One-point structure tensors in Rayleigh-Taylor turbulence

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The dynamics of turbulent mixing zones submitted to Rayleigh-Taylor (RT) instability depends strongly on the structure of the turbulence (like the form of its spectra [1]) which is a concern for turbulence models. When the flow reaches a self-similar state, this structure is frozen. In this case, one-point statistics models are sufficient to predict the evolution of the mixing zone as long as their coefficients are properly calibrated on the self-similar growth rates [2, 3]. On the contrary, when the mixing zone is submitted to a more complex acceleration history, one-point models are much less reliable as they cannot predict accurately any structure modification of turbulence (which proves to be important in case of steep acceleration profile [4]).

One generic reason of this deficiency is that non-local rapid pressure correlations are difficult to close for single-point statistics models as depending strongly on the wave number anisotropy. Now, these terms are mainly responsible for the structure modification of turbulence as expressing the interaction between large and small scales [5]. In particular, it has been noted by [6] that the Reynolds stresses alone cannot capture inhomogeneity or dimensionality characteristics of turbulence which are deeply modified during transient phases of rapid distortion. These phases appear when a rapid modification of the mean velocity occurs (through deformation, shear and rotation) but also in stratified flows if the Froude number is suddenly decreased by a strong varying acceleration for instance [7].

In order to adapt turbulence models to rapid distortion phases, Kassinos, Reynolds and Roger (KRR) [8] introduced new turbulent one-point structure tensors. In addition to the classical Reynolds stress tensor describing the componentality of the turbulence they proposed dimensionality D_{ij}, cirulicity F_{ij} and inhomogeneity C_{ij} tensors all constructed from different contractions of $\overline{\psi'_{ij}\psi'_{kl}}$, where the turbulent vector stream function ψ'_i in incompressible flow is solution of a Poisson equation with the vorticity as a source term:

$$\psi'_{i,ll} = -\omega_i, \qquad \psi'_{i,i} = 0, \qquad \epsilon_{ilp}\psi'_{l,p} = u'_i. \tag{1}$$

As noted by [9], the structure tensors are directly related to the poloidal-toroidal decomposition of velocity. They might provide useful informations for models in order to capture rapid distortion phases and allow for better formulations of the production terms in algebraic stress models (ASM).

In this work, we study the values of the one-point structure tensors in RT mixing zones. The question we address here is how the different tensors envolve when a complex acceleration with rapid phases is applied. However, KRR tensors are not sufficient to capture all the complex structure of RT flows. As for example, they do not bring information about the dimensionality of ρ'. We study an extension the one-point turbulent structure tensors introduced by KRR to variable density flows. One possibility (among others also discussed) consists in adding to the velocity field a dilatational mode like the one appearing in Helmoltz decomposition of compressible flows [10].

We use different direct numerical simulations performed by the incompressible code SURFER to extract one-point structure tensors. One configuration is a RT flow with a step Heavyside profile of acceleration. This allow for an exploration of the the main differences between self-similar phases and rapidly distorted ones. Whether mixing zones created by different forms of initial spectra can be distinguished or not by one-point structure tensors can be studied also.

In order to check if RDT (Rapid Distortion Theory) in complex acceleration history can predict *some* realistic structure modification of turbulence, we provide also a comparison between direct computations and the inhomogeneous linear theory during the rapid phase.

Finally, the possible use of structure tensors to the closure for ASM is discussed.

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