§23. Analysis of Coherent Structures and Development of Turbulence Modeling in MHD or HD Turbulence

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We developed a multi-scale simulation method based on adaptive wavelet basis, called Coherent Vorticity and Current density Simulation (CVCS), for three-dimensional (3D) incompressible magnetohydrodynamic (MHD) turbulence. We also examined scale-dependent statistics of 3D incompressible MHD turbulence without mean magnetic field, and performed direct numerical simulation (DNS) of two-dimensional (2D) compressible hydrodynamic (HD) turbulence with chemical reactions. In the compressible HD turbulence, autoignition process in a homogeneous n-heptane mixture was studied. We summarize the achievement of these studies in the following.

3D incompressible MHD turbulence

CVCS

CVCS is a multiscale method to track the time evolution of coherent vorticity and current density based on the wavelet filtered Navier-Stokes equations and induction equations. At each time step these fields are decomposed into two orthogonal components using an orthogonal wavelet basis, respectively: the coherent fields, each of which corresponds to the coefficients whose modulus is larger than a threshold, and the remaining incoherent fields. The threshold value only depends on the total kinetic and magnetic enstrophies, which evolve in time, and on the constant maximal resolution. To compute the flow evolution, one only retains the coherent wavelet coefficients and some of their neighbours with respect to space, scale and direction in wavelet space, called the safety zone. The quality of the results was assessed in comparison to a DNS of the same flow for a 3D forced homogeneous MHD turbulent flow at 256^3 grid points. The magnetic Prandtl number is set to 1. It is found that, as long as a safety zone is present, CVCS well preserves the statistical predictability of the turbulent flow with a reduced number of degrees of freedom. During the simulation time period, the coherent vorticity sheets and coherent current density sheets are also well preserved even in their position as shown in figure 1, which is in contrast to coherent vorticity simulation of 3D incompressible homogeneous HD turbulence performed by Okamoto *et al.*[1)]

Scale dependent statistics

We examined scale-dependent and geometrical statistics of 3D incompressible homogeneous MHD turbulence in the absence of the imposed uniform magnetic field, using the orthogonal wavelet decomposition. The flow was computed by DNS with a Fourier spectral method at resolution 512^3, and the magnetic Prandtl number is one. Different scale-dependent relative helicities, i.e., kinematic, cross and magnetic relative helicities, yield geometrical information on alignment between the different scale-dependent fields. At each scale, the alignment between the velocity and magnetic field is found to be more pronounced than the other alignments considered here, i.e., the scale-dependent alignment between the velocity and vorticity, and the scale-dependent alignment between the magnetic field and its vector potential.

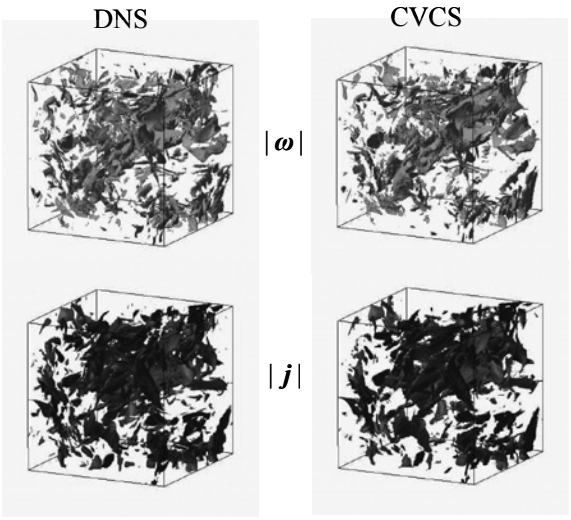

Fig. 1: Visualization of the intense vorticity and current density regions for DNS and CVCS at $t/\tau = 3.25$, where τ is an initial large eddy turnover time. Isosurfaces of vorticity $\boldsymbol{\omega}$ and current density $\boldsymbol{j}$ are shown for $|\boldsymbol{\omega}| = \langle|\boldsymbol{\omega}|\rangle + 3\sigma_\omega$, $|\boldsymbol{j}| = \langle|\boldsymbol{j}|\rangle + 3\sigma_j$, where σ_ω and σ_j denote the standard deviations of $\boldsymbol{\omega}$ and $\boldsymbol{j}$, respectively.

2D compressible HD turbulence with chemical reactions

The influence of turbulence and initial temperature distribution on autoignition process at high pressure was studied using 2D DNSs of compressible turbulence with a reduced chemical kinetic mechanism (33 chemical species) of n-heptane(one of the main ingredients of gasoline)/air (see Ref. 2 for details). For the computation we used a 8th-order finite difference scheme and 4th-order Runge-Kutta method on 1024^2 grid points. The reaction course in the chemical kinetic mechanism of n-heptane/air depends on initial temperature distribution. A detailed analysis showed that in spite of the weak influence of turbulence on time variation of spatially averaged temperature, turbulent enhancement of heat conduction and molecular transport changes the individual reaction course of the chemical mechanism.

1) Okamoto *et al.*, SIAM MMS (to appear).

2) Teraji *et al.*, JSME (to appear).