Thin Shear Layers in High-resolution Direct Numerical Simulations of Turbulence

Takashi Ishihara, Koji Morishita, and J. C. R. Hunt

Abstract Recent studies based on high-resolution direct numerical simulations (DNSs) of turbulence have shown that there are three different types of shear layers in homogeneous and inhomogeneous turbulent flows; at the outer edge (T/NT), in the interior (T/T) and within the buffer layer near the wall (T/W). All the layers play important roles in various turbulence phenomena in the fields of natural sciences and engineering applications. Data analyses showed that all the shear layers act as a barrier of the velocity fluctuations by blocking velocity fluctuations from the one side to the other side. It was suggested that the blocking mechanism of thin turbulent wall (T/W) layers can be used to control the turbulent wake of aerofoils. For high Reynolds number, flows over typical aerofoils at low angle of incidence in the thin turbulent boundary layers (TBLs) have a conditional structure with thin T/W layers which act as a barrier to eddies in the outer part of the TBL. Recent studies indicate that using disturbance—devices at the airfoil surface enhances the blocking effect of the TW barrier and leads—unexpectedly-to reduced shear fluctuations at the wall. This suggests that deeper understanding of the structures and properties of the T/W layers may provide ideas to consider the better strategies for aerofoils designs. In this paper, we review the recent studies on the three different types of shear layers, which are based on the high-resolution DNSs of homogeneous isotropic turbulence (HIT), turbulent boundary layer (TBL), and turbulent channel flow (TCF).

Keywords Turbulence · High Reynolds number · DNS · Thin shear layers · Blocking mechanism

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1   Introduction

Recent developments of supercomputer enable us to perform large-scale direct
numerical simulations (DNSs) of turbulence. A history of the number of grid points
used in the DNS of homogeneous isotropic turbulence shows an increase by a factor
of 10^9 times over the past 40 year. Thanks to this development, we can now analyze
turbulent flow fields in detail at much higher Reynolds number than previously.
Our recent studies using the DNS data of homogeneous isotropic turbulence (HIT),
turbulent channel flow (TCF), and turbulent boundary layer (TBL) have shown that
there are three different types of shear layers in homogeneous and inhomogeneous
turbulent flows; at the outer edge (T/NT), in the interior (T/T) and within the buffer
layer near the wall (T/W) [1]. Since all the layers are related to energy containing
eddies (forcing at large-scales) or boundary conditions in the turbulent flow fields,
they necessarily play important roles in various turbulence phenomena in the fields
of natural sciences and engineering applications.

Analysis of the DNS data of turbulent boundary layers (TBLs) showed that the
conditional cross correlations of streamwise velocity fluctuations near turbulent/non-
turbulent (T/NT) interface are de-correlated across the T/NT interface [2]. Such
de-correlation is consistent with the blocking mechanism proposed by a theoretical
study [3]. Recent studies Szubert et al. [4], Hunt et al. [5] suggested that the blocking
mechanism of T/W layers can be used to control the turbulent wake of aerofoils.
Flows over typical aerofoils at low angle of incidence in the thin turbulent boundary
layers (TBLs) have a conditional structure with thin T/W layers which act as a barrier
to eddies that are generated in the outer part of the TBL. Recent studies indicate that
using some device within the airfoil surface enhances the blocking effect of the T/W
barrier and leads to reduced shear fluctuations at the wall. Therefore, understanding
of the structures and properties of the T/W layers is necessary to consider the better
strategies for aerofoils designs. Note that in typical engineering flows the Reynolds
numbers are very high as shown in this study. Note also that thin shear layers (T/T)
also form in the interior of these boundary layers and wake flows [6].

In this paper, we review our recent studies on the three different types of shear
layers based on the DNSs of homogeneous isotropic turbulence (HIT) ($R_\lambda = 1100$),
turbulent boundary layer (TBL) ($R_\theta = 900 - 2000$), and turbulent channel flow
(TCF) ($R\tau = 5120$).

