Experimental study on artificial environment to promote onset of turbulence

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Abstract

A wind tunnel experiment was performed to investigate the requirements for providing a suitable environment for easily creating a localized turbulent region in a laminar boundary layer. A combination of a short-duration jet and suction was used to prepare a potentially unstable region upstream, and another jet was ejected downstream against the region at various timings and different relative spanwise locations. Based on the results, the combination of the potentially unstable region and the short-duration jet promoted the transition to turbulence only under limited conditions, whereas in most cases, it worked negatively. However, the turbulent spot generation was enhanced when the downstream jet was used at the timing and location that enlarged the low-velocity area created upstream. Moreover, the locally disturbed region generated by the combination of the potentially unstable region and the short-duration jet did not directly grow into a turbulent spot; rather, the turbulent spot grew in the region following the disturbed region.

Keywords : Boundary layer, Local unstable region, Short-duration jet, Onset of turbulence, Turbulent spot

1. Introduction

The onset of turbulence in boundary layers is caused by a sequence of phenomena deriving from flow instability. A path of laminar–turbulent transition through Tollmien–Schlichting (T–S) waves is dominant in a low-disturbance environment, whereas a different path bypassing the T–S waves becomes dominant in a high-disturbance environment. Viscous instability plays a major role in the first path, while inflection point instability initiated by the presence of streaky structures plays a major role (Kachanov, 1994) in the second path. The breakdown to turbulence occurs early in the latter bypass transition case through rapid amplification of velocity fluctuations. The inflectional velocity profile in the wall-normal direction excites the Kelvin–Helmholtz instability and induces a symmetric varicose mode fluctuation. Meanwhile, the spanwise wake-type profile induces an antisymmetric sinuous mode fluctuation. The critical amplitude of the streak strength of the sinuous and varicose modes, respectively, is approximately 26% and 37% of the freestream velocity (Andersson, 2001). As a result of the mode competition, usually the sinuous mode becomes dominant, and the streaky structures are likely to meander (Eloffson et al., 1999; Asai et al., 2002; Asai et al., 2007; Schlatter et al., 2008).

Then, localized turbulent regions known as “turbulent spots” randomly appear in the boundary layer accompanying the breakdown of these streaks. The spots contain densely packed hairpin vortices (Matsui, 1980; Perry et al., 1981; Sankaran et al., 1991; Seifert et al., 1994) and grow in size while traveling downstream, and then, they eventually merge to form a fully developed turbulent boundary layer. Although substantial information is available regarding turbulent spots, a detailed process and the necessary conditions for their generation have not been revealed.
Hairpin vortices are a common structure found in boundary layers and can be generated by a three-dimensional perturbation applied to a two-dimensional laminar boundary layer. Although, as previously mentioned, a turbulent spot consists of densely packed hairpin vortices, its smoothed velocity field also appears like a large single hairpin vortex. Haidari and Smith (1994) observed the generation and regeneration of hairpin vortices repeatedly creating a sequence of symmetric turbulent spots under a controllable injection system. Additional hairpins were formed on both lateral sides and in the wake of primary hairpin by either the lateral inviscid evolution or the rapid eruptions of surface fluid by the effect of the local pressure gradient. Uehara et al. (2010) demonstrated that turbulent spots are more easily generated when a short-duration jet is ejected into a low-speed region of the streaky structures. Yoshikawa et al. (2018a) performed a direct numerical simulation and found that the formation of an inclined streamwise vortex plays a key role in the transition of a flat-plate boundary layer with streaky structures. However, the streaky structures are not essentially necessary for the production of turbulent spots. Okada et al. (2019) prepared a disturbed local area in a laminar boundary layer by adding an artificial disturbance of zero-mass flux, produced by the combination of a short-duration jet and suction. Another jet was ejected downstream at different timings and locations against the disturbed region. They showed that the occurrence of turbulent spots could be enhanced as the triggering jet is ejected to an area between the high- and low-speed regions of a convective unstable region that is not streaky.

