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Kinematics and dynamics of small-scale vorticity and strain-rate structures in the transition from isotropic to shear turbulence

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Abstract

We applied a technique that defines and extracts "structures" from a DNS dataset of a turbulence variable in a way that allows concurrent quantitative and visual analysis. Local topological and statistical measures of enstrophy and strain-rate structures were compared with global statistics to determine the role of mean shear in the dynamical interactions between fluctuating vorticity and strain-rate during transition from isotropic to shear-dominated turbulence. We find that mean shear adjusts the alignment of fluctuating vorticity, fluctuating strain-rate in principal axes, and mean strain-rate in a way that (1) enhances both global and local alignments between vorticity and the second eigenvector of fluctuating strain-rate, (2) two-dimensionalizes fluctuating strain-rate, and (3) aligns the compressional components of fluctuating and mean strain-rate. Shear causes amalgamation of enstrophy and strain-rate structures, and suppresses the existence of strain-rate structures in low-vorticity regions between enstrophy structures. A primary effect of shear is to enhance "passive" strain-rate fluctuations, strain-rate kinematically induced by local vorticity concentrations with negligible enstrophy production, relative to "active," or vorticity-generating strain-rate fluctuations. Enstrophy structures separate into "active" and "passive" based on the level of the second eigenvalue of fluctuating strain-rate. We embedded the structure-extraction algorithm into an interactive visualization-based analysis system from which the time evolution of a shear-induced hairpin enstrophy structure was visually and quantitatively analyzed. The structure originated in the initial isotropic state as a vortex

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sheet, evolved into a vortex tube during a transitional period, and developed into a well-defined horseshoe vortex in the shear-dominated asymptotic state.

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1. Motivation, objectives and approach

The evolution of the small-scales in fully developed turbulence centers on dynamical interactions between vorticity and strain-rate fluctuations ubiquitous over the turbulent regions of the flow. Local concentrations of high strain-rate fluctuation are kinematically induced by distributions of concentrated vorticity that change locally at a rate determined by the magnitudes and relative alignments between vorticity and strain-rate in the regions of overlap. The alignments are altered by interactions with mean strain and rotation-rate depending on the structure of the mean gradients, the relative strengths of mean to fluctuating velocity gradients, and Reynolds number. In this paper we study the effects of mean shear (rotation plus strain) on the kinematic structure and dynamical evolution of the fluctuating vorticity and strain-rate fields in fully developed homogeneous turbulence at Reynolds numbers and nondimensional mean shear rates comparable to the lower inertial layer of wall-bounded shear flows.

To isolate the direct effects of mean shear on the fluctuating vorticity and strain-rate fields we analyze direct numerical simulation (DNS) data during transition from isotropic to shear-dominated fully developed homogenous turbulence. Brasseur and Lin (1991) quantified kinematic contributions of local concentrated regions of fluctuating enstrophy, strain-rate and Reynolds shear stress to global variance, anisotropy, turbulence production, non-Gaussianity, vectoral properties and structural similarity. In this paper we examine the local and global *dynamical* evolution of shear-flow turbulence—vorticity and strain-rate production, alignments between the vorticity and strain-rate tensors, and the creation and evolution of hairpin vortices as primary structures in turbulent shear flows (see also Lin, 1993).

Whereas traditional statistics and probability distribution functions (pdf) are applied in our analyses, we develop also local statistical measures derived from the extraction of "structures" with presumed coherence within local concentrations of vorticity and strain-rate fluctuations. We describe in this paper an algorithm for the systematic identification, extraction, visualization, and quantification of individual three-dimensional "structures" within DNS datasets, as the basis of a combined statistical and visual analysis approach.

2. Simulations of evolving shear-modulated turbulence

We focus here on the dynamics and structure of any fully developed turbulence under the influence of mean shear. Using the pseudo-spectral algorithm developed by Rogallo (1981), we carried out a well-resolved DNS of the transition from isotropic to shear-dominated homogenous turbulence with normalized shear-rate $S^* = Sq^2/\varepsilon$ consistent with shear rates encountered in the quasi-homogeneous regions of boundary layer, jet and wake flows ($S^* \sim 6$–10), where q^2 is twice the turbulent kinetic energy and ε is turbulent dissipation-rate.