Wall-attached momentum transfer structures in drag-reduced flows

Junwoo Jae[1], Hyung jin sung[2], Jinyul Hwang*[1]

1. School of Mechanical Engineering, Pusan National University, Busan, Korea

2. Department of Mechanical Engineering, KAIST, Daejeon, Korea

** E-mail: jhwang@pusan.ac.kr*

ABSTRACT

Reducing skin-friction drag in wall-bounded turbulence is essential for improving energy efficiency in various industrial applications. While numerous strategies for reducing skin-friction drag have been proposed, their effectiveness diminishes significantly at high Reynolds numbers (Re), which are common in practical flows. To address this challenge, it is crucial to understand the multiscale nature of coherent structures, particularly those that extend to the wall, as these structures play a pivotal role in skin-friction generation and reduction. In this study, we investigate wall-attached momentum transfer structures (Qs) in drag-reduced flows, focusing on the impact of Re on skin-friction reduction. Using Navier slip boundary conditions, we analyze drag-reduced flows at bulk Re of 10,000 and 20,000 and compare them to no-slip cases at the same Re. Our results show that wall-attached Qs are the dominant contributors to both skin-friction generation and reduction. These findings enhance our understanding of the scale-dependent behavior of wall-attached structures in drag-reduced flows and provide insights for developing innovative drag reduction techniques by strategically targeting these structures.

KEY WORDS

Turbulent flows, drag reduction, turbulent structure

1. INTRODUCTION

Reducing skin-friction is an important goal to decrease energy consumption in many industries, from massive pipelines for oil and gas transportation to airplanes and ships. These industries are primarily conducted at high Reynolds numbers and face challenges in control due to the complex and chaotic nature of turbulence. Over a long period, studies have been conducted to reduce skin-friction caused by turbulence. Several technologies worked successfully, but as the Reynolds number increased, they experienced reduced performance or faced limitations due to technical constraints.

The aim of this study is to investigate the contributions of wall-attached momentum transfer structures (Qs) to turbulent skin friction in drag-reduced flows, with a focus on the effects of Reynolds number (Re). To achieve this, we conducted direct numerical simulations (DNS) of fully-developed turbulent channel flows at bulk Re of 10,000 and 20,000 under slip boundary conditions and compared the results with DNS data from no-slip boundary conditions. Wall-attached Qs were extracted from instantaneous flow fields, and their roles in skin-friction generation and reduction were analyzed using the FIK identity (Fukagata et al., 2002).

2. Result

To examine the behavior of wall-attached Qs under slip conditions and the influence of Re, we first analyze the identified structures in an instantaneous flow field. Figure 1 displays the iso-surfaces of wall-attached Qs, excluding structures with a volume less than 30^3 wall units (del Álamo et al., 2006; Hwang & Sung, 2018). Green and orange iso-surfaces represent Q2 and Q4 structures, respectively, with shading indicating their proximity to the wall. The extracted structures span a wide range of scales, extending from the near-wall region to the outer region.

Wall-attached Q2 and Q4 structures are aligned side by side in the spanwise direction, suggesting that most of them are organized as side-by-side pairs (Lozano-Durán et al., 2012). Comparing the no-slip (Figure 1a,c) and slip cases (Figure 1b,d), slip conditions reduce the number of structures while elongating them in the streamwise direction and increasing their overall size. Despite the reduction in the number of structures, the total volume remains unchanged.

When considering the Re effect, multiscale phenomena become more pronounced at higher Re. As shown in Figure 1(a,c), both the number of structures and their occupied volume increase with higher Re, emphasizing the growing importance of wall-attached structures. In the slip cases (Figure 1b,d), the reduction in the number of structures is more significant at higher Re, indicating a stronger influence of slip conditions at elevated Re.