The present study performed a wind tunnel experiment to investigate more preferable conditions for the spot generation. The procedure was the same as the one employed by Okada et al. (2019), in which a symmetric fluctuation pattern was prepared as a locally-unstable environment. Numerical observation by Yoshikawa et al. (2018b) suggested that a train of hairpins and a pair of longitudinal vortices were responsible for the generation of a spot. However, it is rare to observe such symmetric structures in natural boundary layer flows because of the freestream disturbance. Thus, we examined the effect of asymmetry of the fluctuation patterns on the onset of turbulence. Three different locally unstable regions were introduced in a laminar boundary layer using the same blowing/suction system, and a weak jet was ejected downstream at various timings and relative locations against them.

2. Experimental setup

2.1. Wind tunnel and flat-plate model

All experiments were conducted in a blowout-type wind tunnel in Tohoku University with a rectangular test section 2,000 mm in length and 500 mm × 500 mm in cross-section. The wind tunnel exhibits a settling chamber of 1,500 mm × 1,500 mm and a contraction nozzle with an aspect ratio of 9:1. Its ceiling is adjustable in the vertical direction, to regulate the pressure gradient in the streamwise direction. A schematic view of the experimental setup is shown in Fig. 1. The flat-plate model was the same as that of Okada et al. (2019). An aluminum alloy plate 1,610-mm long, 490-mm wide, and 10-mm thick was horizontally mounted 185 mm away from the bottom floor of the test section, to avoid contamination caused by the boundary layer developing along the inner wall of the wind tunnel. The plate exhibited a sharp semi-elliptic leading edge with an aspect ratio of 24:1, which suppresses receptivity to the freestream turbulence, and long and short axial radii of 240 and 10 mm, respectively. In addition, a flap with a 190-mm chord length was attached to its trailing edge, to prevent separation on the upper surface near the leading edge by adjusting a stagnation point at the leading edge. The origin of the coordinate system, with the $x$, $y$, and $z$ axes representing the streamwise, wall-normal, and spanwise directions, was located at the center of the leading edge of the plate. Throughout the experiments, the freestream velocity $U_\infty$ was fixed at 8.5 m/s. The ratio of the velocity fluctuation intensity to the freestream velocity in the test section was less than 0.3% of $U_\infty$. The pressure coefficients $C_p$ were adjusted so that their variations would be less than 1% (ie., negligibly small) in the streamwise direction of the test section.

2.2. Local flow destabilizer and triggering jet

A local flow destabilizer (LFD) at $x = 300$ mm was used to generate a potentially unstable region. The LFD is a circular aluminum disk 100 mm in diameter, with nine 1-mm-diameter small holes opened on its surface. The center hole was positioned at $z = 0$ mm, and each hole was aligned 10-mm apart in both the streamwise and spanwise directions. A circular part of the plate of the LFD was designed to be replaceable so that its configuration can be easily changed. An additional hole was prepared at $x = 550$ mm and $z = 0$ mm, 250 mm downstream from the LFD for ejecting a jet that would trigger the turbulent spot generation refer to as a triggering jet (TJ). Each hole of the LFD and the TJ was independently connected to a loudspeaker (VISATON, FRS7) beneath the plate via a funnel and a 6mm-diameter tube, so that the strength and timing of the operation at each hole could be individually controlled by changing the electrical signal provided by a personal computer via a digital-analog (D/A) converter (INTERFACE, PCI-3300) and a power amplifier. The short-
Fig. 1  Schematic view of the experimental setup.

Fig. 2  The Local Flow Destabilizer; ejection (red), suctions (blue), and non-used (white).

