Contributions of coherent structures to subgrid-scale energy transfer in low-Re channel and higher-Re boundary-layer flows

V. K. Natrajan and K. T. Christensen (ktc@uiuc.edu)
Department of Mechanical and Industrial Engineering
University of Illinois, Urbana, IL 61801 USA

Recent experimental and computational studies of wall turbulence provide evidence that individual hairpin-like vortices streamwise-align to form larger-scale entities termed vortex packets. This organization is characterized by a series of hairpin vortices whose heads are inclined away from the wall at a shallow angle and a region of momentum deficit enveloped beneath the interface due to the collective induction of the vortices in a packet [1]. The present effort documents the role that such structures play in subgrid-scale (SGS) energy transfer, $\varepsilon_{sgs} = -\tau_{ij}\widetilde{S}_{ij}$, between the resolved and unresolved scales in the context of large-eddy simulation (LES).

Particle-image velocimetry (PIV) is used to measure 2-D velocity fields in the streamwise–wall-normal plane of turbulent channel flow at $\mathrm{Re}_\tau = 1185$ and a turbulent boundary layer at two higher Reynolds numbers: $\mathrm{Re}_\tau = 3450$ and 6000. Several thousand statistically-independent realizations are acquired for each case. The instantaneous PIV realizations are then filtered using a top-hat filter of width $\Delta = 0.09\delta$ in the homogeneous streamwise direction, generating an ensemble of resolved-scale velocity fields in the spirit of LES. The subgrid-scale dissipation, $\varepsilon_{sgs} = -\tau_{ij}\widetilde{S}_{ij}$, is estimated using in-plane velocities and gradients since the PIV data is 2-D. This estimate of the true SGS dissipation is shown to be appropriate for intense energy-transfer events using data from a DNS of turbulent channel flow [2].

The low-Re channel-flow data reveals significant instantaneous forward scatter in the region between consecutive hairpin heads within a packet near the intense ejections of low-speed fluid away from the wall induced by the individual vortices. In contrast, localized backscatter is noted around each hairpin head, coincident with the outward- and inward-interaction events generated by the vortex. In addition, a region of significant instantaneous backscatter is often noted at the trailing edge of a vortex packet, particularly when a second packet is observed at its upstream end.

These instantaneous observations are corroborated by estimates of the conditionally-averaged forward and backward scatter fields given the presence of a spanwise vortex core (a hairpin head) in the low-Re channel data. Significant forward scatter is found to occur, on average, along the inclined interface formed by the heads of the hairpins in a vortex packet. In contrast, localized backscatter around the hairpin heads is noted in estimates of the conditionally-averaged backscatter field given the presence of a vortex core. This estimate also reveals a strong region of backscatter 0.5δ upstream of the event location, coincident with the trailing edge of the average packet structure represented by the estimate of the conditionally-averaged velocity field given a spanwise vortex core.

Similar instantaneous and statistical analysis of the higher-Re boundary-layer data is in progress in order to clarify whether such behavior extends to higher-Re wall turbulence where LES would primarily be employed. Initial indications are that both individual hairpin structures and vortex packets at higher-Re continue to play a crucial role in SGS energy transfer, particularly within the log layer.

References

[1] R. J. Adrian, C. D. Meinhart and C. D. Tomkins. Vortex organization in the outer region of the turbulent boundary layer. *J. Fluid Mech.*, 422:1–54, 2000.
[2] J. C. Del Alamo, J. Jimenez, P. Zandonade and R. D. Moser. Scaling of the energy spectra of turbulent channels. *J. Fluid Mech.*, 500:135–144, 2004.

Keywords: Wall turbulence