SPECTRAL LINEAR STOCHASTIC ESTIMATION OF SELF-SIMILAR STRUCURE IN TURBULENT PIPE FLOW

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ABSTRACT

According to Townsend's attached eddy hypothesis, the streamwise turbulence intensities exhibit a logarithmic variation at extremely high Reynolds numbers (Re). However, the spanwise component shows a logarithmic even at very low Re, absent in the streamwise component. We investigate this discrepancy by focusing on self-similar motions responsible for the logarithmic variation of the wall-parallel component. Both of the attached self-similar contributions of wall-parallel component show logarithmic variation of turbulent intensity. The energy contribution associated with very-large-scale motions interferes with the observation of the logarithmic law, but this contribution is much smaller in the transverse velocity component. These differences of contributions between wall-parallel components can explain the logarithmic variation of the spanwise turbulence intensity at lower Re.

KEY WORDS

Direct numerical simulation, Turbulent pipe flow, Coherent structure

1. INTRODUCTION

Townsend's attached eddy hypothesis[1] provides a theoretical explanation for the logarithmic region of turbulent statistics through coherent structures that exhibit self-similarity with respect to the distance from the wall (y). According to the attached eddy model, the streamwise and transverse turbulence intensities should vary logarithmically at very high Reynolds numbers (Re). However, while transverse turbulence intensity shows a clear logarithmic behavior even at low Re, the streamwise turbulence intensity does not exhibit a distinct logarithmic law, even at high Re. It has been reported that by isolating only the self-similar structures contributing to the logarithmic law in the streamwise direction, the logarithmic behavior of turbulence intensity can be observed. However, a comparative analysis of the self-similar structures in the streamwise and transverse directions is still lacking.

This study aims to investigate these differences by analyzing the self-similar structures in the logarithmic region. Direct numerical simulation data of turbulent pipe flow at Re_τ=1000–6000 was used for the analysis. Using linear stochastic estimation, the energy of attached structure was extracted in the spectral domain to determine whether these structures align with Townsend's attached eddy hypothesis.

2. METHOD

2.1 Spectral linear stochastic estimation

The total contribution at y_O is represented as Φ, and the cumulative contribution of structures at y_O that show coherence with y_r is represented as Φ'.[2] The formula for Φ' is as follows, and it is calculated using the velocity signals of y_r and y_O.

$$\Phi'(y_O, y_r; \lambda_x, \lambda_z)=|H_L(y_O, y_r; \lambda_x, \lambda_z)|^2\, \Phi(y_r; \lambda_x, \lambda_z) \quad (1)$$

H_L is scale-specific transfer kernel for estimate result at y_O.

2.2 Extract contribution of single attached eddy

After calculating $\Phi'(y_O, y_h)$ for y_h higher than y_O, we find the difference $\Delta\Phi'(y_r, y_O, y_h)$. When $\Delta\Phi'$ is greater than zero, it represents the contribution of attached structures between y_O and y_h. By using the following formula, we can separate the contribution $\delta\Phi'$ of the attached structure at a height level of $y_m=(y_h+(y_h+\Delta y_h))/2$.

$$\Delta\Phi'(y_r, y_O, y_h)|_{>0} - \Delta\Phi'(y_r, y_O, y_h+\Delta y_h)|_{>0} = \delta\Phi'(y_r, y_O, y_m) \quad (2)$$

3. RESULT

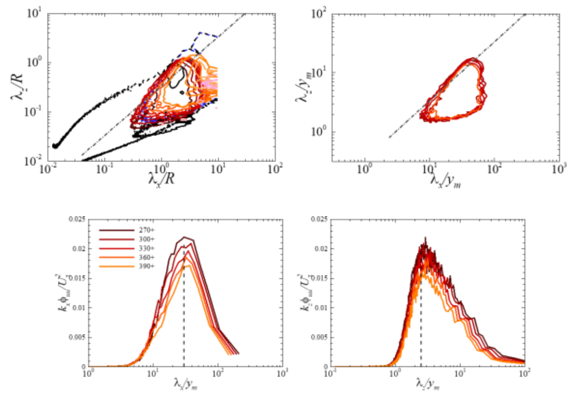

Fig.l: 2D spectrum of $\delta\Phi_{uu}'(y_r^+=15, y_O^+=100, y_m)$ plot for (a): λ/R, (b): λ/y_m, Premultiplied 1D spectrum of $\delta\Phi_{uu}'$ at wall scaling wall-normal distance range plot for (c): λ_x/y_m, (d): λ_z/y_m

Figure 1 shows the 2D and 1D streamwise spectrum results at y_o^+=100. As y_m increases, the self-similar feature of structure growth is observed, and the wall scaling is well represented within a specific range of y_m, highlighting the characteristics of structures contributing to the logarithmic law.

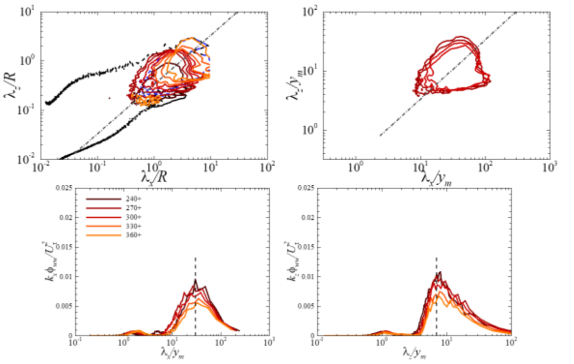

Fig.2: 2D spectrum of $\delta\Phi_{ww}$'(y_r^+=15, y_O^+=100, y_m) plot for (a): λ/R, (b): λ/y_m, Premultiplied 1D spectrum of $\delta\Phi_{ww}$' at wall scaling wall-normal distance range plot for (c): λ_x/y_m, (d): λ_z/y_m

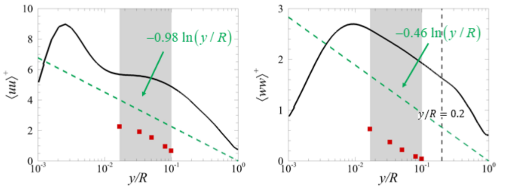

Fig.3: Normalized turbulent intensities of (a) streamwise velocity, (b) spanwise velocity. Red squares are turbulent insities obtained by integrating $\delta\Phi$' for wall scaling range.

Figure 2 shows the transverse structure results at y_o^+=100. The scaling characteristics observed in *w* are similar to those of *u*. However, for *w* structures above y/R=0.1, the contribution of attached structures was very small. This was further confirmed by integrating over the wall-scaling y_m range, as shown in Figure 3, which revealed that the turbulence intensity was very low. This suggests differences between the attached structures of *u* and *w*, indicating that further analysis is needed to fully explain the logarithmic law for *w*.

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