Table 1  Operating conditions of the Local Flow Destabilizer

| Case              | Layout of holes | $v_{jet}$, $v_{suc}$ | Time delay $\tau_{(z)}$ |
|-------------------|-----------------|----------------------|-------------------------|
| Basic-noDelay     | Basic           | ejection: 0.38 m/s    | suction: -7.6 ms (-10 mm) |
| Basic-withDelay   | Basic           | suction: 0.42 m/s     | ejection: 0 ms (0 mm)    |
| Tilted-noDelay    | Tilted          | same as above        | 0 ms                    |
duration suctions at certain holes were obtained by applying a signal similar to the ejection case but with an opposite sign, which is represented by the function,

$$\text{Amp}(t) = \begin{cases} \frac{At}{T} & (0 \leq t < T) \\ A \exp(-B(t - T)) & (T \leq t), \end{cases}$$

where $A$ [arb. unit] is the maximum amplitude, $B = 0.0008 \text{s}^{-1}$, and $T$ [s] is the rise time of the driving signal.

In Fig. 2, it can be noted that only three out of nine holes in both “Basic layout” and “Tilted layout” of the LFD, which could be three holes aligned in the $I$-direction at $x = 300 \text{ mm}$ or three diagonal holes, were used. Here, the central hole was always used for blowing, while two side holes were used for suction. In some cases, using the Basic layout, a time difference of $\tau$ was given between the operation of the central hole and the side holes. As a specific case, the suction from the hole at $I = -10 \text{ mm}$ took place 7.6 ms earlier, while the suction from the hole at $I = 10 \text{ mm}$ took place 7.6 ms later, compared to the blowing at the central hole.

Because the accuracy of the velocity measured by a hotwire probe can be very low in low-velocity regions, especially with less than 1 m/s, the velocity of the ejected jet $v_{\text{jet}}$ was measured using smoke images taken by a high-speed camera (Nikon 1, 1200 fps). The funnel and tube connected to the loudspeaker were filled with smoke before the loudspeaker was operated. Figure 3 displays a series of images used for the measurement. The front edge locations of the ejected smoke
were identified from the images and then plotted in Fig. 4. Here, \( t = 0 \) indicates the time the smoke first appeared in the frame. The separated free-shear layer rolled up into a vortex ring, traveling upwards by a self-induced velocity. The measured smoke velocities can be separated into two regions: (I) near the exit and (II) with a distance from the exit. The line segments in the figure represent a trajectory of the smoke in both regions linearized by a least-squares method. Both regions showed reasonable velocities of 0.50 m/s (region I), corresponding to the movement of the smoke caused by the induced velocity at the center of the vortex ring and 0.22 m/s (region II), for the translational velocity of the vortex ring. Mohseni (2006) and Krieg and Mohseni (2013) demonstrated that the translational velocity of a vortex ring ejected from a Helmholtz-type generator was approximately half the piston speed. Therefore, the ejection velocity \( v_{\text{jet}} \) was defined as twice the translational velocity of the vortex ring measured in region (II).

Changing the maximum amplitude \( A \) in Eq. 1, the translational velocities of the vortex ring were measured, as shown by the plots in Fig. 5. Based on the figure, the translational velocity of the vortex ring is proportional to the maximum voltage supplied to the loudspeaker. The approximated straight-line segment in the figure is represented by the equation

\[
v_{\text{jet}} = 3.9 \times 10^{-3} A - 3.25 \times 10^{-4},
\]

which was used to obtain the jet velocity. Table 1 gives a summary of the blowing/suction conditions, where the velocity produced by the suction \( v_{\text{suc}} \) is assumed as equal to that of blowing \( v_{\text{jet}} \). Unlike in the previous study of Okada et al. (2019), the net-mass flow was not zero in the present conditions, as the suction velocity was set to be larger than the ejection velocity.

2.3. Measurement methods

The velocity was measured using a single-type hotwire probe with a constant-temperature anemometry (CTA) circuit. A three-dimensional traversing mechanism was used to change the probe location. Another fixed probe was used for two-point simultaneous measurements. High-frequency components of the hotwire signal were removed using a fourth-order Butterworth-type low-pass filter at the cut-off frequency of 2.5 kHz, to prevent aliasing errors. The filtered signal was converted to digital data and stored in a personal computer via a 16-bit analog–digital (A/D) converter (INTERFACE, PCI-3155) operating at the sampling frequency of 5 kHz. The number of data for one series of sampling was \( 2^{14} \).

