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Computing turbulence structure tensors in plane channel flow

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ABSTRACT

This paper is concerned with the computation of turbulence structure tensors in plane channel flow. It has been pointed out that the previously computed turbulence structure tensors, for this configuration, used an inconsistent set of boundary conditions. But it was claimed that this had no influence on the computed structure tensors since the velocity field reconstructed by the vector potential only had a constant offset when compared to the original velocity field. In this paper it is shown that this is not the case. Based on a highly resolved LES simulation, the turbulence structure tensors are computed both using the previously employed boundary conditions and a consistent set of boundary conditions. The results exhibit considerable differences in a significant part of the domain.

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1. Introduction

Turbulent fluid motion consists of many interacting coherent structures commonly referred to as ‘eddies’. These eddies vary greatly in size, shape, and kinematic character, the distribution of which is highly case dependent. The type of eddies present in a flow significantly affects its dynamic response to external forcing. In particular, the large energy containing eddies play an active role in the flow dynamics. One way to quantify the turbulence structure of a flow is through two-point correlations of the velocity field. The computation of such correlations can however be exceedingly costly, and one-point measures of turbulence structure is therefore desirable from both a flow diagnostic and turbulence modeling perspective.

A comprehensive mathematical framework for structure-describing one-point measures was developed by Kassinos and Reynolds [1]. They introduced the concept of one-point turbulence structure tensors, which have been used for both modeling and turbulence diagnostic purposes [2,3]. They also demonstrated that two turbulent fields can have the same Reynolds stress and still have different turbulence structure leading to a difference in the interaction between the turbulence and the mean flow field. This means that a description of turbulence based solely on Reynolds stress is fundamentally incomplete. Some turbulence structure information must be included for a complete one-point description.

The definition of turbulence structure tensors is based on the vector potential of the fluctuating velocity field. A prerequisite for computing the tensors is thus the ability to compute the vector potential. While the three-dimensional vector potential has been used in several algorithms involving fluid flow [4–10], and descriptions of how to compute them for general domains exist [11–14], the computation of the turbulence structure tensors has, until recently, been limited to simple geometries [2]. Recently, however, a general framework for the computation of the turbulence structure tensors has been proposed [15].

In [15] it was also pointed out that the computations of the structure tensors for turbulent channel flow presented in [2] used an inconsistent set of boundary conditions for the computation of the vector potential. It was claimed that this had no influence on the computed turbulence structure tensors since the velocity field reconstructed by the vector potential only had a constant offset when compared to the original velocity field. In this paper it is shown that this is unfortunately not the case. Based on a highly resolved LES simulation, the turbulence structure tensors are computed both using the previously employed boundary conditions and a consistent set of boundary conditions. The results exhibit considerable differences in a significant portion of the domain.

2. Turbulence structure tensors

Using index notation, the vector potential, ψ_i, commonly called the stream function, is defined by the following relations

$$u_i = \epsilon_{ijk}\psi_{k,j}, \quad \psi_{i,i} = 0, \quad \psi_{i,kk} = -\omega_i, \tag{1}$$

where u_i and ω_i are the fluctuating parts of the turbulent velocity and vorticity fields, respectively, ϵ_{ijk} is the cyclic permutation symbol, and indices found after a comma denote differentiation.

In the above notation, the components of the Reynolds stress, R_{ij}, which are also referred to as the components of componentality, can be expressed in terms of the stream function as follows

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$$R_{ij} = \langle u_i u_j \rangle = \epsilon_{ipq}\epsilon_{jrs}\langle \psi_{q,p}\psi_{s,r}\rangle, \quad (2)$$

where $\langle \cdot \rangle$ denotes averaging. By employing the well known relation between the product of cyclic permutation symbols and the Kronecker delta, δ_{ij}, the following constitutive relation is obtained

$$R_{ij} + D_{ij} + F_{ij} - (C_{ij} + C_{ji}) = 2k\delta_{ij}, \quad (3)$$

where $2k = R_{kk}$ is twice the turbulence kinetic energy, and the various structure tensors, and their associated normalized and anisotropic forms, are defined as follows:

$$\text{Componentality} \quad R_{ij} = \epsilon_{ipq}\epsilon_{jrs}\langle \psi_{q,p}\psi_{s,r}\rangle \quad r_{ij} = R_{ij}/R_{kk}$$
$$\tilde{r}_{ij} = r_{ij} - \delta_{ij}/3, \quad (4)$$

$$\text{Dimensionality} \quad D_{ij} = \langle \psi_{k,i}\psi_{k,j}\rangle \quad d_{ij} = D_{ij}/D_{kk}$$
$$\tilde{d}_{ij} = d_{ij} - \delta_{ij}/3, \quad (5)$$

$$\text{Circulicity} \quad F_{ij} = \langle \psi_{i,k}\psi_{j,k}\rangle \quad f_{ij} = F_{ij}/F_{kk}$$
$$\tilde{f}_{ij} = f_{ij} - \delta_{ij}/3, \quad (6)$$

$$\text{Inhomogenity} \quad C_{ij} = \langle \psi_{i,k}\psi_{k,j}\rangle \quad c_{ij} = C_{ij}/D_{kk}$$
$$\tilde{c}_{ij} = c_{ij} - c_{kk}\delta_{ij}/3. \quad (7)$$

The lower case letters represent the normalized tensors and $\tilde{(.)}$ denotes the anisotropic form. The various structure tensors carry complementary statistical information about the turbulence, and detailed discussions of their physical interpretation can be found in [1,2,16]. Here, only a short description is provided.

