TURBULENT-TURBULENT SPOT ACROSS THE BUFFER LAYER OF THE TURBULENT ZERO-PRESSURE-GRADIENT FLAT-PLATE BOUNDARY LAYER

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ABSTRACT

We define turbulent-turbulent spot as a local concentration of vortices with high level of swirling strength originating from hairpin packet in a turbulent boundary layer. We also define bypass transition in the narrow sense as the breakdown of the Blasius boundary layer beneath freestream homogeneous isotropic turbulence with an initial amplitude of 1 to 4 percent. We present evidence for the existence and plurality of turbulent-turbulent spots across the buffer layer within the first 100 wall units. Infant/young turbulent-turbulent spot is a hairpin packet, more matured ones are a mixture of hairpin vortices and random vortex filaments. Although structurally analogous to the transitional-turbulent spots, these turbulent-turbulent spots are nevertheless generated locally in the chaotic fully-turbulent environment instead of being transported from the far-upstream transition, and they are robust with the variation of detection threshold. Viscous sublayer streaks are strongly indented, segmented and often terminated by the turbulent-turbulent spots. Evidence is extracted from our spatially-developing direct simulation, which carries the inlet Blasius boundary layer through a bypass transition (in the narrow sense) arriving at the canonical turbulent boundary layer state over a moderate Reynolds number range. The present results seem to be at odds with the widely-held belief that the buffer layer is dominated by random quasi-streamwise vortices. Accuracy of the direct simulation statistics is demonstrated by comparing with established turbulent boundary layer measurements. For the present bypass transition in the narrow sense at 3 percent inlet freestream turbulence intensity, we also found that the transitional turbulent spot inception mechanism and laminar boundary layer breakdown process is analogous to the secondary instability of boundary layer natural transition. Long streak meandering does occur, but in our flow it mostly happens when a streak is in the vicinity of an existing transitional-turbulent spot. Streak meandering and breakdown is therefore not the mechanism for the inception of transitional turbulent spot, but only facilitates the growth and spreading of existing transitional-turbulent spots.

INTRODUCTION

One of the corner-stones of modern fluid mechanical science is the incompressible flow over a smooth flat-plate at zero pressure-gradient (canonical boundary layer), which forms the limiting case and calibration benchmark of many practical aeronautical engineering flows. Starting from a Blasius boundary layer, there are numerous ways of generating the downstream transitional and turbulent boundary layers. The most fundamental route, natural transition, is that the layer being subjected to infinitesimal disturbances in the sense of Schubauer & Skramstad [1], who verified through experiments the existence of Tollmien-Schlichting wave predicted by linear stability theory. The second most fundamental route, bypass transition in the narrow sense, is a superposition of the canonical boundary layer, in its freestream, with the simplest possible turbulent flow – initially homogeneous isotropic turbulence of (mildly) finite amplitude. There is a pronounced plurality of this case compared to the case of natural transition since the length-scale and intensity of the isotropic grid turbulence participating in the superposition are the extra independent variables. Westin et al. [2] pointed out the need for creating "standard" conditions in transition experiments, and mentioned that if the freestream turbulence intensity (FST) level is larger than 5% transition will be rapid and occurs at the minimum Reynolds number for self-sustained boundary layer turbulence to exist. It is also obvious that for boundary layers with very high FST level, e.g., 5%, the superposition will severely distort the basic boundary layer profile right at the inlet. For purposes of investigating mechanisms of bypass transition in the narrow sense, it has been accepted to only consider a narrow FST window between approximately 1% and 4% at the leading edge. The lower threshold 1% is chosen so that the Tollmien-Schlichting wave will not be the dominant mechanism. One important piece of experimental result from Westin et al. is confirming, for bypass transitional flows in the narrow sense, a quasi-linear dependence of squared peak streamwise turbulence intensity with streamwise distance. This linearity is an important result of the "algebraic/transient growth" theory, see Anderson et al [3]. Matsubara and Alfredsson [4] extended the experiments of Westin et al. [2] by varying leading edge freestream turbulent intensity