2   DNS Data of Turbulent Flows

In this study, we use the DNS data of three different types of incompressible turbu-
lence including homogeneous isotropic turbulence (HIT), turbulent boundary layer
(TBL), and turbulent channel flow (TCF). The DNS data of HIT in this study are
those used in Kaneda et al. [7] and Ishihara et al. [8]. A fully alias-free Fourier
spectral method was used in those DNSs. The TBL data are from Ishihara et al. [2]

in which the DNSs were performed using a Fourier spectral method in the streamwise and spanwise directions combined with a Jacobi polynomial expansions in the wall-normal direction (after changing the variable) [9]. The TBL can be assumed to be periodic in the streamwise direction by introducing a fringe region downstream, although the flow is changing in the streamwise direction as the boundary layer grows, c.f. Spalart and Watmuff [10]. The DNS data of TCF are those used in Morishita et al. [11] and Kaneda et al. [12], where a Fourier-spectral method was used in the streamwise and spanwise directions and a Chebyshev-tau method was used in the wall-normal direction. The parameters used in the DNSs of three different types of turbulence are listed in Table 1.

Table 1. Parameters of the DNSs; **a** HIT (from Ishihara et al. [8]), **b** TBL (from Ishihara et al. [2]), **c** TCF (from Kaneda et al. [12])

(a) HIT; N: number of grid points in one direction, R_λ:Taylor microscale Reynolds number, L: integral length scale, λ: Taylor microscale, η: the Kolmogorov length scale

Run	N	R_λ	L	λ	η
256-1	256	167	1.13	0.203	0.00797
512-1	512	257	1.02	0.125	0.00395
1024-1	1024	471	1.28	0.0897	0.00210
2048-1	2048	732	1.23	0.0558	0.00105
4096-1	4096	1131	1.09	0.0339	0.00051

(b) TBL; $N_x * N_y * N_z$: number of grid points in the streamwise (x), wall-normal (y), spanwise (z) directions, R_θ: Reynolds number based on momentum thickness, θ_0: momentum thickness at the inlet, Λ_x, Λ_z: domain size in x and z directions, Δx^+, Δz^+: grid size in x and z directions

Run	$N_x * N_y * N_z$	R_θ	Λ_x/θ_0	Λ_z/θ_0	Δx^+	Δz^+
R900	1920 * 256 * 384	344–1130	1221	91.6	10.4	3.91
R2500	4608 * 512 * 768	835–2443	1293	97.0	10.2	4.72

(c) TCF; R_τ: friction Reynolds number, h: channel half-width, $N_x * N_y * N_z$: number of grid points in the streamwise (x), wall-normal (y), spanwise (z) directions, L_x, L_z: domain size in x and z directions, Δx^+, Δz^+: grid size in x and z directions, Δy_c^+: grid size in y direction at the center

| R_τ	L_x/h	L_z/h	$N_x * N_y * N_z$	Δx^+	Δy_c^+	Δz^+
640	π	$\pi/2$	256 * 384 * 256	7.9	7.9	3.9
1280	π	$\pi/2$	512 * 768 * 512	7.9	7.9	3.9
2560	π	$\pi/2$	1024 * 1536 * 1024	7.9	7.9	3.9
5120	π	$\pi/2$	2048 * 1536 * 2048	7.9	15.9	3.9

3   Three Different Types of Thin Shear Layers

3.1   T/T

In HIT studies of vorticity fields obtained by using DNS showed that there is a transition in the forms of intense vortical structures from isolated vortex tubes at $R_\lambda = O(100)$ to dense vortex clusters (thin shear layers) at $R_\lambda = O(1000)$ [13, 14]. A series of analyses of conditional statistics of the thin shear layers in HIT showed the following [14]; (i) The size and thickness of the layers are O(L) and O(λ), respectively. (ii) Across the layer there is a velocity jump of O(u_{rms}). (iii) Strong micro-scale vortices are generated inside the layer with strength of order $R_\lambda^{1/2}$ greater than that predicted by K41. (iv) These vortices are associated with strong energy dissipation (of order R_λ greater than the mean) and high net energy transfer with large fluctuations within the layer. (v) The interfaces of the layers act partly as a barrier to the fluctuations outside the layer.