Growth of locally disturbed regions was discussed by applying Taylor’s frozen-eddy hypothesis to the measurement data. This hypothesis is valid for large-scale motions at a certain height in boundary layer flows because the spatial structures associated with turbulence only slowly change their shapes while moving downstream. David and Timonthy (2008) obtained an appropriate convection velocity using a space–time correlation map constructed from particle image velocimetry (PIV) data, and they compared it with the local mean velocity. The researchers demonstrated that the local mean is a suitable estimate for convection velocity. However, one must be careful when comparing the fields obtained...
by Taylor’s hypothesis of different heights because their relative locations are quite sensitive to the estimated error of convection velocity. In this study, the velocities of the base laminar flow were used as the convection velocities because the disturbed regions are generated only intermittently, and the boundary layer remains laminar most of the time. Instead of the Taylor’s approximation, an inverse time scale, defined using an elapsed time after activation of the LFD, could be used to compare the disturbed flow patterns at different heights.

The turbulence intensity was measured by the rms value of the deviation of velocity from the ensemble-averaged value,

\[
\bar{u}(t) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} <u'>_i^2},
\]

\[
<u'> = u_i(t) - <u(t)>,
\]

where \(N\) is the number of ensemble averaging that corresponds to the number of blowing/suction events, \(u_i\) the velocity of the \(i\)th event, and \(<u(t)>\) the ensemble-averaged velocity. Hereafter, \(\bar{u}\) is denoted as “the intensity of random components”.

3. Results and discussion

3.1. Base flow and artificial disturbance

Figure 6 shows the profiles of the time-averaged velocity of the base flow measured at various \(x\) stations of \(z = 0\) mm, where the vertical axis denotes the nondimensional height from the wall (\(\eta\)) given as

\[
\eta = y \sqrt{\frac{U_\infty}{v_x}},
\]

In the absence of blowing and suction, all velocity profiles agreed well with the Blasius profile, in which the virtual origin location was approximately 110-mm upstream of the leading edge. The profiles show that the boundary layer was laminar throughout the measurement region, \(x = 300 \sim 900\) mm, despite the several holes opened on the plate surface.

Only the boundary-layer blowing/suction was applied to the Blasius boundary layer. The resulting fluctuations were measured at the station matching the downstream ejection hole at \(x = 550\) mm. Figure 7 shows the contour maps of the ensemble-averaged fluctuation \(<u'>\) in the \(zt\) plane at \(\eta = 1, 2, 3,\) and \(4\), when the upstream LFD was driven by each operating condition listed in Table 1, whereas the downstream TJ was absent. The time-series data were obtained every 2 mm in the spanwise direction by a hotwire probe. A total of 20 runs were performed to obtain each ensemble-averaged value. The target disturbed regions displayed very weak strength, within \([-0.012, 0.012]\), or almost one-fifth to one-sixth
Fig. 7 Contour maps of velocity fluctuation $<u'>$ in constant $\eta$ planes generated by Local Flow Destabilizer at $x = 300$ mm for (a) Basic-noDelay, (b) Basic-withDelay, and (c) Tilted-noDelay cases. Measurements are performed at $x = 550$ mm; $t = 0$ indicates the time when the jet is ejected from the central hole.
that found by Okada et al. (2019). In all cases, high- and low-speed regions appeared alternately near the wall in both the streamwise and spanwise directions, though their patterns were slightly different. They gradually weakened further downstream, with no sign of turbulent transition throughout the measuring section, and thus, the LFD did not directly trigger the transition to turbulence.