from 1.5%, 2.2% to 6% and by performing flow visualization. They emphasized a plausible connection between their experiments and transient growth theory from three different angles: the aforementioned linearity, a collapse of y/δ^* versus $u_{rms}/u_{rms,peak}$ profiles at different streamwise locations onto the prediction from theory, and visualization images of high and low streamwise velocity streaks. Here, δ^* is boundary layer displacement thickness, y is wall-normal coordinate. In particular, they noted that interpretations of their results are guided by the algebraic/transient growth theory: receptivity giving rise to streaks, transient growth of streaks, breakdown of the flow owing to a secondary instability of the streaks. Though interesting, it seems that the experiments of Matsubara & Alfredsson [4] should not be viewed as a full validation of the theory; especially considering that no causality was established between streak and breakdown from their visualization, and also considering that no causality was established between streak and the statistical properties. Following the same line of thought, many authors such as Jacobs & Durbin [5] also reported DNS studies on the problem of bypass transition in the narrow sense with a synthetic grid turbulence manufactured by superposing modes of the continuous spectrum of the Orr-Sommerfeld and Squire equations. They suggested that the breakdown into turbulent spots is related to local secondary instabilities of these streaks. Jacobs & Durbin [5] observed that when upwelling lifts the streaks away from the wall they become a receptivity site for smaller scale freestream turbulence which initiates an instability near the top of the boundary layer and results in breakdown. Overall, it seems that most of these studies suggest that bypass transition in the narrow sense develops its own primary instability in the form of streaks whose algebraic/transient growth leads to secondary instability (streaks meandering or streak interaction with free-stream eddies), and eventually breakdown of the laminar layer.

Our idea is that there may exist the possibility that at least a sub-category of bypass transition in the narrow sense might be approximated with the secondary instabilities of boundary layer natural transition, implying a partial unification of these two branches of study. There is actually some literature support for this partial unification conjecture. Klebanoff et al. [6] wrote "Increasing the ribbon amplitude had no significant effects on the character of the wave generated except to move the point of departure and breakdown further upstream. With sufficiently large amplitude, it was possible to by-pass the linear (TS-wave) range completely. This was graphically demonstrated by observing the behavior of a wave of such frequency that it should damp according to the linear theory. At low amplitudes the wave damped as expected, but at a sufficiently high amplitude it did not damp and very rapidly led to breakdown of laminar flow in much the same manner as a wave within the amplified zone." Their statement is remarkable and particularly relevant here because they semi-explicitly equated bypass transition with secondary instabilities of natural transition. The statement is further interesting because it seems to us that this was the first time the word "bypass" appeared in an archival journal within the context of boundary layer transition. In comparison, the often quoted first naming of bypass transition by Morkovin actually occurred seven years later in 1969. From the perspective of accurate boundary layer simulation, most of the previous DNS studies on bypass transition in the narrow sense were performed prior to the recent resurgence in boundary layer DNS. As a result, they made compromises due to hardware limitations, on streamwise domain size, boundary conditions, grid

resolution and used synthetic inflow grid turbulence manufactured by superposing modes of the continuous spectrum of the Orr-Sommerfeld and Squire equations. The past few years have seen remarkable advances on very-large-scale (VLS) boundary layer DNS, in terms of both statistical accuracy and resolution of coherent structures: Wu & Moin [7], Schlatter & Orlu [8], Lee & Sung [9], Sayadi et al [17], which provided unprecedented easy access to the details of boundary layer coherent structures. Prior to 2009, it had been quite difficult to detect these coherent structures from the then existing DNS databases (Adrian [10]). In light of this quasi step-change in boundary layer DNS capability since 2009, we are of the opinion that it is logical and imperative to revisit the simulation on bypass transition in the narrow sense so that this problem is re-examined using the new and improved more realistic approach. We are particularly interested in a resolution on our conjecture that a sub-class of bypass transition in the narrow sense might be viewed as the secondary instabilities of natural transition.