The componentality, or Reynolds stress, provides information about the amplitude of the various components of the fluctuating velocity field. The dimensionality is a measure of the spatial extent of the turbulent structures. A small value of dimensionality means that there is a large coherence length present in the turbulent field in that direction. This indicates the presence of elongated structures in that direction. The circulicity is a measure of the average large scale circulation in the turbulent field. A large value of circulicity is thus an indicator of the presence of “vortical” eddies with axis oriented in a particular direction. Finally, the inhomogeneity tensor is a measure of the deviation from a homogeneous turbulence state. This interpretation of the inhomogeneity tensor is supported by the observation that Eq. (7) can be recast, using the Euclid gauge condition ($\psi_{i,i} = 0$), into the following form

$$C_{ij} = \langle \psi_i \psi_{k,j}\rangle_{,k}, \quad (8)$$

which clearly is zero for homogeneous turbulence.

2.1. Anisotropy measures

The anisotropy tensors associated with componentality, dimensionality, and circulicity are symmetric second rank trace-free tensors. This means that they have two independent anisotropy invariants that can be used to characterize the anisotropy state of the tensors. One commonly used set of invariants is

$$II_x = -\frac{1}{2}x_{ij}x_{ji} \quad (9)$$

$$III_x = \frac{1}{3}x_{ij}x_{jk}x_{ki}. \quad (10)$$

For these tensors all possible states fall within the Lumley triangle [17] in $(III_x, -II_x)$-space. One useful way to characterize a turbulent flow is to plot the invariant coordinates for different positions in the physical domain. This results in a graphical representation of the change in turbulence structure as a parametric function of position, which is very useful for analyzing the flow. This method will be employed to highlight the differences in the turbulence structure predicted using the different boundary conditions.

3. Boundary conditions for the vector potential

For general multiply connected domains, such as a plane channel flow, an appropriate set of boundary conditions for the vector potential takes the following form [12,15]

$$\epsilon_{ijk}\psi_{k,j} = \epsilon_{ijk}n_j u_k \text{ and } n_i\psi_i = 0 \text{ on } \Gamma, \quad (11)$$

where Γ denotes the boundary of the computational domain and n_i is its unit normal.

As pointed out in [15], the computations of the structure tensors for turbulent channel flow presented in [2] used an inconsistent set of boundary conditions for the computation of the vector potential. The boundary conditions used for these calculations were of the form

$$\epsilon_{ijk}n_j\psi_k = 0 \text{ and } \psi_{i,i} = 0 \text{ on } \Gamma. \quad (12)$$

It was then claimed that this had an insignificant effect on the computed turbulence structure tensors, since it only leads to a constant offset of the velocity field reconstructed from the vector potential. This is, however, not the case. A constant velocity field is reconstructed from a stream function with non-zero gradients, which necessarily also changes the turbulence structure tensors.

Consider a turbulent channel flow domain aligned with the coordinate axis such that x is the streamwise coordinate, y is the wall normal coordinate, and z is the spanwise coordinate. A constant velocity field in the streamwise direction is then given by

$$c_i = \epsilon_{ijk}\psi_{k,j}, \quad (13)$$

where $c_i = c\delta_{1i}$ and c is a constant. The vector potential of c_i takes the form

$$\psi_i = cy\delta_{3i} + constant. \quad (14)$$

This yields the following partial derivatives of the vector potential

$$\psi_{i,j} = c\delta_{3i}\delta_{2j}, \quad (15)$$

which is clearly non-zero and will thus contribute to the turbulence structure tensors.

4. Computational setup

A highly resolved LES simulation of a turbulent channel flow with $Re_\tau = 395$ has been carried out on a domain with dimensions $(2\pi H, 2H, \pi H)$, where H is the channel half height. The code used for this simulation was the incompressible flow solver Cliff from Cascade Technologies. It is an unstructured collocated nodal-based finite volume code that solves the primitive variable Navier–Stokes equations using a fractional-step method. It is algorithmically similar to the CDP code, which is described in [18–20]. After each step, the required Poisson equations are solved in order to compute the stream function, and the structure tensors are computed based on this calculation. The coordinate system is aligned such that x is the streamwise direction, y is the wall normal direction and z is the spanwise direction. This is the same case as presented in [2]. The number of computational points used in the different directions are $(N_x, N_y, N_z) = (87, 169, 156)$, which results in the near wall resolution $(dx^+, dy^+, dz^+) = (30, 0.4, 8)$.

For this configuration, the structure tensors were computed using both the inconsistent boundary conditions from Eq. (12) and the consistent boundary conditions found in Eq. (11). When the boundary conditions in Eq. (12) are employed, the calculation of

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