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SPATIO-TEMPORAL SPECTRA OF ADVERSE PRESSURE GRADIENT TURBULENT BOUNDARY LAYERS

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Abstract. Spatio-temporal energy spectra of a non-equilibrium adverse pressure gradient (APG) turbulent boundary layer (TBL) have been investigated using a direct numerical simulation (DNS) database. A deficit in the mean velocity develops due to the effect of APG. This defect has several effects. The energy carrying structures in the inner layer that are observed in zero pressure gradient gradually decay. At the same time, larger and different energy carrying structures appear in the outer layer. The turbulence activity in the inner layer gradually decreases and become negligible once the velocity defect is large enough. A more detailed analysis of the size and intensity of the structures that carry the turbulent energy will be performed in the final paper.

1 INTRODUCTION

Turbulent boundary layers (TBLs) subjected to an adverse pressure gradient (APG) are encountered in many engineering applications. Despite the technological importance of APG TBLs, our understanding of their nature remains unclear. Skaare and Krogstad[1] have examined the effect of APG on TBLs and reported that significant turbulent production exist in both near-wall region and outer layer of the boundary layer. Harun et al.[2] have studied TBLs with favorable pressure gradient (FPG), zero pressure gradient (ZPG) and APG. They have investigated energy spectra and reported that increase in the turbulence activity in the outer layer is greater than increase in the inner layer. Lee[3] has analyzed energy spectra of a ZPG TBL and three APG TBLs. He demonstrated that while energy spectra of the streamwise velocity fluctuations of ZPG TBL has one peak that is in the inner layer, APG TBLs have two peaks. The second appears in the outer layer and its strength increases with increasing velocity defect when the energy is normalized with the friction velocity. Also, Maciel et al.[4] have showed that the turbulent kinetic energy peak in the outer layer in APG TBLs. Together, these studies indicate the importance of the outer layer in APG TBLs. The aim of this study is to examine the energy carrying large scale structures in the outer layer using spatio-temporal spectra.

2 RESULTS

The DNS code solves the three-dimensional incompressible Navier-Stokes equations in a three-dimensional rectangular volume. The bottom surface is a flat plate with a no-slip boundary condition. The side boundary conditions are periodic. The far field boundary condition is adjusted in the form of suction and blowing in order to apply favorable/adverse pressure gradients. The inlet condition is obtained from an auxiliary simulation running concurrently. The code is written in Fortran and uses the fractional-step method to solve the governing equations. Fourier decomposition is used in the periodic spanwise direction, while compact finite differences are used in the aperiodic wall-normal and streamwise directions. The equations are stepped forward in time using a modified three sub-step Runge-Kutta scheme[5]. The code is parallelized in a hybrid OpenMP-MPI approach and is scalable up to 32,768 cores[6]. The computational box dimensions of the current case are $(L_x, L_y, L_z)/\theta_{mid} = 151, 29, 42$, where θ_{mid} is the momentum thickness taken at the middle of the box, corresponding to N_x, N_y, $N_z = 4609, 736, 1920$ grid points.

In Figure 1, low- and high-speed velocity regions of the streamwise velocity fluctuations are presented. The fluctuations are normalized with the local rms values. The blue structures are for $u = -1.75\sigma$ and the red ones are for $u = 1.75\sigma$. The axes are normalized with the boundary layer thickness at the inlet. When the velocity defect is small, the low- and high-speed velocity regions are streamwise elongated and streaky. As the defect increases under the effect of the APG, the structures become more voluminous. Their length and width rapidly increase.

