On the existence of self-similar structures in turbulent pipe flow

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Townsend’s attached eddy hypothesis forms the basis for one of the most far-reaching concepts in the analysis of the logarithmic layer in wall-bounded turbulent flows. The hypothesis proposes that the eddying motions in the inertially dominated region are energetic and geometrically self-similar eddies that scale with the distance from their eddy center to the wall, implying that these three-dimensional eddies can be completely scaled using a single length scale. The attached eddy hypothesis has been used successfully to predict turbulence statistics and the spectral behaviour in wall-bounded flows, which has been verified both by experiments (Hultmark et al., 2012) and simulations (Jimenez & Hoyas, 2008; Lee & Moser, 2015).

Although these findings on logarithmic scaling implicitly support the attached eddy hypothesis, they do not reveal the nature of the self-similar coherent structures themselves. Hellström et al. (2016) performed a POD analysis of turbulent pipe flow, and found that the modes had a self-similar cross-section in the wall-normal and spanwise plane. Here, we expand on these findings by experimentally investigating the relationship between the streamwise and spanwise length scales.

We consider a fully-developed turbulent pipe flow at $Re_\tau \approx 2390$, where the data is simultaneously acquired at two pipe cross-sections using two stereo PIV systems having a streamwise separation that ranges from 0 to 9.97R. The velocity fields are decomposed azimuthally into Fourier modes, where the flow structures are unconditionally sorted by their spanwise length scale ($\lambda_\theta$). The sorted structures are thereafter investigated using their two-point correlations, with the resulting correlations shown in figure 1. The correlations are shown to exhibit a self-similar behaviour with respect to a its spanwise length scale for structure sizes spanning more than a decade. Adding to the findings from Hellström et al. (2016), his single length scale ($\lambda_\theta$) provides a complete description of the shape of the self-similar eddies.

REFERENCES


Figure 1. Streamwise correlations of the azimuthally Fourier decomposed velocity field, for azimuthal wave lengths $\lambda_\theta \in \{5, 40\}$. (a) correlations scaled in outer coordinates; (b) correlations scaled by its spanwise lengthscale ($\lambda_\theta$).