Uniform momentum zones in turbulent pipe flow

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ABSTRACT

Wall-bounded turbulent flows are composed of spatial regions with relatively uniform streamwise velocity, known as uniform momentum zones (UMZs). These UMZs vary in size, and multiple UMZs coexist along the wall-normal direction in instantaneous flow fields. Although UMZs are essential coherent structures for understanding the multiscale phenomena and momentum transport in wall turbulence, there remains a question about which UMZs contribute to the logarithmic layer of wall turbulence. In this study, we explore relatively thick UMZs that span from the near-wall region and cross the logarithmic layer using the direct numerical simulation dataset of turbulent pipe flows at Reτ = 550, 1000, 3000, and 6000. The wall-attached UMZs contribute to the logarithmic layer and explain turbulence statistics consistent with Townsend's attached eddy hypothesis.

KEY WORDS

Direct numerical simulation, turbulent pipe flow, uniform momentum zone, wall turbulence

1. INTRODUCTION

The logarithmic law of the mean velocity is one of the fundamental characteristics of wall-bounded turbulent flows. It is often used for modeling turbulent structures near the wall or predicting skin friction. It is necessary to study the turbulent structures that follow the logarithmic law to analyze the mechanisms that sustain this log region is crucial.

Wall-bounded turbulent flows are composed of relatively UMZs with nearly constant streamwise velocity. UMZs exist at various length scales, spanning from near the wall to the outer region. They are separated by thin shear layers and exhibit a hierarchical distribution.

This study analyzes the UMZs that contribute to the logarithmic laws of mean velocity and streamwise turbulent intensity in turbulent pipe flow. To achieve this, direct numerical simulations (DNS) data of fully developed turbulent pipe flow at Re_τ = 550 to 6000 were utilized. The UMZs were detected using the histogram method, and their characteristic velocity and length scales were examined. Finally, the contribution of these UMZs to the logarithmic laws of mean velocity and streamwise turbulent intensity was analyzed.

2. DETECTION METHOD

Adrian et al. (1995)(1) and DeSilva et al. (2016)(2) used the histogram method to detect UMZs. To analyze the self-similar characteristics of the detected UMZs, the joint probability density function (PDF) of their height and thickness was examined. Among these, UMZs exhibiting a linear relationship were analyzed to investigate their contribution to the logarithmic laws of mean velocity and streamwise turbulence intensity.

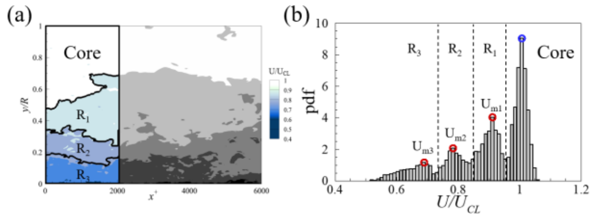

Fig 1. (a) Illustraition of detection sample for UMZs applied to an instantaneous velocity filed at Ret = 6000. (b) The histogram of U constructed using the included region indicated in (a). The core region is not included in UMZ detection.

3. RESULTS AND CONCLUSION

The thickness of these UMZs is linearly proportional to the wall-normal distance, and the velocity jump across the shear layer between different UMZs scales with the friction velocity. The mean streamwise velocity profile is reconstructed from these UMZs, and it shows the existence of the logarithmic layer, which is supported by a clear plateau in the indicator function even in low Reτ. Additionally, the wall-normal turbulence intensity and the Reynolds shear stress profiles exhibit a region with constant values over the logarithmic layer. These findings indicate that the identified wall-attached UMZs directly contribute to the logarithmic layer and are important instantaneous structures that can explain the asymptotic behaviors of turbulence statistics predicted by Townsend's attached eddy hypothesis.

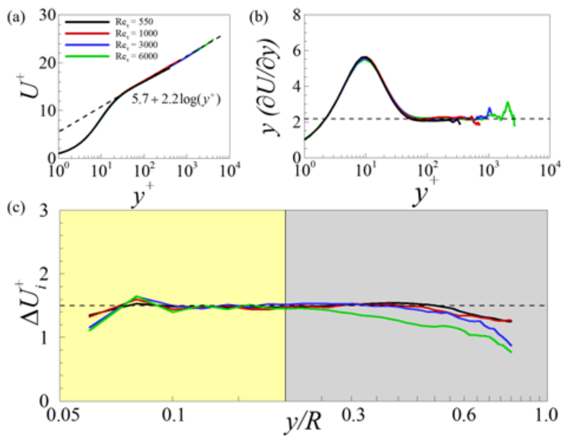

Fig 2. (a) Mean velocity profile and (b) log law indicator function reconstructed from UMZs. (c) Friction velocity of the shear layer as a function of height.

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a Example of a footnote