Here, we would like to briefly look into the high- and low-speed regions which appeared at $-t = -0.07 \text{ to } -0.11$ s in Fig. 7. The LFD creates vortical structures by locally deforming the Blasius boundary layer. Yoshikawa et al. (2018b) demonstrated that when the boundary layer was destabilized by ejecting a short-duration jet from the wall, a necklace vortex was generated on the upstream side, and a train of hairpins and a pair of longitudinal vortices were created on the downstream side. It can be assumed that similar or more complicated vortical structures are generated by the LFD. The velocity gradient of the boundary layer stretches the vortices in the streamwise direction. The stretched vortex pair induces an upwash at the center and downwashes on two sides. The upwash between the vortices appears as the low-speed region, while the downwashes are responsible for the high-speed regions. The traveling speed of the vortices created by the LFD matched the local mean velocity of the $\eta = 1$ plane, suggesting that the Taylor’s frozen-eddy hypothesis is applicable. The opposite-signed fluctuations after the passage of these primary disturbed regions are caused by a vortical structure different from the one directly generated by the LFD. The detail of this trailing vortical structure and how it is created are still unrevealed.

The pattern in the “Tilted-noDelay” case appeared a little weaker and unclear compared to the rest. The pattern in the “Basic-noDelay” case was almost symmetrical about the $x$ axis, whereas it leaned to the positive spanwise direction in the “Basic-withDelay” case, which reflects a time delay between the operations at the holes. The temporal difference between the blowing and suctions was much larger than the spatial misalignment of the suction holes in the streamwise direction. Accordingly, with the measured convection velocity of 3.2 m/s, the time difference between the two suction events of 15.2 ms in “Basic-withDelay” corresponded to approximately 49 mm in actual distance, whereas the streamwise spacing between two suction holes in the “Tilted-noDelay” case was only 20 mm. On this basis, only the “Basic-noDelay” and “Basic-withDelay” cases were compared in the succeeding sections.

### 3.2. Interaction of convecting disturbed region and triggering jet

The TJ was ejected against the convecting disturbed regions at three streamwise locations, $z = 0$, -5, and -10 mm for various timings and strengths. It should also be noted that the TJ itself was not strong enough to trigger the transition to turbulence either. In the experiments, the LFD location was actually shifted to the positive $z$ direction to change the relative position between the LFD and the TJ. A total of 17 trials were performed every 5 ms, from $t = 57.6 \text{ to } 137.6$ ms.
The ejection velocity was changed from 0.63 – 0.96 % of the freestream velocity, which was larger than the blowing/suction velocities of the upstream device. Accordingly, the disturbed field provided by the LFD displayed sufficiently good reproducibility for both operating conditions, “Basic-noDelay” and “Basic-withDelay.”

The effect of the TJ on the generation of a localized turbulent region downstream was evaluated by using the probability of turbulence generation $\gamma$,

$$\gamma = \frac{\text{Occurrences of turbulent region generation}}{\text{Total number of trials}},$$

where the “Total number of trials,” equal to 100, is the same as the number of jet ejections. Whether a local turbulent region was generated or not was judged based on the amplitude of the velocity fluctuations exceeding a certain threshold value, which was determined by observing the raw velocity signal at $x = 950$ mm, $\eta = 2$, and $z = 0$ mm in the “Base-noDelay” condition.
case. Figure 8 shows a histogram of the turbulent/non-turbulent state occurrences, where a turbulent signal was detected in 312 occasions among the 636 total trials. The turbulent and non-turbulent regions were clearly separated at around $|u'|/U_\infty = 0.1$ as a boundary.

Using the same criterion, the probabilities of turbulence generation $\gamma$ were measured at three spanwise stations, $z = 0, -5, \text{ and } -10 \text{ mm}$. Figures 9, 10, and 11 show a comparison of the corresponding probabilities $\gamma$ at $x = 950 \text{ mm}$ and $\eta = 2$. The effect of differences in the ejection timing was small, and no remarkable change in the tendencies could be found between the two configurations. At $z = 0$ and -10 mm of the “Basic-noDelay” case, when the jet velocity of the TJ was high, $\gamma$ tended to be lower than the “Triggering Jet only” case; otherwise, low jet velocities, it was comparatively higher. In the other cases, a slightly stronger jet was required to obtain the same $\gamma$ as the “Triggering Jet only” case in most conditions. Based on these results, the conclusion exists that a weakly disturbed flow created by the LFD promotes
the transition to turbulence only under limited conditions but works negatively in most cases.

