主　論　文　の　要　約

論文題目　**Role of the Turbulent Structures on the Behavior of the Pressure Fluctuations in Turbulent Channel Flow from Direct Numerical Simulation**
(チャネル乱流中の圧力変動挙動に関する乱流構造の役割：直接数値計算に基づく解析)

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論　文　内　容　の　要　約

Pressure fluctuations consider a significant ingredient in the turbulence field. For incompressible flows, the pressure at any point is affected by the whole flow domain by the solution of Poisson's equation. Hence, pressure fluctuations play an important role in the transport of turbulent kinetic energy and Reynolds stress. Besides, the pressure fluctuations are responsible for the structural vibrations at the surfaces of vehicles and pipelines, as well as the induced noise generation within the aircraft cabin. In fact, the responsibility of the pressure fluctuations for these structural vibrations and noise generation represents the imprint of the turbulent motions within the flow field. Consequently, it is important investigating the relation between the pressure fluctuations and the structures of the turbulent flow in order to suppress the level of the effects generated by the pressure field.

The present study concentrates on investigating the role of the turbulent structures within the flow on the behavior of the pressure fluctuations in turbulent channels along with addressing the Reynolds number dependency. In the present study, we rely on the analysis of direct numerical simulation (DNS) dataset of fully developed turbulent channel flow which covers a relatively wide range of Reynolds number Re_τ from 180 to 4000, based on the channel half-depth h and the friction velocity u_τ.

The study can be divided to three main parts. In the first part, we explore the role of the turbulent structures in generating the positive and negative wall pressure high-amplitude peaks. The peaks of the wall pressure are especially interesting due to their significant contributions to the root-mean square (rms) wall pressure.

Positive and negative pressure peaks are associated with the small-scale vortex structures identified by Q −criterion. The averaged eddy structure conditioned by the positive pressure peaks is symmetric with respect to the $x-y$ plane (x and y refer to the streamwise and wall-normal directions, respectively), and its shape resembles a hairpin eddy downstream of the positive pressure peaks. The negative pressure peaks are consistent with the cores of the small-scale vortex structures, with the negative pressure peaking adjacent to the wall. The averaged eddy structure has an undefined shape that scales in wall units with Reynolds number.

The positive pressure peaks are associated with a large-scale sweep event of $\mathcal{O}(h)$ originating from the outer layer, which constitutes a shear layer confined in the near-wall region (up to $y^+ \approx 100$, where $y^+ = yu_\tau/\nu$ and ν is the kinematic viscosity). When normalized by the outer variable, the average size of this sweep event is independent of Reynolds number. The inclination of the averaged shear layer with respect to the streamwise direction decreases with the increase in the Reynolds number under the influence of the shearing action of the mean velocity (decreases from approximately 35° at $Re_\tau = 180$ to around 14° at $Re_\tau = 4000$). The negative pressure peaks are associated with a large-scale sweep motion of $\mathcal{O}(h)$ at the downstream side. This motion was comparable in size but lower in amplitude than the sweep motion obtained by the positive pressure peaks. Such large-scale sweep motions constitute a shear layer at the downstream side of the negative pressure peaks. The streamwise separation between the negative pressure peaks and the shear layer interface depends on the Reynolds number.

According to these results, the positive and negative pressure peaks are associated with structures from both the inner and outer layers. This is consistent with the scaling of the streamwise lengths of the pressure peaks, which change with Reynolds number when normalized by the inner variable.

The contributions of the large- and small-scale structures to the positive and negative wall pressures were estimated by splitting the pressure into its rapid and slow components. Structures of both size scales equally contribute to the positive wall pressure events, but small motion scales dominate the negative events (with a relative contribution of approximately 60%). The slow pressure contribution is a weakly increasing function of Reynolds number. Finally, from the association between the positive and negative wall pressure events and the structures in the inner and outer layers, we inferred that the pressure events did not scale with the wall units. The associations are also consistent with the statistical analysis of the instantaneous field, which indicated that negative and positive wall pressure events will likely occur consecutively, with the negative events occurring upstream of the positive ones.

In the second place of our study, we move away from the wall where the turbulent structures within the flow induce a logarithmic profile for the pressure intensity $\langle {p^+}^2 \rangle$, where $p^+ = p/\rho u_\tau^2$ and ρ is the fluid density. The pressure intensity $\langle p^{+^2} \rangle$ shows a log-profile when plotted versus the distance from the wall y. However, the distribution of the pressure variance is not directly derived from any model, rather it is an empirical observation. Hence, we attempted exploring the structures associated with the pressure intensity log-profile along with an investigation of the Reynolds number dependency. Acknowledging that the spanwise velocity w shows its logarithmic intensity profile at the same Reynolds numbers, we extend our analysis to w and discuss the similarity between the pressure and spanwise velocity fluctuations.

The pressure variance starts its logarithmic profiles at wall-normal location of approximately 150 in wall units, while the log-profile of the spanwise velocity variance starts closer to the wall at around 90 in wall units, independent of Reynolds number. The upper bounds of both profiles show linear relations with Re_τ with the same slope of around 0.2. The log-regions of $\langle p^{+^2} \rangle$ and $\langle w^{+^2} \rangle$ overlap each other over significant portions of the wall-distance, and the minimum Reynolds number estimated for both log-regions to be identified is $Re_\tau \approx 500$. Additionally, we have studied the higher-order moments of p and w, where the $2n-$order moments raised to the power of $1/n$, with $n = 1$, ..., 4, follow the logarithmic behaviors within the same regions where $\langle p^{+^2} \rangle$ and $\langle w^{+^2} \rangle$ confirm the log-profiles. In addition, the higher-order moments of p and w follow super-Gaussian behaviors which reinforce the similarity between p and w. The implication of the logarithmic scaling of the higher-order moments of p and w fluctuations is their association with a hierarchical organization of self-similar eddies.

The coherent structures related to the pressure intensity log-profile, and hence and the spanwise velocity, are also investigated. The scales of motion $\mathcal{O}(h)$ or less showed that they are the main contributors to the log-trends of p and w. The conditional sampling around the positive high-amplitude small-scale pressure fluctuations at different wall-normal locations results in hairpin eddy structures. Positive pressure fluctuations are located between the legs of the hairpin eddy, while the negative pressure fluctuations are consistent with the head part of the hairpin eddy. Positive and negative spanwise velocity fluctuations are strongly positioned consistently with the legs and neck of the hairpin eddy. The eddy structure shows a strong link between p and w fluctuations, both of which occur at relatively smaller scales. The intrinsic feature of this structures is their self-similarity. They are geometrically self-similar in the sense that their length and their width increase linearly with the distance from the wall. Supporting also this self-similarity feature is the analysis of the higher-order moments. The logarithmic scaling of the higher-order moments of p and w fluctuations implies their association with a hierarchical organization of self-similar eddies.

In the final part of this dissertation, we address the propagation velocity of the pressure fluctuations. With the association of the pressure fluctuations with the different structures across the channel, it is expected that the pressure convection velocity depends on the scales of motion. This decency on the scale is significant close to the wall. This gives rise to the reason of the inapplicability of Taylor's hypothesis in the near wall- region. In the present study, we examined the applicability of Taylor's hypothesis of the pressure field. Statistically, Taylor's frozen hypothesis can be applied for the pressure field above $y^+ \approx 20$, whereas it is inapplicable in the near-wall region (from the wall up to $y^+ \approx 20$). Hence, a correction to the convection velocity has been estimated. In the near-wall region, the averaged pressure convection velocity approaches constant values of around $11u_\tau$ to $12u_\tau$.