Wall bounded turbulence

Large-scale coherent structures in fully developed turbulent pipe flow

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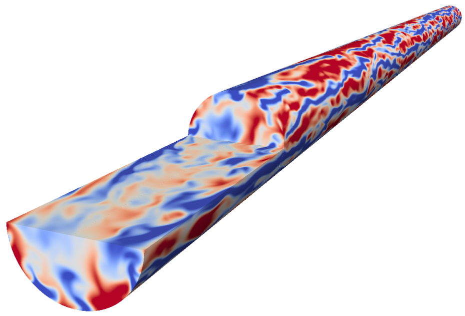

***Figure 1:** Contours of streamwise velocity fluctuations normalized by bulk velocity at bulk Reynolds number of $Re_b = 5.3\times10^3$ (flow direction from right to left).*

In Short

- Large-scale coherent structures have a significant contribution to transport of momentum and energy in wall-bounded turbulent flows.
- Reaching a deeper understanding of their nature and dynamics has great industrial and scientific relevance.
- Direct Numerical Simulation (DNS) of turbulent pipe flow with length of $L/R = 50$ will be conducted at bulk Reynolds number range of $5.3\times10^3 < Re_b < 25\times10^3$.
- A Dynamic Mode Decomposition (DMD) will be applied to the DNS data in a moving frame of reference.

For almost a century, wall bounded turbulent shear flows have been regarded as an attractive topic for physicists, mathematicians and engineers and have inspired wide ranges of studies. In most practical and industrial applications, flows at high Reynolds numbers lead to large energy losses which are caused by turbulence dissipation. Therefore, reaching a deeper understanding of this phenomenon can result in a more realistic prediction of losses, efficient flow control and ultimately reduction of energy consumption.

The same motivation has triggered study and observation of large-scale turbulent coherent structures which are known by many studies as Large and Very Large Scale Motions (LSMs and VLSMs) in wall bounded turbulent flows [1]. In spite of vast range of studies attempting to shed light on the nature of these structures, a solid definition of their mechanics and vivid understanding of their evolution is still missing.

The main goal of this project is to investigate the kinematic and dynamic properties of the mentioned structures. This includes for instance, their length scales, life times, contributions to turbulence properties and the interactions between different length scales.

For this purpose, direct numerical simulations are being performed at bulk Reynolds number range of $5.3\times10^3 < Re_b < 25\times10^3$ for pipe length of $L/R = 50$, using a hybrid (MPI/OpenMP) parallel DNS code [2]. The Navier-Stokes equations are solved using a pseudospectral solver in cylindrical coordinates for an incompressible flow fulfilling mass and momentum conservations. The governing equations are solved for velocity and pressure discretized in space using a combined Fourier-Galerkin and Finite Difference method. The solution is advanced in time using a semi-implicit fractional-step applying second-order-accurate backwards differences and second order linear extrapolation for nonlinear term. More details on the numerical scheme can be found in the study by Shi et al. (2015) [2].

Contours of streamwise velocity fluctuations are plotted in figure 1 for a simulation at bulk Reynolds number of $Re_b = 5300$. In this figure, the entire pipe is cut along the streamwise and azimuthal directions at radial distance of $r/R = 0.9$ which corresponds to a wall distance of $y^+ = 18$. Colors vary from -0.2 to 0.2 corresponding to blue and red respectively.

The simulation results are analysed using several techniques. The footprints of the structures are followed by observing the peaks in premultiplied velocity spectra. The spectral peaks are associated with LSMs and VLSMs and determine their length scales, energy contents at each wavenumber and their wall normal locations. In figure 2 the premultiplied energy spectrum of streamwise velocity component is plotted for the simulation at bulk Reynolds number of $Re_b = 5300$, where a prominent peak is observable at $y^+ = 15$ for the wavelength of $\lambda_x \simeq 4R$.