For over sixty years one central theme in fundamental fluid mechanics research has been the search for the basic constitutive organized vortex structure in the turbulent, zero-pressure-gradient, smooth flat-plate boundary layer (ZPGSFPBL), particularly inside the wall/inner layer less than 100 viscous units away from the plate where most of the turbulence kinetic energy is produced (Smits et al [11], Marusic et al [12], Sharma & McKeon [13]). The issue is an important one because it tests our intellectual ability to identify the elemental vortex structure in even the simplest wall-bounded external aeronautical flow. Apparent consensus seems to have been reached that the inner region of the turbulent ZPGSFPBL is populated by randomly distributed quasi-streamwise vortices as well as elongated high- and low-momentum streaks; the streaks participate in a self-sustaining bursting cycle including streak generation, lift-up, oscillation, breakdown, and streak regeneration (McKeon [14]).

Sustained efforts have also been devoted to study properties and dynamics of (transitional) turbulent spots in the natural or bypass transitions of the ZPGSFPBL. The long-cherished hope is that information extracted from the transitional-turbulent spots (TRTS) during the inception of boundary layer turbulence may shed light on the wall layer dynamics of turbulence regeneration in the fully turbulent ZPGSFPBL. Though certainly logical and sensible, such noble objective has proven to be elusive and research on TRTS has been firmly confined within the domain of boundary layer transition with only a few exceptions. It was conjectured that transitional turbulent spot eventually develops into the large-scale eddying motion (LSM) of the fully turbulent boundary layer in the form of a bulge protruding into the freestream (Delo et al [15]). Even though it is quite obvious now that this conjecture has major problems, the attempt to directly connect transitional turbulent spot with turbulent boundary layer eddying motion is nevertheless noteworthy. Up until this point, it seems that there has been no direct evidence to structurally connect transitional turbulent spots with the inner layer dynamics in the fully turbulent ZPGSFPBL.

We demonstrate that the buffer region of the canonical turbulent boundary layer is populated by locally generated turbulent-turbulent spots (TUTS), which in turn exert strong indentations and segmentations on the viscous sublayer streaks. The turbulent-turbulent spots are structurally analogous to their transitional counter-parts but without any direct causality connection. Although these evidences are at odds with the widely-held belief

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that the buffer region is dominated by quasi-streamwise vortices, they nevertheless highlight an alternate avenue for near-wall turbulence theory and modeling, and contribute to the unification of the two previously segregated research areas on late-stage boundary layer transition and on near-wall turbulent boundary layer dynamics. We will also provide convincing evidence to demonstrate that the inception mechanism of transitional-turbulent spot is analogous to the secondary instability of boundary layer natural transition rather than the meandering and breakdown of long streaks. Streak meandering does occur, but it merely facilitates the growth and spreading of existing TRTS.

METHOD

Starting from a Blasius boundary layer, there are many approaches of generating the downstream transitional and turbulent boundary layers. The most fundamental route, natural transition, is that the layer being subjected to infinitesimal disturbances with downstream exponential growth of the Tollmien-Schlichting wave. The second most fundamental route, bypass transition in the narrow sense (defined here), is a superposition of the Blasius ZPGSFPBL, in its freestream, with the simplest possible turbulent flow, initially homogeneous isotropic turbulence (HIT), of finite amplitude between 1 to 4%. Bypass transition in the general sense, refers to the breakdown of a laminar boundary layer under unspecified type of finite-amplitude external disturbances such as passing wake, roughness, blowing and suction, etc.

