Ph.D. Thesis Defense

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“Studies of Turbulence Structure Using Well-Resolved Simulations With and Without Effects of a Magnetic Field”

Abstract:
Turbulence is characterized by disorderly fluctuations that span a wide range of scales in length and time, especially at high Reynolds numbers. The fluctuations in the small scales can take extremely large amplitudes (also known as extreme events), and exhibit rapid oscillations in sign. Recent computational work suggests that topological features of the extreme events differ from conventional notions as the Reynolds number increases, while values of cancellation exponent, which quantifies sign oscillation, have discrepancies in the literature. The first part of the thesis is thus focused on the small scales in isotropic turbulence. Specifically, effects of spatial and temporal resolution are examined with up to $8192^3$ grid points using visualizations. The results show spurious topological features would arise if the resolution is not adequate. To allow a systematic study of sign oscillations, cancellation exponents are computed in all three dimensions. Measures in two and three dimensions give similar values consistent with theory while one dimensional measure can give smaller values. It is shown that coherent structures may affect values of cancellation exponents.

In many applications body forces can lead to strong anisotropy and departures from classical descriptions. In particular electrically conducting fluids in a magnetic field are subjected to the Lorentz force of electromagnetic induction, which causes anisotropy at all scales in magnetohydrodynamic (MHD) turbulence. The second part of the thesis presents the development of anisotropy in MHD turbulence using up to $32768 \times 4096^2$ grid points, with an emphasis on the use of elongated domains to allow the rapidly-growing integral length scales to develop naturally. Both isotropic and anisotropic initial conditions are used, where the latter is obtained after axisymmetric contraction. It is found that at late times, a quasi-two-dimensional state results. Specifically the small scales display axisymmetry about the magnetic field direction, along which the velocity gradients decrease substantially. In comparison, the anisotropy in the Reynolds stress depends on the relative orientation of straining and the magnetic field. In addition to the velocity field, scalar mixing in MHD turbulence, which occurs at low Schmidt numbers due to high molecular diffusivity of liquid metals, is also briefly studied. It is seen that the magnetic field affects the mixing indirectly via modifications of the velocity field by the Lorentz force.

The thesis clarifies the characters of the extreme events and the sign oscillation properties, and improves the understanding of MHD turbulence in general. Moreover, the work benefits substantially from well-resolved direct numerical simulations that are performed on the state-of-the-art supercomputers (Stampede2, TACC; BlueWaters, NCSA).

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