In order to examine the structures in more detail, temporal data from $y-z$ planes at four streamwise positions corresponding to H=1.6, 2.0, 2.5 and 2.8 have been collected. The streamwise locations are shown in Figure 1 with green lines. In Figure 2, temporal plane data from the streamwise position where H=1.6 and 2.5 (the first and the third positions in Figure 1) are presented. Time is converted to x by using the outer velocity scale Zagarola-Smits velocity ($U_{ZS} = U_e\delta^*/\delta$), where U_e is the mean velocity at the edge of the boundary layer and δ^* is the local displacement thickness. The z axis is normalized using the local boundary layer thickness (δ). For the sake of clarity, only the region between 0.4-0.6 δ is presented. This temporal data illustrates more clearly that the size of the structures increases with velocity defect. Also, the structures are longer in the streamwise direction when they are normalized with the local boundary layer thickness. Streaks are now present in the outer layer, whereas upstream they are in the inner layer.

Pre-multiplied frequency spectra of the streamwise velocity ($f\psi_{uu}$) as a function of

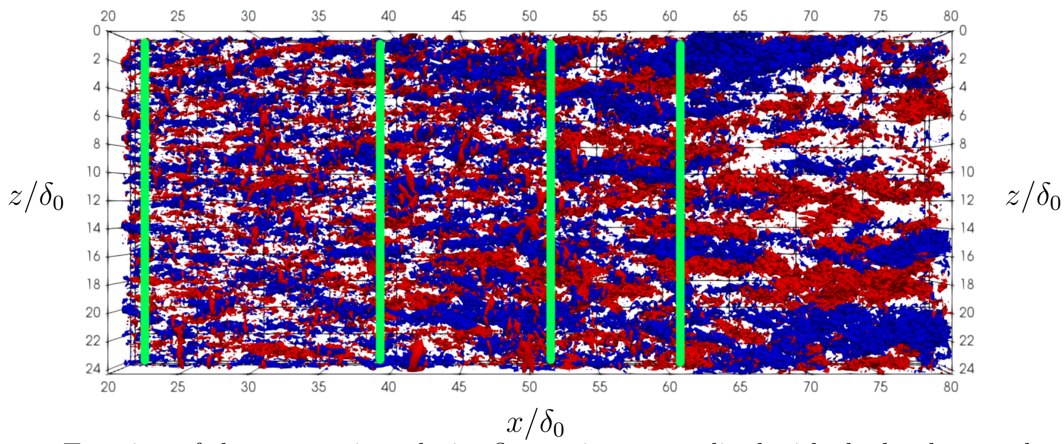

Figure 1: Top view of the streamwise velocity fluctuations normalized with the local rms values. Red and blue stand for u=1.75 σ and u=-1.75 σ, respectively. The axes are normalized with the inlet boundary layer thickness(δ_0). Green lines indicate plane locations at H=1.6,2.0,2.5 and 2.8