Recently, Elsinga et al. [15] showed quantitatively using the eigenframes of rate-of-strain tensor that there are transitions of vortical structures in turbulent flows as Re increases. Figure 1 shows that strong microscale vortices in a layer-like region with a skewed distribution of a vortex component induce a shear flow across the layer. Similar T/T structures have been found in experiments [16]. Also, similar layers were observed in much higher Reynolds number turbulence ($R_\lambda = 2300$) obtained by recent highest resolution DNS with $12{,}288^3$ grid points [17]. Recently, it was suggested that the thin shear layer which was analyzed in detail in IKH is generated by a forcing at large-scale as a part of double spirals around a large-scale low-pressure vortex. Micro-scale double spirals around a tubular vortex were firstly observed by Kida and Miura [18] in a DNS of decaying turbulence at $R_\lambda = 106$. The double spiral structure at $R_\lambda = O(1000)$ is similar to that observed in Kida and Miura [18] but is different in that it is constructed as a cluster of intense microscale vortices.
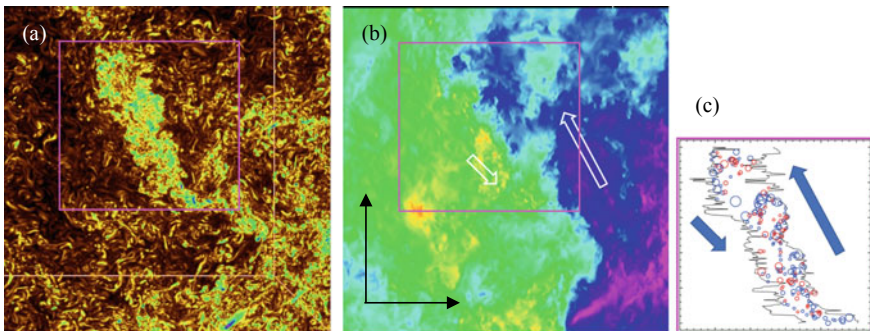
Fig. 1.   Contour plots of **a** enstrophy and **b** z-component of velocity in a x-z plane. The size of the plotted domain is $1.16L \times 1.16L$ (L is the integral scale). **c** High |ω_y| peakes in the layer; blue circles are for $\omega_y > 0$ and red circles are for $\omega_y < 0$. The pink square region in (**a**, **b**) is plotted (From IKH).
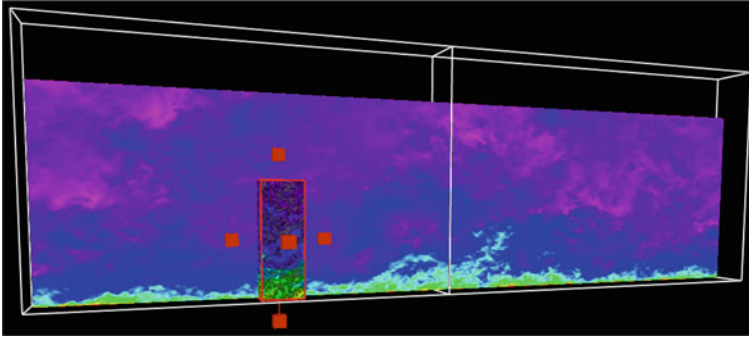
Fig. 2. A contour plot of streamwise velocity component in a plane perpendicular to the spanwise direction. The bottom of the bounding box is one of the wall of the TCF, the top is the channel center. The depth of the bounding box indicates a 1/8 part of the computational domain in the spanwise direction
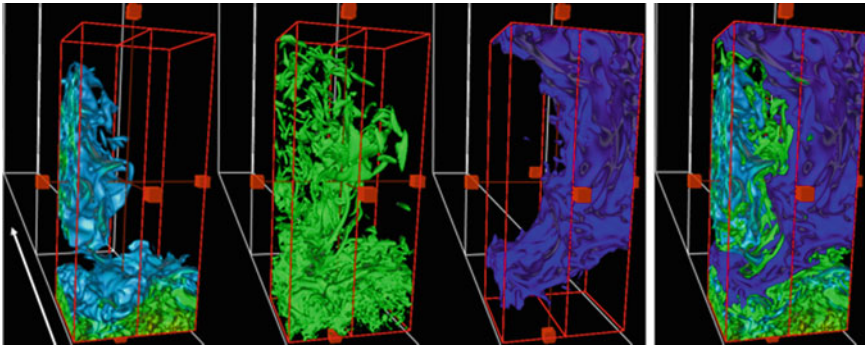
Fig. 3. Iso-surfaces indicating low speed zone, high enstrophy regions, high speed zone, and their superpositions, in a red subdomain shown in Fig. 2

