Experimental Thermal and Fluid Science 35 (2011) 1223–1229

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Time resolved visualization of structures of velocity gradients measured with near Kolmogorov-scale resolution in turbulent free-shear flows

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ARTICLE INFO

Article history:
Received 30 August 2010
Received in revised form 22 December 2010
Accepted 26 January 2011
Available online 3 February 2011

ABSTRACT

A three-dimensional visualization of velocity gradients at the finest scales in a turbulent free-shear flow is obtained using a time-resolved scanning PIV system with near Kolmogorov-scale resolution. A minimal observation volume capable of capturing single velocity gradient structures is used. The structures are identified by iso-surfaces revealing four basic shapes in the makeup of the velocity gradients: sheets, tubes, square ribbons and spherical blobs. Their size is also obtained. The 3D local acceleration structure is visualized showing strong anti-alignment with the convective acceleration. The statistics of the velocity gradient, and higher order moments (skewness and kurtosis) are calculated and compared favorably with published experimental work and with homogeneous isotropic theory.

1. Introduction

Although the fine-scale structures of turbulent flows have been widely studied [1,2], they still remain a challenging problem. This is the case when trying to resolve with near Kolmogorov-scale resolution turbulent flow structures to obtain a detail three-dimensional representation of their geometry. The Kolmogorov scale arguably represents the smallest scales in the flow where viscous dissipation dominates and where the energy cascade ends. Fully resolving the smallest scales can then provide a better understanding of the local viscous dissipation process, its relation to larger scales in the energy cascade process in turbulence as well as characterizing the high intermittency in turbulence (intense burst of vorticity and strain) [3].

Studying turbulence in three-dimensional space with a resolution of the order of the Kolmogorov scale, η, has been generally done using direct numerical simulations (DNS) [4,5]. Briefly, a restriction of DNS is that all scales of the flow must be resolved, from the Kolmogorov scale to the large eddies present in the flow. As a result, the larger the range of scales present (i.e.: high Reynolds number), the larger the computational cost. In general, the computational grid number is reduced by limiting the smallest scales resolved to a value on the order of η [6].

There have also been, over the last couple of decades, a number of experimental techniques corresponding to single-point measurements and 2D measurements (PIV) that have calculated the velocity gradients with a resolution on the order of η in turbulent flows [7–9]. For instance, [9] uses a hotwire technique to obtain the nine component of the velocity gradient at a point. Of particular interest to the present work are velocity measurement techniques that are applied in three-dimensional space. These include digital Holographic PIV [10,11], tomographic PIV [12], and 3D PTV [13] among others. Although these represent the state of the art in 3D optical velocity measurement techniques, and have in general addressed many aspects of turbulent flows, to date they have not resolved the nine velocity gradients in a measuring volume with η resolution in a free-shear flow. A three-orthogonal-plane PIV [3] has been able to resolved these quantities in a volume, but the method requires that the volume be small enough (region image of 1.8η) such that the variation of the velocity over 3D-space can be assumed linear. This size limitation prevents visualizing the smallest structures of the flow which are much larger [2]. Two planar techniques have been to date the only ways to obtain these gradient measurements in a larger field of view. These include measurements between two planes using dual-plane stereo PIV or in a pseudo-volume by applying the Taylor's frozen hypothesis to consecutive high speed PIV [1,14,15]. A well proven technique, scanning PIV, which combines conventional PIV with scanning techniques will be applied to obtain the velocity gradients and their three-dimensional structural shapes with near Kolmogorov-scale resolution. For scanning frequencies adjusted sufficiently high compared to the characteristic time scale of the flow, the measurements can be considered quasi-instantaneous over a scan cycle. The method has been applied successfully to extract the large vortical structures present in turbulent jets [16], but to our knowledge it has never been applied to fully resolve the three-dimensional structure of the velocity gradient with near η resolution in a turbulent flow.

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doi:10.1016/j.expthermflusci.2011.01.014