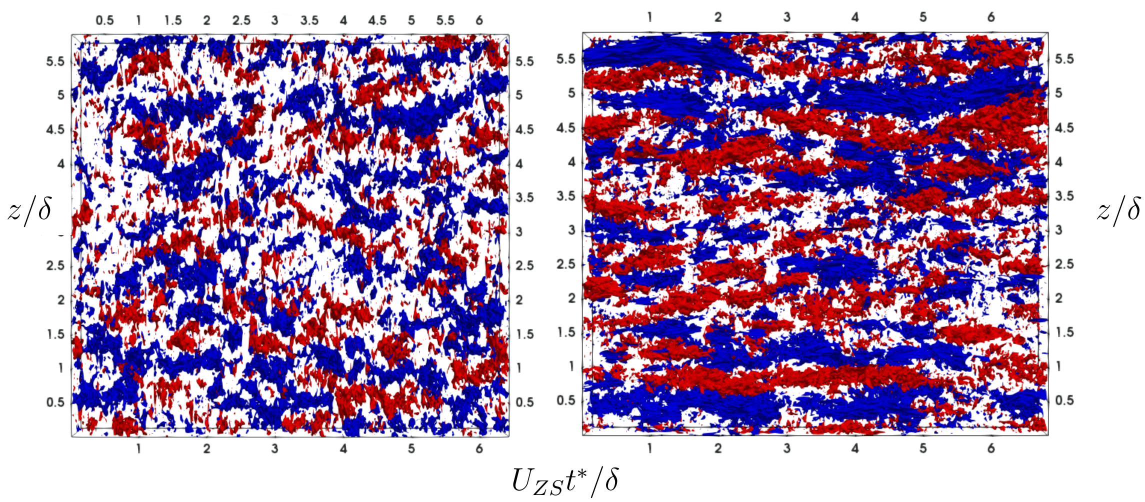

Figure 2: Temporal evolution of the streamwise velocity fluctuations at two streamwise positions corresponding to H=1.6 (Left) and 2.5 (right). The fluctuations are normalized with the local rms values. Red is for $u = 1.75\sigma$ and and blue is for $u = -1.75\sigma$. The z axis is normalized with the local boundary layer thickness and the x axis is normalized with the Zagarola-Smits velocity and the local boundary layer thickness.

period and wall-normal distance and pre-mutltiplied spanwise-wavenumber spectra of the streamwise velocity $(k_z\varphi_{uu})$ as a function of wavelength and wall-normal distance are given in Figure 3 for two streamwise positions corresponding to small and large velocity defects. Both types of energy spectra possess two energy peaks when the velocity defect is small. One of them is in the near-wall region, below $y = 0.1\delta$ and the other one is in the outer layer. When the velocity defect is large, the turbulent activity in the inner layer mostly vanishes. The energetic structures are now found in the outer layer. A more detailed analysis of the characteristics of the energy carrying structures in the outer layer will be presented in the final paper.

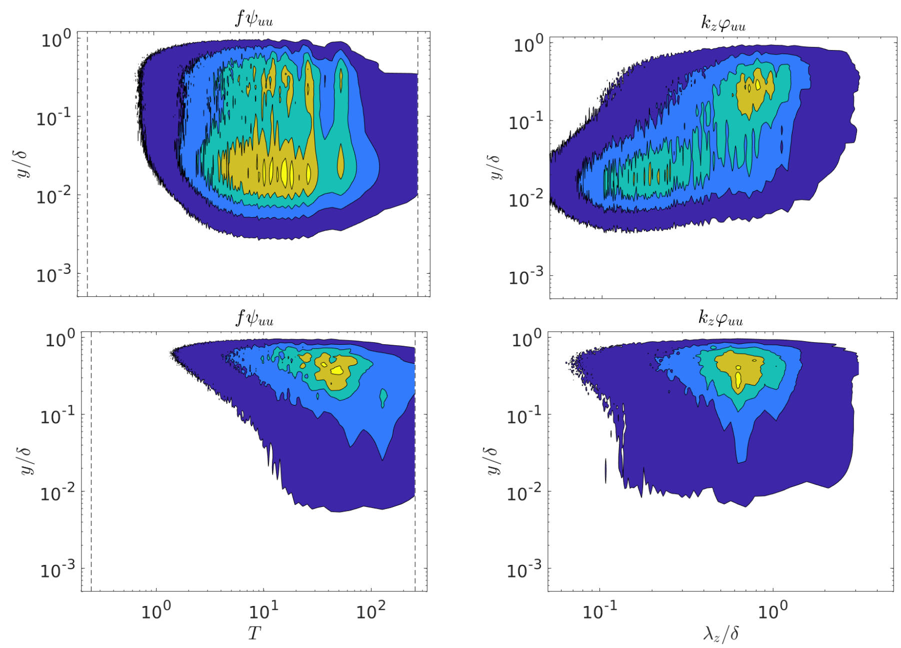

Figure 3: Pre-multiplied energy spectra of the streamwise velocity as a function of period (left), spanwise wavelength (right) and wall-normal distance at two streamwise positions corresponding to H=1.6 (top) and H=2.5 (bottom). The wall-normal distance and the wavelength are normalized with the local boundary layer thickness. The levels are 0.1, 0.3, 0.5, 0.7 and 0.9 of the maximum of the energy spectra.

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