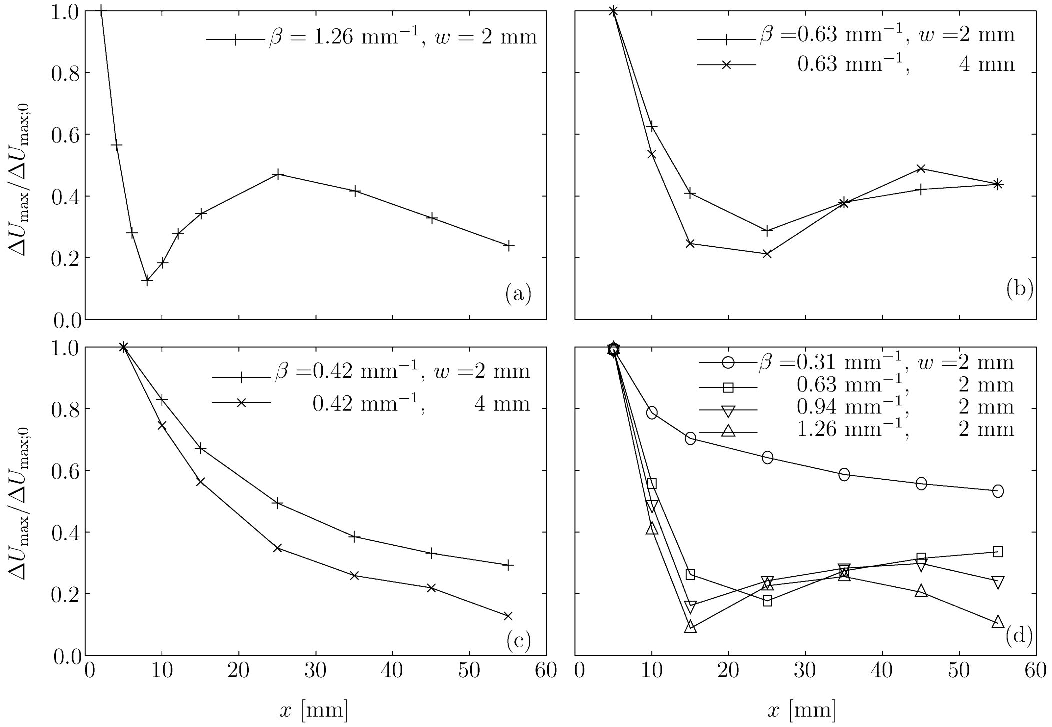

Fig. 8. Maximum amplitudes of the main components in wave-number spectrum of the separated flow perturbations vs. stream-wise distance: (a) 5 mm spacing between the roughness elements; (b) 10 mm spacing between the roughness elements with $w = 2$ mm and 4 mm width; (c) 15 mm spacing between the roughness elements with $w = 2$ mm and 4 mm; (d) behaviour of four first wave number components at 20 mm spacing between the roughness elements. The amplitudes are reduced by their values at $x = 5$ mm.

The results of such data processing are summarized in Fig. 8 as stream-wise growth (decay) of several first harmonics of the perturbations which could be reliably resolved in each of the experimental regimes. Fig. 8(d) also shows similar data for higher harmonics in the case $\lambda = 20$ mm which are in a good agreement with those of Fig. 8(a)–(c). As one can see, under the conditions of present experiments the wave-number components amplified in the separation bubble are those of $\beta = 2\pi/\lambda \geqslant 0.63$ mm^{-1}. Particularly the disturbances with these wave numbers contribute to the observed growth of the streamwise velocity deviations behind the point of separation. Notice some effect on the development of wave-number harmonics produced by changing the roughness width from 2 to 4 mm. However, this does not mask the overall tendency: the smaller the span-wise spacing between the perturbations, the stronger their initial decay succeeded by the amplitude growth.