In this work, DNS of incompressible ZPGSFPBL beneath a continuous flow of homogeneous isotropic FST was performed on a mesh of $16384 \times 500 \times 512$. Momentum thickness Reynolds number Re_θ develops from 80 to 3000, with a corresponding FST decay from 3 to 0.8%. The domain size is $21562.5\theta_0 \times 2250\theta_0 \times 843.75\theta_0$, θ_0 is the inlet momentum thickness. The boundary layer thickness δ increases from $7.55\theta_0$ at the inlet to $312\theta_0$ at the exit. $Re_\tau = u_\tau \delta / \nu$ reaches 1003 at the exit. Grid resolutions are $3.5 < \Delta x^+ < 5.5$ and $4.5 < \Delta z^+ < 7$, respectively. Measured using the local Kolmogorov length scale $\eta = (\nu^3/\varepsilon)^{1/4}$, at the station $Re_\theta = 2900$, $2 < \Delta x/\eta < 3$ for $y/\delta < 0.1$, and $0.5 < \Delta x/\eta < 2$ in the outer region; $0.4 < \Delta y/\eta < 2$ throughout the layer. Inlet FST generation used the strong recycling methodology as described in Wu [16]. Frist, 25 independent temporally decaying HIT blocks were created using an auxiliary set of DNS. The velocity derivative skewness factor of the blocks is -0.47, and their longitudinal and transverse velocity correlation functions satisfy the relation from incompressible HIT theory. Ten random combination sets of the 25 independent HIT blocks were then created, and the resulting 250 blocks were aligned sequentially, forming a narrow cuboid-shaped band of $210937.5\theta_0 \times 843.75\theta_0 \times 843.75\theta_0$. At the inlet plane, the HIT band is aligned with the mean freestream so that it is transported into the boundary layer DNS domain by the mean freestream speed U_f; and the lower edge of the band is located at $15\theta_0$ away from the plate to ensure that the inlet Blasius boundary layer is undistorted. Temperature is also included in the DNS at unit molecular Prandtl number. The non-dimensional temperature φ is 1 at the wall, and 0 in the upper boundary. At the inlet φ is prescribed using the Blasius profile without any fluctuations. Time step of the DNS is $\Delta t = 1.125\theta_0/U_f$. After reaching statistically steady state, the full velocity, pressure and temperature fields were saved at a rate of

every $100\Delta t$ for a duration of $30000 \Delta t$. Each of these saved data files has a size of 203GB. The entire computation took nearly five year's wall-clock time to complete.

RESULTS

Our predicted skin friction coefficient C_f agrees with analytical solution prior to laminar flow breakdown, and agrees with classical experimental data in the fully turbulent region, see Figure 1. During transition, C_f follows closely the trend of the T3A bypass transition experiment. Decay of FST length scale as function of Re_θ is documented, which include η, Taylor microscale $\lambda = [2u'^2_{rms}/\overline{(\partial u/\partial x)^2}]^{1/2}$, and large eddy scale $L = [TKE]^{1/2}/\varepsilon$. Mean streamwise velocity, turbulence intensities and Reynolds shear stress are compared with existing experimental and DNS ZPGSFPBL data. Mean wall-normal velocity at boundary layer edge as well as wall and peak rms pressure fluctuations are in overall agreement with those in Schlatter & Orlu [8], Lee & Sung [9]. Wall shear stress fluctuation τ'^+_w is nearly constant (between 0.42 and 0.43) for $1000 < Re_\theta < 3000$. It is useful to quantify the effect of such penetration in terms of boundary layer statistics. Figure 2 presents conditionally sampled second-order statistics in the early transitional region $Re_\theta = 150$. The probability of detecting FST at a wall-normal location, $\gamma(y)$, is also presented in the figure by plotting the quantity $1-\gamma$. Here, the instantaneous event of detecting cold FST at a location is defined as $\varphi(x, y, z, t) < 0.01$. Conditional sampling is also based on this criterion. In other words, if $\varphi(x, y, z, t) > 0.01$, then the instantaneous contribution to boundary layer statistics from the (cold) FST fluid at this location is considered to be zero. It is seen from the figure that at this very-low Reynolds number, the Reynolds shear stress has not been developed yet; and v' rms and w' rms increase monotonically away from the wall approaching their FST values. The probability γ is nearly zero below y = 0.75δ. For the locations $0.75 < y/\delta < 1$ where γ is mild, the conditionally averaged contributions from FST to all the turbulence intensities are above the respective total values. This characterizes the early transitional stage of the flow. Figure 3 presents the conditionally sampled results in the late transitional stage at $Re_\theta = 670$. As the transition process progresses towards completion, the degree of penetration of FST into the boundary layer increases substantially. At the same time, however, there are also extreme events in which the conditionally-averaged contribution of FST to the local streamwise intensity and shear stress exceed the respective mean values. For the turbulent ZPGFPBL under mild FST, the FST affects the outer 50% of the layer, whereas the influence of the wall-fluid extends to 150% of the layer. Visualizations of the TRTS and TUTS are presented in Figure 4 and Figure 5, respectively.