T/T layers similar to those observed in the above studies have been also observed by experiments within turbulent boundary layers [6]. Recently, de Silva et al. [19] observed uniform momentum zones (UMZ) in TBLs. They observed that shear layers of intense vortices separate each zone. However, the relation between the UMZ and the thin shear layers in high Re wall turbulence has not been studied in detail yet. Figure 2 shows a contour plot of streamwise velocity component on a wall-normal cross section in the streamwise direction of TCF at $R_\tau = 5120$. We can observe sharp changes (jumps) in the streamwise velocity component at some parts of the contours. The observation indicates also that the edges of the UMZ are not always strong (T/T) shear layers.

Figure 3 shows low speed zone, high speed zone, and high enstrophy regions in a sample subdomain. It shows that the clusters of strong vortices are generated at the thin regions between the low speed zone and high speed zone. As observed in the

figure, high speed and low speed zones are fully three-dimensional and the internal thin shear layers are not always parallel to the wall. Therefore, the geometrical shapes of the thin shear layers are more complex and cannot be studied by two-dimensional as proposed de Silva et al. [19]. Our observations based on three-dimensional visualizations of the high Re TCF agree well with the conceptual scenario (nested packets of hairpins or cane-type vortices growing up from the wall) given by Adrian et al. [20]; see Fig. 25 in their paper. However, Fig. 3 suggests that it may be appropriate to replace the packets of large-scale hairpins or cane-type vortices in their Fig. 25 by the thin shear layers constructed by dense vortices when the Reynolds number is high enough. The similar is expected for the T/T layers within high Re TBLs.

3.2   T/NT (of TBL)

Analyses of the conditional statistics near the external turbulent/non-turbulent (T/NT) interface of the TBLs (the momentum-thickness-based Reynolds numbers, $R_\theta = 500 - 2200$) [2] showed that the T/NT interface can be well determined as the outer-most iso-surfaces of the vorticity-amplitude. We used $\omega = \alpha U/\delta$ ($\alpha = 0.7$) as the threshold, where U is the streamwise velocity at $y = \infty$ and δ is the boundary layer thickness (see Fig. 4a). The average height of the T/NT interface is about 0.8δ. We observe that there is a velocity jump of order u_{rms}, where u_{rms} is the rms value of the streamwise velocity component near the T/NT interace.

Analyses of the conditional statistics near the T/NT interface showed that the T/NT layer has an inertia-viscous double structure which consists of a turbulent sublayer with a thickness of the order of the Taylor micro-scale and its outer boundary with a thickness of the order of the Kolmogorov length scale. The analysis also showed that the conditional cross correlations of the streamwise or the wall-normal velocity fluctuations change sharply across the interface, suggesting that the T/NT layer acts as a barrier to the external velocity fluctuations.

