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Analysis of conditional statistics obtained near the turbulent/non-turbulent interface of turbulent boundary layers

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ABSTRACT

Direct numerical simulations of turbulent boundary layers (TBL) along a flat plate are used to study the properties of turbulent/non-turbulent (T/NT) interface of the TBL. The values of the momentum-thickness-based Reynolds numbers, Re_θ, used for this study, are 500–2200. Analysis of the conditional statistics near the interface of the TBL shows that there are a small peak in the spanwise vorticity, and an associated small jump in streamwise velocity. It is shown that the interfacial 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 velocity jump near the T/NT interface of the TBL is of the order of the rms value of velocity fluctuations near the interface. Conditional cross correlations of the streamwise or the wall-normal velocity fluctuations change sharply across the interface, which are consistent with the blocking mechanism of the interface.

1. Introduction

Turbulent boundary layers (TBL) are ubiquitous in high-speed engineering devices and vehicles. When the Reynolds number is very high, we can observe very sharp turbulent/non-turbulent (T/NT) interfaces of the TBL. The T/NT interfaces of the TBL are known to have large fluctuations (Adrian et al., 2000). Such large fluctuations of the T/NT interfaces of the TBL contribute significantly to the pressure fluctuations at the wall, and affect the large scale flow pattern in the wake (including the location of separation) (Braza et al., 2006; Hunt et al., 1990). Note also that the T/NT interfaces play important roles in generating and shielding the sounds by the eddies impacting on the interfaces (Ffowcs Williams and Purshouse, 1981). Therefore qualitative and quantitative understanding of the properties and roles of the T/NT interface is useful for developing accurate numerical methods for the prediction of the TBL phenomena (e.g. Deri et al., 2011).

The framework to understand and analyze interfaces between turbulent and non-turbulent flows was first given by Corrsin and Kistler (1955). They defined a laminar superlayer as a thin layer matching irrotational region to a vortical flow. The first detailed computational analysis of the T/NT interface of a turbulent wake behind a flat plate with and without artificial forcing is given by Bisset et al. (2002). They distinguished between a laminar (viscous) superlayer and a T/NT

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interface, and defined the latter as a layer of turbulent fluid, associated with all major changes between the irrotational outer fluid and the relatively uniform, fully turbulent interior fluid. Also, they used conditional statistics to characterize the properties of the T/NT interface. Here the conditional statistics are obtained by taking averages conditioned on the distance from the interface.

Recently, conditional statistics near the T/NT interfaces in inhomogeneous turbulence have been extensively studied to characterize the properties of the interfaces (see Westerweel et al., 2009; da Silva and Pereira, 2008, and a recent review paper by da Silva et al., 2014). However, scales and dynamics of the T/NT interface have not been fully understood. Conceptually the laminar superlayer forms the outer boundary of the turbulent/non-turbulent interface (Bisset et al., 2002). Recently, Taveira and da Silva (2014) have observed and characterized the viscous superlayer in shear free turbulence and in planar turbulent jets. Also, as shown by the experiments in a jet flow by Gampert et al. (2013), the thickness of the T/NT interface scales with the Taylor micro-scale (see also Bisset et al., 2002; Westerweel et al., 2005; da Silva et al., 2014). However there has been no model and data to show how the T/NT interface and the viscous superlayer are adjacent to each other.

As for the dynamics, Hunt and Durbin (1999) proposed the blocking mechanism of the T/NT interface theoretically. But the blocking mechanism has not been confirmed yet. Also, the dependence of the conditional statistics on the value of the Reynolds number as well as the dependence on the flow type has not been fully understood. As for the T/NT interfaces of TBL, the conditional statistics have not been studied systematically.

In this study we perform an analysis of conditional statistics near the T/NT interface of TBL using several instantaneous fields from a time-dependent direct numerical simulations (DNS) of TBL; the values of the momentum-thickness-based Reynolds numbers, Re_θ, used for this study, are 500–2200. Particular attention has been paid to the characteristic scales of the interfacial layer. Therefore, we analyze the Reynolds number dependence of the conditional statistics near the interface. Also, by analyzing conditional two point cross correlations, we study how the interface of the TBL acts as a barrier to the irrotational fluctuations outside the TBL, as suggested by Hunt and Durbin (1999).

2. DNS of turbulent boundary layers

In the DNS of TBL, we consider a flow obeying the three-dimensional incompressible Navier–Stokes equations, in a semi-infinite domain. By introducing a fringe region downstream (Spalart and Watmuff, 1993), although the flow is changing in the x direction as the boundary layer grows, the flow can be assumed to be periodic in both spanwise z and flow x directions. There are a no-slip condition at the wall, and a free stream condition at infinity. Fundamental periodic lengths in the streamwise and spanwise directions are Λ_x and Λ_z, respectively. Following Spalart et al. (1991), we use the Fourier spectral method in the streamwise and spanwise directions and Jacobi polynomial expansions in the wall-normal (y) direction after changing the variable. The fringe region, in which the thickness of the TBL is reduced, extends from $3\Lambda_x/4$ to Λ_x. The momentum thickness, θ_0, of the TBL at the inlet of the computational domain is controlled appropriately in this DNS. The parameters used in this DNS are shown in Table 1. The Reynolds number, $\mathrm{Re}_\theta = U_\infty \theta/\nu$, is measured in the range 0–$3\Lambda_x/4$.

3. Conditional statistics near the T/NT interface of TBL

3.1. Detection of the T/NT interface and conditional average near the interface

Fig. 1 is a contour plot of the amplitudes of vorticity on a plane parallel to the streamwise and wall-normal directions, obtained from a snapshot data of the DNS of the TBL. This figure demonstrates that vorticity changes sharply at the outermost points of the rotational region of the TBL. Following the analysis by Westerweel et al. (2009), we define the T/NT interface as a set of the outermost points of the rotational region with the absolute values of vorticity greater than $\alpha U_\infty/\delta_{99}$, where α is a constant, U_∞ is the free stream velocity and δ_{99} is the boundary layer thickness. Once the interface is defined, conditional statistics, $\langle\ \rangle_c$, are determined by averaging the data at fixed distances in the y direction relative to the interface ($y = y_I$). Thus the average $\langle\ \rangle_c$ is a function of $y - y_I$ (see Fig. 1). In this study, a conditional average of any quantity, f, for a particular value of Reynolds number, Re_θ^*, is calculated at a statistically steady state ($t = t_0$) by averaging f with respect to Re_θ (or x), z and time t, where $\mathrm{Re}_\theta^* - 50 < \mathrm{Re}_\theta < \mathrm{Re}_\theta^* + 50$, $0 < z < \Lambda_z$ and $t_0 < t < t_0 + 10\Lambda_x/U_\infty$.

After investigating the α dependence of the resulting conditional statistics ($\langle\omega\rangle_c$) near the interface in accordance with the study by Bisset et al. (2002), we adopted the value of 0.7 for α for the analysis in this paper. We confirmed that when α is larger than 0.4 and is less than 1.0, the α dependence of the statistics and the interface location is very weak. Also, we confirmed that when α is less than 0.1 the change of the values of $\langle\omega\rangle_c$ at $y = y_I$ is not sharp (i.e. $\alpha < 0.1$ is not appropriate to

Table 1
Parameter values in the DNS of the TBL.

Run	Re_θ	Λ_x/θ_0	Λ_z/θ_0	Δx^+	Δz^+
Run 1000	344–1130	1221	91.6	10.4	3.91
Run 2500	835–2443	1293	97.0	10.2	4.72

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