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Computation of the one-point turbulence structure tensors in fully-developed turbulent pipe flow

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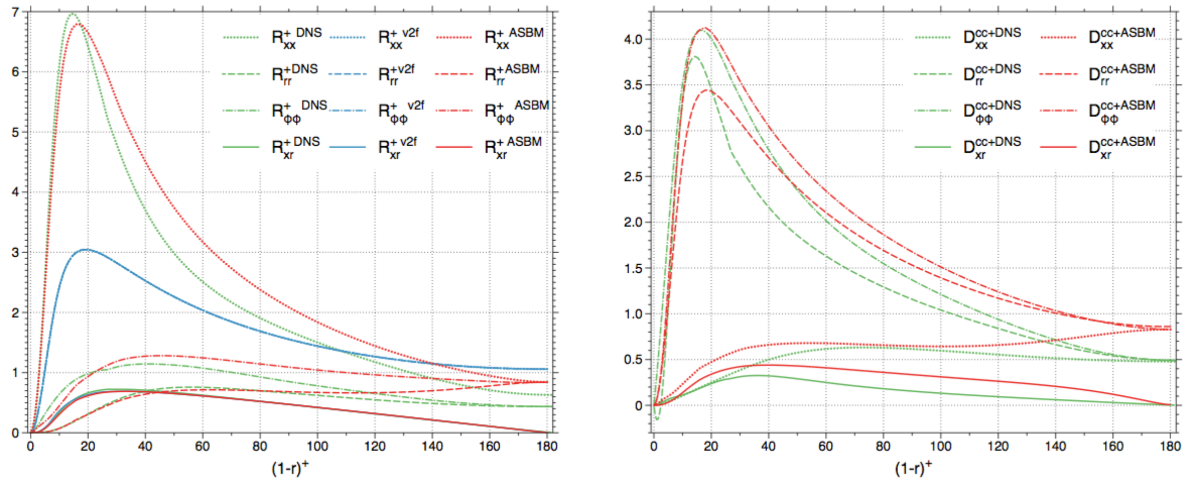
The one-point turbulence structure tensors provide an accurate description of the energy-containing turbulence structures. Kassinos and Reynolds [1] introduced these tensors in the context of turbulence modelling. They have shown that one-point models that use solely the Reynolds stress tensor Rij to characterize the turbulence are fundamentally incomplete for flows with mean rotation. The basic problem is that the Reynolds stresses describe only the componentality of the turbulence (information about which velocity components are more energetic), but provide no information about the morphology of the turbulence structures. The one-point structure tensors contain the information missing from the Reynolds stresses. These are: the structure dimensionality D_{ij} (giving information about the directions of independence in the turbulence), structure circulicity Fij (giving information on the large scale fluctuating vorticity vector), inhomogeneity Cij (describing the degree of inhomogeneity of the turbulence), and stropholysis Q_{ijk} (important when mean rotation breaks the reflectional symmetry). Exact definitions of these tensors are given in [2].

While the structure tensors were introduced in the context of turbulence modelling, they also have been used as a diagnostic tool for quantifying the anisotropy of the structure of turbulence fields [3]. Since these tensors are closely linked with the large-scale energy-bearing turbulence structures, they can be computed both via DNS or LES.

In this study, we compute for the first time the structure tensors in a fully developed turbulent pipe flow using DNS and RANS simulations, at a low Reynolds number (Re_τ=180, Re_b=5300). The exact definitions of the structure tensors involve statistics of the fluctuating stream-vector-function. For the DNS case, three Poisson equations are solved at each time step in-order to extract the stream-vector. These Poisson equations are coupled through the appropriate boundary conditions specified for the stream-vector. Note that stream-vector stems from a set of Poisson equations, and thus carries non-local information that is transferred into the structured tensors. The analysis of the structure tensors indicates the existence of streaky structures and quasi-streamwise vortices (visualized using velocity iso-surfaces and λ_2 criterion on instantaneous turbulent fields). Similar studies for channel flows can be found in [2,3].

The second part of this study consists of the calculation of the structure tensors using RANS closure models. An advanced engineering model should be able to predict accurately not only the Reynolds stress tensor, but also the rest of the one-point structure tensors. The Algebraic Structure-Based Model (ASBM) is one of the very few models that can provide information on the structure tensors. The ASBM model is described in detail in [4,5,6]. We have used the v2f model coupled with the ASBM closure to compute the fully developed turbulent pipe flow. A comparison between DNS, v2f and v2f-ASBM data, for the Reynolds stress and homogenized dimensionality tensor takes place in Fig.[1]. The ability of the ASBM to represent accurately a turbulent flow is imprinted on the profiles of the structure tensors. The Boussinesq approximation used in the v2f fails to produce the correct profiles for the normal Reynolds stress components. In contrast, the ASBM data are very close to the DNS data for all the structure tensors. The discrepancies in the centerline region are attributed to the zero mean deformation tensors, which forces ASBM to return an isotropic state for the structure tensors.

These results are useful for the ongoing development of structure-based turbulence models for complex turbulent flows. As part of this effort, we have now developed a numerical framework that enables us to compute the turbulence structure tensors in complex geometries either on structured or unstructured grids.



Fig[1]: Comparison between DNS, v2f and v2f-ASBM data, for the Reynolds stress (left) and homogenized dimensionality tensor (right).

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