3.3   T/W

In general wall-bounded turbulent flows, we observe a change of functional form of mean velocity profile at the region (about $10\nu/u_\tau$ from the wall) between the viscus layer and log-law region, where ν is kinematic viscosity and u_τ is the friction velocity. In the actual snapshots of velocity profiles it is expected that we may observe much sharper velocity jumps near the wall. To characterize such a sharp velocity jump, we tried to determine the T/W interface by using $\omega = \alpha U/\delta$ ($\alpha = 7.0$, 8.0, and 9.0) as the threshold values for the TBL ($R_\theta = 900$). The resulting PDFs of the heights of the interface are plotted in Fig. 5. The average heights, which are 40, 31, and 25 in wall units for $\alpha = 7.0$, 8.0, and 9.0, respectively, depend on the threshold values, while the peak heights of the PDFs (12.7, 11.9, and 10.4, respectively) have
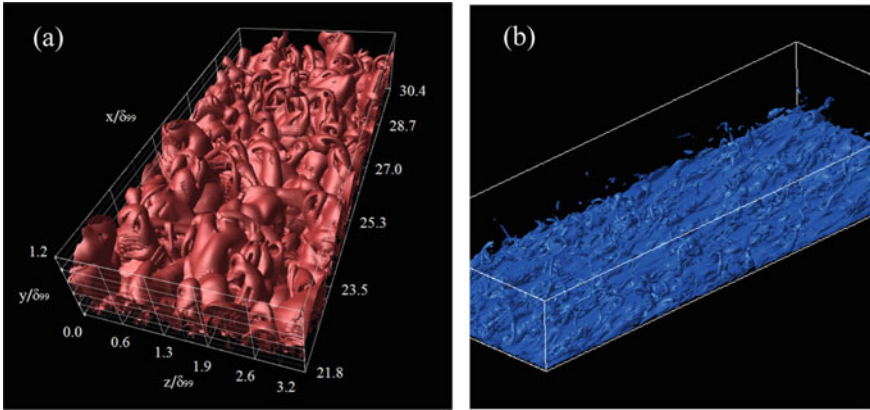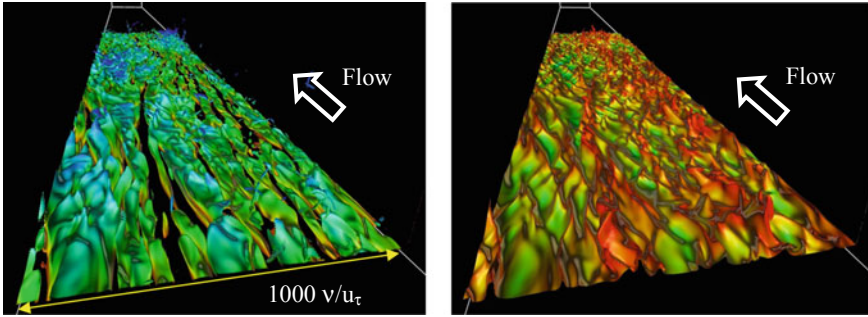
Fig. 4. Iso-surfaces of vorticity amplitude showing **a** T/NT interface determined by $\omega = 0.7U/\delta$ and **b** T/W interface determined by $\omega = 7U/\delta$
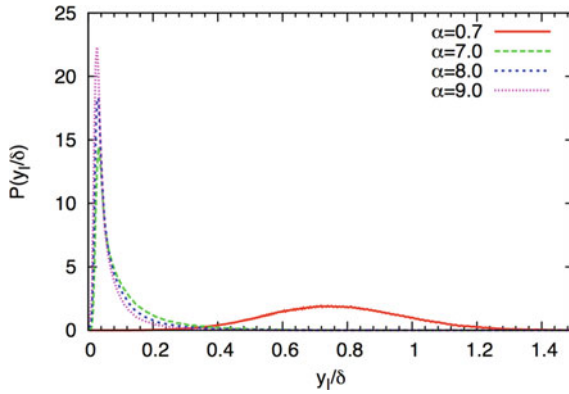
Fig. 5. PDFs of the height of the T/W interface in the TBL ($R_\theta = 900$) determined by $\omega = \alpha U/\delta$ ($\alpha = 7.0, 8.0, 9.0$). The corresponding data for the T/NT interface ($\alpha = 0.7$) are also plotted for comparison
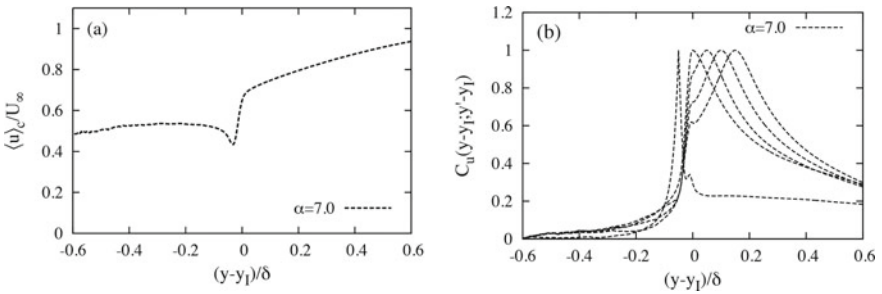
Fig. 6. **a** Conditional average of the streamwise velocity component near the T/W interface defined by $\omega = 7.0U/\delta$ in the TBL ($R_\theta = 900$). **b** Conditional cross correlations of the streamwise velocity fluctuations for the T/W interface