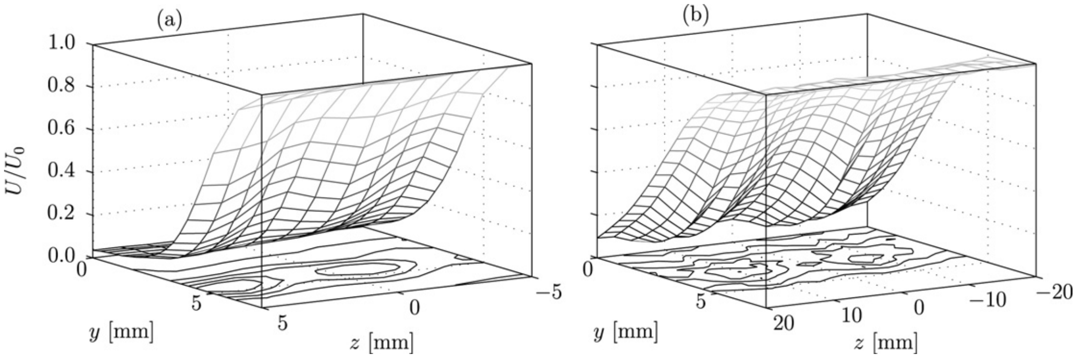

Fig. 9. Non-stationary perturbations of the separation region (*contours*) versus the mean flow modulation by the streaks (*mesh plots*): equidistant contours of r.m.s. amplitude of non-stationary stream-wise disturbances at the 5 mm spacing between the roughness elements, $x = 35$ mm, the frequency band is from 5 to 128 Hz, the contour step is 0.1% of U_0 in the range from 0.1 to 0.5% of U_0 (a); the same for the 20 mm roughness spacing with the contour step of 0.05% of U_0 in the range from 0.05 to 0.25% of U_0 (b).

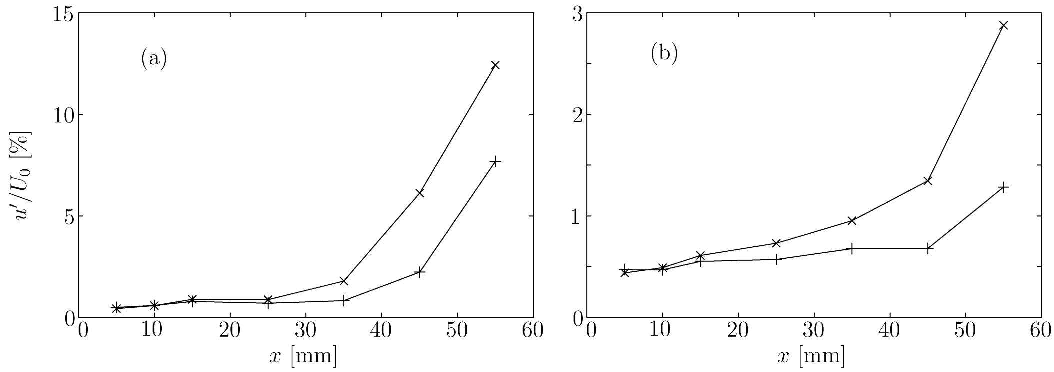

Fig. 10. Stream-wise variations of the maximum r.m.s. amplitudes of non-stationary stream-wise disturbances in the separation bubble perturbed by the streaky structures. Growth curves obtained in peaks ($\times$) and valleys ($+$) of the flow periodicity in the span-wise direction with low frequencies cut off at 5 Hz for 5 mm (a) and 20 mm (b) spacing.

Besides modulation of the mean-velocity distribution, the roughness elements have a pronounced effect upon the oscillatory flow component. In Figs. 9 and 10 one can observe a correlation of the spatial arrangement of unsteady velocity fluctuations with the mean flow pattern. Also, an increase of their intensity compared to the undisturbed separation region is clearly seen which can be explained by modification of mean velocity gradients and local stability characteristics of the separated flow by the streaky structures. Thus, the amplifying unsteady perturbations can be considered as secondary ones of the separated flow with the embedded primary streaks, similar to that found in other shear flows perturbed by the stream-wise structures, see, e.g., [40]. In power spectra the disturbances appear as wave packets of velocity oscillations as is illustrated in Fig. 11 for 5-mm spacing between the roughness elements (cf. Fig. 3). Apparently, the growth of secondary disturbances promoting laminar-turbulent transition behind the separation point is larger at the smaller spacing between the roughness elements, i.e. in the case of generation of the streaks amplifying behind the separation point, see Fig. 10.