The tendency of turbulence occurrence against a TJ was evaluated by a weighted average, $\varepsilon$,

$$\varepsilon = \int_0^1 \frac{v_{\text{jet}}}{U_{\infty}} (1 - \gamma) d\gamma. \tag{6}$$

Here, smaller $\varepsilon$ corresponds to higher triggering efficiency. Figure 12 shows a comparison of the triggering effect of various ejection timings at the spanwise stations, $z = 0, -5,$ and $-10$ mm, for each case, where $\overline{\gamma}$ denotes the value averaged for all ejection timings at each spanwise station. A negative value of $\varepsilon - \overline{\varepsilon}$ indicates that a transition can be caused by a weaker TJ. Accordingly, the most effective timings were $-t = 0.06$ at $z = -10$ mm for the “Basic-noDelay” case and $-t = 0.1$ at $z = -10$ mm for the “Basic-withDelay.” In Fig. 13, the effective and ineffective timings, evaluated on the basis of a threshold of $\pm 2.5\%$ of $(\varepsilon - \overline{\varepsilon})/\overline{\varepsilon}$, are marked in the $\eta = 1$ plane of the target disturbed field. Many effective timings
Fig. 12  Comparison of relative triggering effects $(\varepsilon - \overline{\varepsilon})/\varepsilon$. Measurements are performed at $z = 0, -5, \text{and} -10\text{mm}$ of $x = 950\text{mm}$ and $\eta = 2$.

Fig. 13  Efficient and inefficient timings and locations for Triggering Jet in generating turbulent regions. Efficient timings are marked by circles and inefficient timings are by crosses in circles.
and locations were located around the low-speed region and inside the subsequent high-speed region, which suggests that the ejection of a jet at such timings contributed to the expansion of the low-speed region where the wall-normal velocity profile exhibits an inflection point that causes the region to be more unstable. Conversely, direct ejection to the low-speed region was not effective. Ejecting the TJ just before the arrival of the low-speed region was also ineffective. Based on this result, the size of the low-speed region may be more important than its strength. It should be noted that the most effective timing of $-t = -0.06$ at $z = -10$ mm for the “Basic-noDelay” case corresponds to ejecting the TJ against the undisturbed region at the downstream side of the high-speed region.

3.3. Evolution local turbulent region

A two-point simultaneous measurement was performed to investigate the evolution of the turbulent region in the “Basic-withDelay” configuration. The triggering was chosen at $-t = -0.1$ s and $z = -5$ mm, which was one of the effective timings and locations shown in Fig. 13 (b). The TJ was ejected at the strength of $v_{\text{jet}}/U_\infty = 0.08$, corresponding to the transition probability of $\gamma = 0.5$. A reference probe was installed downstream at $x = 970$ mm, $\eta = 2$, and $z = 0$ mm, to detect the passage of the convecting turbulent region. Each experiment was repeated 50 times. Subsequently, the ensemble averages of the conditionally sampled data were computed at each station. The contour maps of the velocity fluctuations $< u' >$ and the intensities of random components $\tilde{u}$ at $x = 950$ mm in the $zt$ planes at $\eta = 1$ and in the $yt$ planes at $z = 0$ mm are shown in Fig. 14, where researchers found that areas where the intensity of random component $\tilde{u}$ become higher roughly corresponded to areas where velocities are low. Moreover, the overall shape of the turbulent region in the $zt$ plane could be described as an arrowhead, a typical feature of a turbulent spot. The opening angle of the sharp front end of the turbulent region was approximately 22 degrees, whereas the rear end was blurry and gradually attenuating. The turbulent
region reached \( \eta = 8 \), which is beyond the outer edge of the boundary layer, \( \eta = 5 \). A very similar pattern was observed when the TJ was weaker as \( \gamma = 0.2 \). From the geometric resemblances, the turbulent region generated was judged as a typical turbulent spot (Wygnanski et al., 1982; Gutmack and Blackwelder, 1987). Meanwhile, when the TJ failed to promote transition, only a low-speed region elongated in the streamwise direction at around \( z = 0 \) mm was left in the boundary layer downstream, and the intensity of the random components was close to zero everywhere.