Fig. 7. Visualizations of the T/W layer in a DNS of the TCF at $R_\tau = 5120$; **a** iso-surface of vorticity amplitude ($\omega^+ = 0.6$) colored by the value of u (Blue is fast and yellow is slow) and **b** iso-surface of streamwise velocity component ($u^+ = 10$) colored by the value of vorticity amplitude (Green is large and red is small).

weak dependence on the threshold values. Figure 4b shows the iso-surface of vorticity amplitude determined by $\omega = 7.0U/\delta$. As observed in Fig. 4b, the iso-surface consists of the base part and hairpin vortices. The results in Fig. 5 with the visualization in Fig. 4b suggest that the majority of the T/W interfaces lies in the region about $10\nu/u_\tau$ from the wall. Note that $\omega = 7.0$–$9.0U/\delta$ for $R_\theta = 900$ corresponds to $\omega^+ \sim 0.4$–0.5. Therefore, for the extraction of the T/W interface, the threshold values of $\omega^+ \sim 0.4$–0.5 are appropriate for different Reynolds numbers.

Figure 6 shows the conditional average of the streamwise velocity component and conditional cross correlations of the streamwise velocity fluctuations. We observe sharp velocity jumps of order (0.2–0.3U) across the T/W interface. Also, we can observe the strong de-correlation of velocity fluctuations at the T/W interface. This indicates that the blocking mechanism at T/W interfaces is stronger than that at T/NT interfaces.

To understand the structure of the T/W layer in high Reynolds number TBLs, we investigate the T/W layer in a DNS of the TCF at $R_\tau = 5120$ in Fig. 7. As in the case of low Reynolds number TBL, the T/W layer in Fig. 7a is constructed by the base part and hairpin vortices. The base part of the T/W layer has scale-like thin structures and has cracks in the streamwise direction. The top of the base part is blue and the bottom is yellow. We confirm from these colors that the T/W layer is a shear layer. The iso-surface of the streamwise velocity in Fig. 7b has flame-like structures and has mountain ranges extending in the streamwise direction. The mountain ranges correspond to low-speed streaks (see, e.g., [21]). Their positions agree well with those of cracks observed in Fig. 7b.

4 Conclusions

In this paper, we have compared the characteristics and role of the thin shear layers that are found in the high-resolution DNSs of HIT, TCF, and TBL. Three types of thin shear layers are found in high Re turbulence; internal T/T layer in HIT and in TCF, external T/NT layer in TBL, and T/W layers in TBL and in TCF. We observed that the T/T layer in high Re HIT and TCF has a velocity jump across the layer, which is composed by dense microscale vortices. Also, we observe the decorrelation of velocity fluctuations at all the layers and that the decorrelation of velocity fluctuations at the T/W interface of TBLs are stronger than that at T/NT interfaces of TBLs. The T/W layers are at y^+ ~10 and they have scale-like vortical structures when the Reynolds number is high. Stabilizing the T/W layers may be the key to controlling the wall-bounded turbulent flows.

As shown by Xu et al. [22], the velocity fluctuations in T/W is highly non-Gaussian. Numerical experiments to confirm these results would be interesting.

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