An effect one expects due to the three-dimensional modulation of the mean flow and amplification of the secondary oscillations is modification of the large-scale energetic vortices shedding from the region of boundary layer separation. Similarly, in unstable free shear layers, three-dimensional perturbations of the base flow compete with two-dimensional instabilities destroying the two-dimensional coherent vortex motion [41–43].

The observed reversal of the stream-wise mean velocity defect associated with the development of streaks is a clear indication of the transient amplification of non-modal disturbances. Those with zero initial stream-wise velocity component are the subject of the theory of optimal disturbances [16–20]. Due to downstream transient processes such perturbations exhibit transformation to the streaks accompanied by pronounced growth of their stream-wise velocity. Under the present experimental conditions, the stream-wise perturbation component virtually vanishes in the course

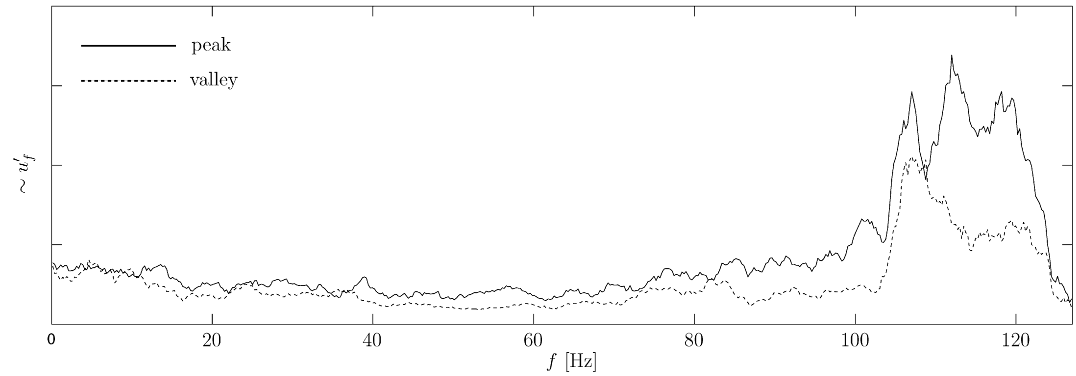

Fig. 11. Power spectra of the velocity perturbations shown in Fig. 10(a) measured at $x = 55$ mm.

of the reversal process occurring in the separation region, see Fig. 8(a), (b). Apparently the disturbances are close to the optimal ones and their development can be compared with results of computations based on the application of the corresponding theory. At the moment only linear computations of optimal disturbances [44] based on parallel local approximation are available for quite close flow conditions. The computations accurately reproduce the shape of the streamwise velocity component of the stationary disturbances. However, the used local theory of optimal disturbances as is cannot predict the velocity reversal or its location.

In the future work on the present topic, it seems reasonable to focus on a comparison of experimental results on the transient growth and computations based on more advanced theories or DNS to achieve a solid conclusion on the applicability and reliability of the concept of optimal disturbances being applied to flow separation; further examination of the secondary high-frequency disturbances evolving in the separation region perturbed by the primary streaky structures; and optimization of the streak generators in respect of their effect upon the separated flow characteristics and its reattachment.

4. Conclusions

Wind-tunnel experiments clearly demonstrate a pronounced effect of three-dimensional stationary perturbations induced in two-dimensional separating boundary layer upon the mean and oscillatory flow components in the separated flow region. With a suitable size of the roughness elements placed close to separation line and span-wise spacing between them, it is possible to generate streamwise stationary disturbances subject to transient growth accompanied by secondary instability to unsteady disturbances promoting the laminar flow breakdown. In this way, the instability phenomena dominating the nominally two-dimensional separation bubbles, promoting the amplification of velocity fluctuations even at small Reynolds numbers, can be altered. Thus, the injection of stationary disturbances in the separation region followed by their transient amplification is a promising way of flow control.

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