Drag is reduced by 33% and 44% in the low and high Re cases, respectively. To analyze the contribution of wall-attached structures to this reduction, we decompose the skin friction coefficient (C_f) using the FIK identity (Fukagata et al., 2002):

$$C_f = \frac{6}{Re_b}\left(1-\frac{\langle U_s\rangle}{U_b}\right)+\frac{6}{U_b^{\,2}}\int_0^1\left(1-\frac{y}{\delta}\right)\langle -uv\rangle\, d\left(\frac{y}{\delta}\right). \quad (4)$$

Here, the first and second terms in the right-hand side correspond to the laminar and turbulent contributions (C_{f1} and C_{f2}), respectively. For no-slip cases, U_s = 0. Since the integrand of C_{f2} contains $\langle -uv\rangle$, we further decompose C_{f2} into three components based on the identified structures: wall-attached Qs (C_{fa}), wall-detached Qs (C_{fd}), and others (C_{fo}). Thus, $C_{f2} = C_{fa} + C_{fd} + C_{fo}$.

Figure 2 presents the corresponding results. For both Re, C_{f2} dominates, contributing over 90% of C_f, while C_{f1} becomes less significant with increasing Re. Wall-attached Qs (C_{fa}) primarily drive turbulent skin friction, accounting for nearly 50%, despite occupying only 6% of the total volume. This underscores the critical role of wall-attached structures in skin friction generation. Furthermore, these structures contribute significantly to the reduction of C_f, as illustrated in the pie chart in Figure 2. The contribution of each structure to the total reduced C_f (ΔC_f) is calculated as the ratio of the reduced skin friction for each structure (ΔC_{fi}) to the total reduced skin friction. Wall-attached Qs contribute approximately 40% to ΔC_f. Notably, at higher Re, the contribution of wall-attached structures increases, while the contributions of wall-detached and other structures decrease. These findings highlight the dominant role of wall-attached structures in turbulent skin friction reduction, a role that becomes increasingly significant at higher Re. This behavior likely arises from the broad range of scales over which these structures exist, extending from the near-wall region to the outer region, as shown in Figure 1.

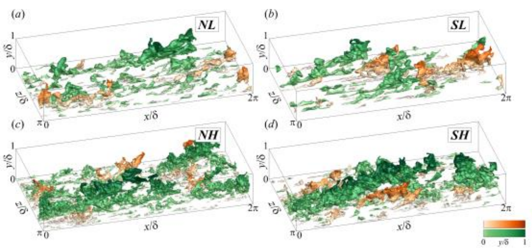

Figure 1. Identified wall-attached Q2 and Q4 structures in an instantaneous flow field: (*a*) NL; (*b*) SL; (*c*) NH; and (*d*) SH. The Q2 and Q4 structures are represented in green and orange, respectively.

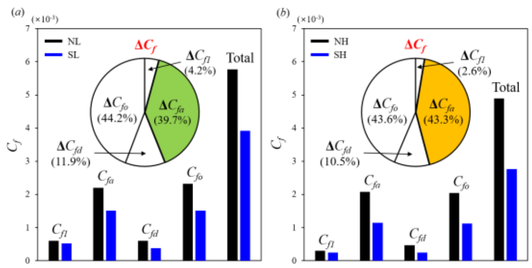

Figure 2. Decomposition of the skin-friction coefficient and the contribution to the reduced skin-friction coefficient using FIK identity: (*a*) low Reynolds number; (*b*) high Reynolds number

REFERENCES

(1) Fukagata, K., Iwamoto, K., & Kasagi, N., 2002, "Contribution of Reynolds stress distribution to the skin friction in wall-bounded flows", Physics of Fluids Vol. 14, pp. L73-L76.

(2) del Álamo, J. C., Jiménez, J., Zandonade, P., & Moser, R. D., 2006, "Self-similar vortex clusters in the turbulent logarithmic region", Journal of Fluid Mechanics Vol. 561, pp. 329-358.

(3) Hwang, J., & Sung, H. J., 2018, "Wall-attached structures of velocity fluctuations in a turbulent boundary layer", Journal of Fluid Mechanics Vol. 856, pp. 958-983.

(4) Lozano-Durán, A., Flores, O., & Jiménez, J., 2012, "The three-dimensional structure of momentum transfer in turbulent channels", Journal of Fluid Mechanics Vol. 694, pp. 100-130.