Furthermore, the evolution process of the turbulent spot shown in Fig. 14 was investigated in detail. Again, the LFD was utilized in the “Basic-withDelay” mode, and the TJ was operated at \( -t = -0.1 \) s and \( z = -5 \) mm. Figure 15 shows the ensemble-averaged profiles of velocity fluctuation and intensity of random components both at \( \eta = 2 \) and \( z = 0 \) mm.

Fig. 15 Evolution of turbulent spot by ensemble-averaged velocity fluctuations \( \langle u' \rangle \) (black line) and intensities of random components \( \tilde{u} \) (red line) at different streamwise stations of \( \eta = 2 \) and \( z = 0 \) mm. The abscissa represents the elapsed time from the arrival of target disturbed region to each measurement station.
Fig. 16  Contour map of velocity fluctuation $< u' >$ in $\eta = 2$ plane when turbulent region is detected by reference probe at $x = 950$ mm. Measurements are performed at $x = 750$ mm station.

and at different streamwise stations ranging from $x= 600 – 950$ mm. Data sampling took place each time the downstream reference probe, which was at the same height as the sampling probe, detected the passage of the turbulent region. Here, the abscissa represents the elapsed time from the arrival of the target turbulent region to the measuring station, and the time series was treated with Taylor’s approximation. Initially, a wave of high and low velocity fluctuation, ranging from -0.12 to -0.18 s in Fig. 7 (b), transiently amplified until $x = 650$ mm (indicated by the black arrows), and then eventually decayed without causing any transition to turbulence. Instead, a different low-speed region started to appear at $x = 650$ mm station and grew downstream. As the velocity became lower, the turbulence intensity became higher, creating typical velocity and turbulence intensity fluctuations that accompanied a turbulent spot at the stations of $x = 850$ and 950 mm. Figure 16 shows a contour map of the velocity fluctuation $< u' >$ measured at $x = 750$ mm in the $\eta = 2$ plane when a turbulent region was detected by the reference probe at $x = 950$ mm, where a pair of high-speed regions appearing on both spanwise sides of the low-speed region could be observed. This low-speed region was one that turns into a turbulent spot at $x = 850$- and 950-mm stations downstream. Such a fluctuation pattern can be often observed in flow fields associated with a pair of longitudinal vortices or a hairpin vortex. Consequently, this secondary structure caused the generation of the turbulent spot in Fig. 14 and not directly the unstable region generated by the combination of the LFD and the TJ. A similar phenomenon was observed in a numerical study of a boundary layer flow (Yoshikawa et al., 2018b), where the boundary layer was destabilized by ejection of a short-duration jet from a single hole in the wall surface. Nevertheless, this calls for a study of the process by which a turbulent spot is generated at a location different from where the flow is locally disturbed.

4. Conclusions

The wind tunnel experiment conducted here was aimed at investigating the conditions for providing a suitable environment where a localized turbulent region can be generated easily in a laminar boundary layer. The potentially unstable region was prepared upstream by a combination of a short-duration jet and suction, i.e., the local flow destabilizer (LFD). Another device, namely a triggering jet (TJ), was ejected downstream against them at various timings and relatively different spanwise locations. The experimental results confirmed that combining the LFD and the JT promoted the transition to turbulence only under limited conditions but worked negatively in most cases. However, the turbulent spot generation was enhanced when the TJ was used at the timing and location that enlarged the low-velocity area created upstream by the LFD. This suggests that expanding the low-speed region would be a necessary condition for the onset of turbulence. Moreover, the locally disturbed region generated by the combination of the LFD and the TJ did not directly grow into a turbulent spot. Instead, the turbulent spot grew in the region following the disturbed region.

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