Figure 2 depicts the carpet plot of streamwise velocity fluctuations for one time step, taken at the same wall normal distance where the spectral peak was detected. In this figure regions of high velocity fluctuation are clearly visible representing a similar streamwise extent as it was observed in the energy spectrum. While the insight gained by studying the flow in wave number

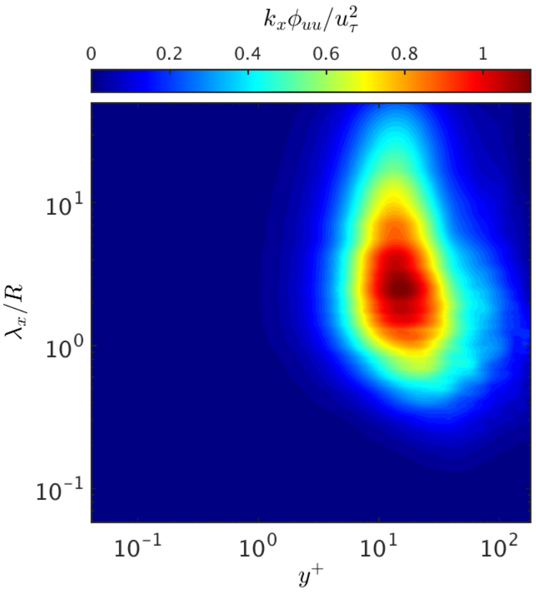

Figure 2: *Premultiplied energy spectra of streamwise velocity component for turbulent pipe flow at Re_b = 5300.*

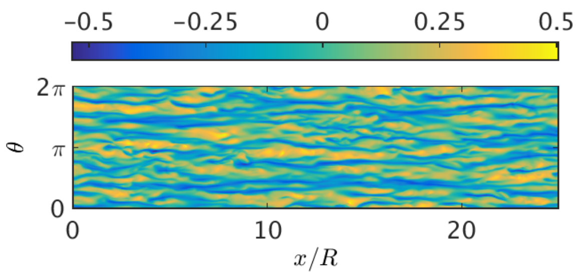

Figure 3: *Carpet plot of streamwise velocity fluctuations normalized by bulk velocity taken at wall-normal location of y^+ = 15 at Re_b = 5300. Only 25R of the simulated pipe length is plotted.*

space is valuable for characterisation of the structures, it is not sufficient to learn about their spatio-temporal evolution and interactions.

Given the transport-dominated nature of wall-bounded turbulent structures, standard decomposition methods such as Dynamic Mode Decomposition (DMD) will fail to reconstruct a reduced-order model of the flow with a minimal number of modes. Therefore, the essence of the present study is based on detecting the structures in a moving frame of reference along the characteristics of the flow, using a Characteristic Dynamic Mode Decomposition (CDMD) [3].

In this approach, the structures are followed in a properly chosen frame of reference along the characteristics representing their convective velocity. The latter will take place using a coordinate transformation from physical space into spatio-temporal space. The transformation is in form of a rotation in space and time with the rotation angle corresponding to the most dominant group velocity u_g in the flow, determined by the maximum drop of the singular values.

The transformed snapshots are decomposed via the standard DMD algorithm. The dynamic modes being reconstructed in the spatio-temporal space will be transformed back to physical space. The latter will represent a reduced order model of the flow using a few modes accommodating the structure with the dominant group velocity. These reduced-order models will be used to find answers to the questions raised in this report.

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WWW

https://www.b-tu.de/en/research/research-projects/fluid-mechanics

More Information

[1] A. J. Smits, B. J. McKeon, I. Marusic, *Annu. Rev. Fluid Mech* **43**, 353-375, doi:10.1146/annurev-fluid-122109-160753, (2010).

[2] L. Shi, M. Rampp, B. Hof, M. Avila, *J.Computers and Fluids* **106**, 1-11, doi: 10.1016/j.compfluid.2014.09.021, (2015).

[3] J. Sesterhenn, A. Shahirpour, *Theor. Comput. Fluid Dyn.* doi:10.1007/s00162-019-00494-y, (2019).

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