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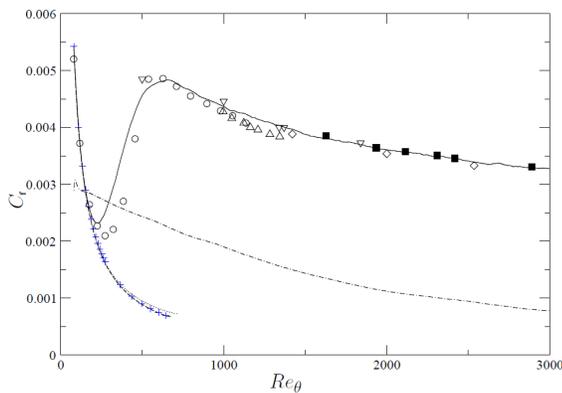
Figure 1. Variation of skin friction coefficient with Re_θ. Present DNS: solid line: case B3K with 3% inlet FST; dotted line: case B2Ka1 with 1.3% inlet FST; dashed line: case B2Ka2 with 0.01% inlet FST. Dash-dot-dashed line: one-tenth of the FST in case B3K. Plus: Blasius solution. Other symbols: previous experimental and DNS data.
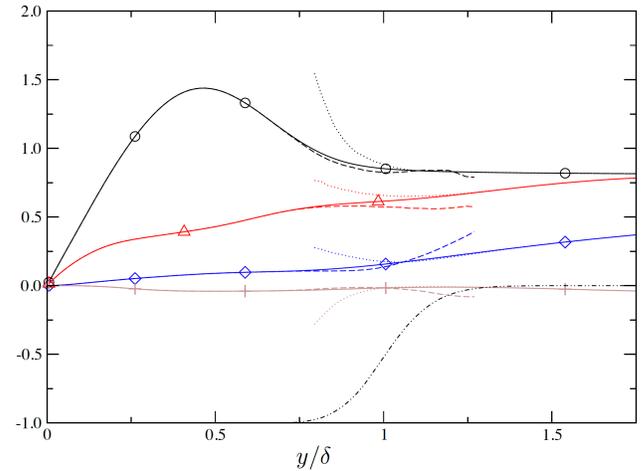

Figure 2. Conditionally sampled second-order statistics at $Re_\theta = 150$. Circle $u'^+_{\rm rms}$; diamond $v'^+_{\rm rms}$; triangle $w'^+_{\rm rms}$; plus $\overline{u'v'}^+$. Solid line: total contribution; dotted line: mainly from cold freestream fluid; dashed line: mainly from hot near-wall fluid. Dash-dot-dot-dashed line: $1-\gamma$, where γ is the probability for detecting the cold FST fluid.
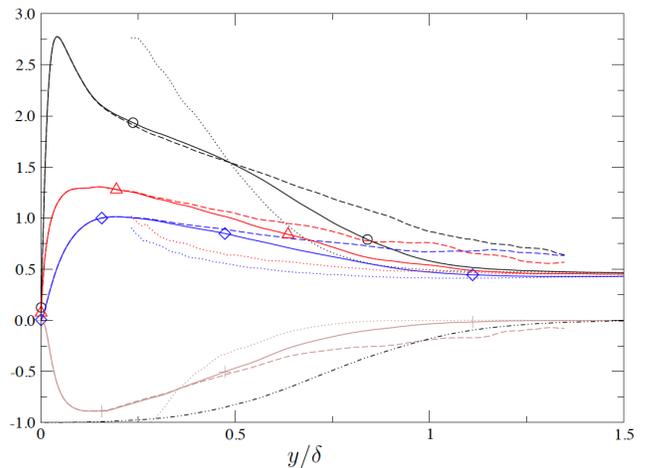

