COHERENCE IN TURBULENCE: NEW PERSPECTIVE

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Abstract

It is claimed that turbulence in fluids is inherently coherent phenomenon. The coherence shows up clearly as strongly correlated helicity fluctuations of opposite sign. The helicity fluctuations have cellular structure forming clusters that are actually observed as vorticity bands and coherent structures in laboratory turbulence, direct numerical simulations and most obviously in atmospheric turbulence. The clusters are named BCC - Beltrami Cellular Clusters - because of the observed nearly total alignment of the velocity and vorticity fields in each particular cell, and hence nearly maximal possible helicity in each cell; although when averaged over all the cells the residual mean helicity in general is small and does not play active dynamical role. The Beltrami like fluctuations are short-lived and stabilize only in small and generally contiguous sub-domains that are tending to a (multi)fractal in the asymptotic limit of large Reynolds numbers, $Re \to \infty$. For the model of homogeneous isotropic turbulence the theory predicts the leading fractal dimension of BCC to be: $D_F = 2.5$. This
particular BCC is responsible for generating the Kolmogorov $-5/3$ power law energy spectrum.

The most obvious role that BCC play dynamically is that the nonlinear interactions in them are relatively reduced, due to strong spatial alignment between the velocity field $\mathbf{v}(\mathbf{r}, t)$ and the vorticity field $\omega(\mathbf{r}, t) = \text{curl}\mathbf{v}(\mathbf{r}, t)$, while the physical quantities typically best characterizing turbulence intermittency, such as entropy, vorticity stretching and generation, and energy dissipation are maximized in and near them. The theory quantitatively relates the reduction of nonlinear interactions to the BCC fractal dimension $D_F$ and subsequent turbulence intermittency.

It is further asserted that BCC is a fundamental feature of all turbulent flows, e.g., wall bounded turbulent flows, atmospheric and oceanic flows, and their leading fractal dimension remains invariant and universal in these flows. In particular, theoretical and numerical evidence is given indicating that BCC in turbulent channel/pipe flows have the depth at the walls proportional to the square root of the Reynolds number in wall units, $L_y \propto \sqrt{Re}$, which is equivalent to the fractal dimension in normal to the walls $y$ direction $D_F^y = 0.5$, and the total dimension $D_F = D_F^{x,z} + D_F^y = 2 + 0.5 = 2.5$. Similar BCC structure and the same fractal dimension are suggested for geophysical turbulence, in near agreement with the recent comprehensive analysis of experimental and observational data. It is asserted that the atmospheric and oceanic events, e.g., tropical hurricanes, tornadoes and other mesoscale phenomena, and probably ocean currents are manifestations of BCC and their environs.

Generally BCC should be rather seen as the turbulence core, while the whole surrounding 3D flow as being created and sustained by the intense vorticity of BCC by means of induction, in a manner similar to that for an electric current generating magnetic field.

It is further argued that BCC is not only a theoretical concept important for fundamental grasp on turbulence, but may be a practical asset furnishing tools for turbulence management in regular fluids and plasmas.

The concept of helical fluctuations in turbulence goes 25 years back in time, and while never totally abandoned nevertheless has been residing on the fringes of research activity.
Experiment and numerical simulations had not been able to either validate or repudiate decisively the concept. However, recent large scale direct numerical simulations and proliferation of experimental and observational data showed convincingly how ubiquitous is the phenomenon of helicity fluctuations in various turbulent flows, from hurricanes and tornadoes to turbulent jets to solar wind plasma turbulence to turbulent flows in compressible fluids. This allowed a fresh look at the concept and led to a quantitative theory exposed in this paper.

The paper concludes with a brief discussion of possible similarities between turbulence and certain other complex non-equilibrium systems generating smart intrinsic coherence in the course of dissipative dynamical evolution.