Figure 3. Conditionally sampled second-order statistics at $Re_\theta = 670$. Circle $u'^+_{\rm rms}$; diamond $v'^+_{\rm rms}$; triangle $w'^+_{\rm rms}$; plus $\overline{u'v'}^+$. Solid line: total contribution; dotted line: mainly from cold freestream fluid; dashed line: mainly from hot near-wall fluid. Dash-dot-dot-dashed line: $1-\gamma$, where γ is the probability for detecting the cold FST fluid.
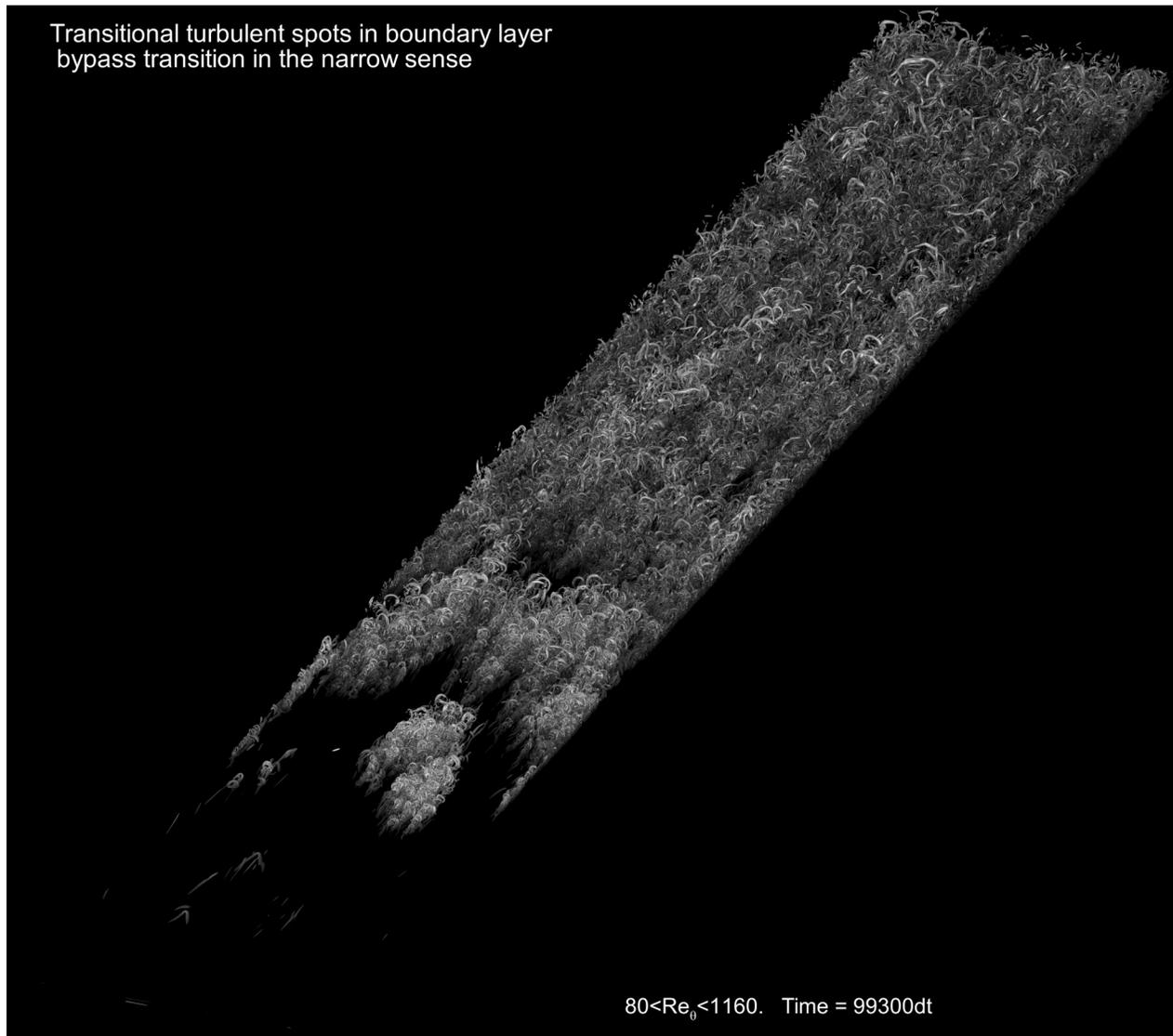
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Figure 4. Transitional-turbulent spots (TRTS) in the present boundary layer bypass transition of the narrow sense under 3% inlet FST. The spots are made visible using isosurfaces of swirling strength. White color indicates that the isosurfaces are higher than the local boundary layer thickness.
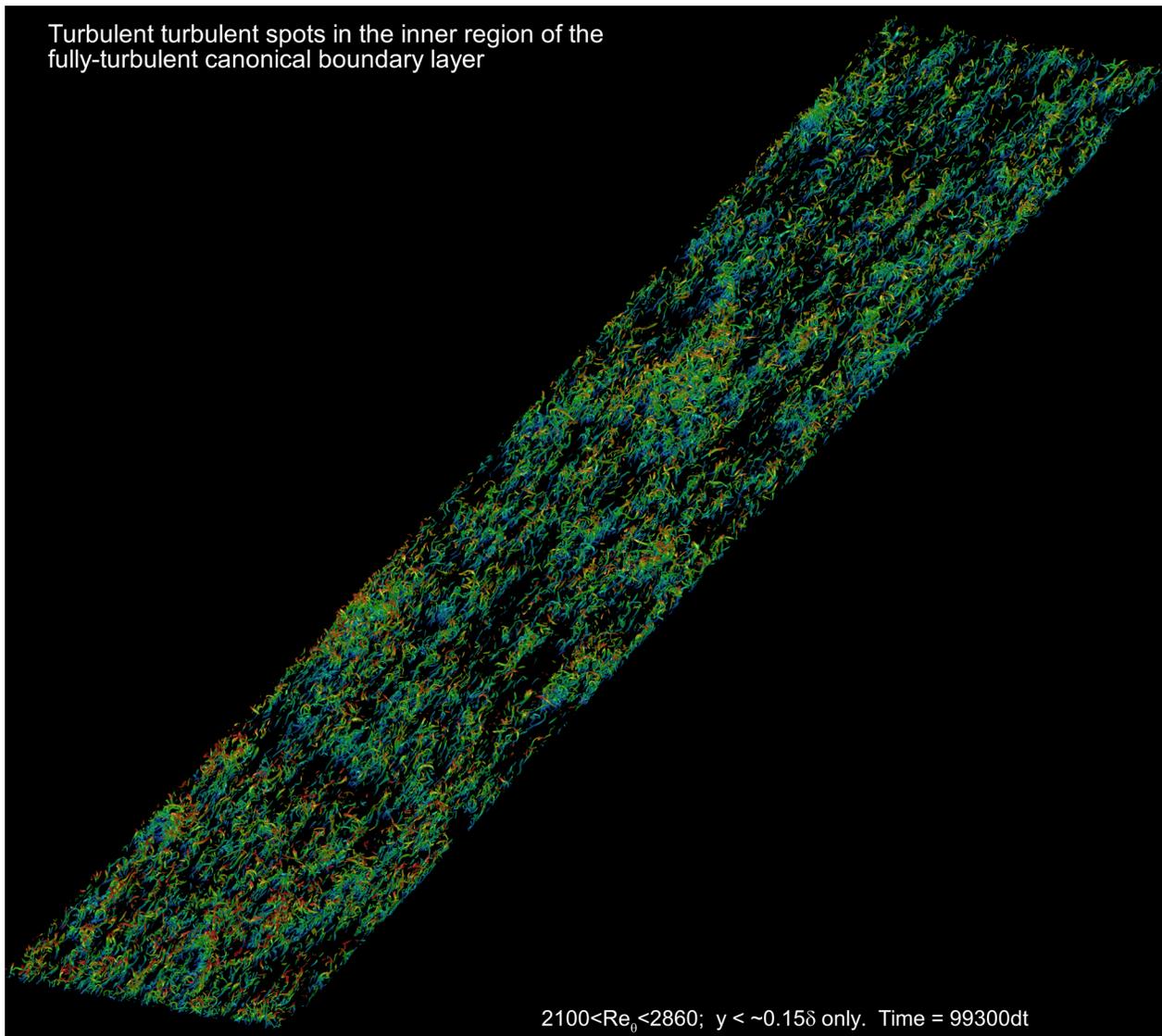
Figure 5. Turbulent-turbulent spots (TUTS) inside the buffer region of the present fully-turbulent flat-plate boundary layer. The spots are made visible through concentrations of the isosurfaces of swirling strength. Red color indicates that the isosurfaces are above 120 wall units. Yellow color incates that the structures are approximately 60 wall units away from the flat-plate.