The fine scale features of turbulent shear flows

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1 Introduction

Turbulence has been described as the "most important unsolved problem of classical physics" by Nobel prize winning physicist Richard Feynman, yet most practical flows of engineering significance are turbulent. It is inherently multi-scale, with the smallest (and most rapid) motions dissipating the kinetic energy of the flow and determining the drag on a body, dispersion of pollutants and chemical mixing. Until very recently these small scales have been accessible only to direct numerical simulations (DNS) at moderate Reynolds numbers[1,2,3]. Engineering type large eddy simulations (LES) have predicted these small scale motions using uncertain models and theories, which have assumed them to be "universal". This study makes use of state of the art laser diagnostic techniques to make fully three-dimensional measurements as well as instantaneous synchronised multi-scale measurements of theses small scale motions possible **for the first time**. In addition, these experiments are supplemented by LES and DNS computations in order to validate these cutting edge techniques, and feed back to the applicability of various sub-grid turbulence models. Access to this data from two different shear flows, a nominally two-dimensional mixing layer and an axisymmetric jet, will allow this study to make the first tentative steps towards answering the question *is fine scale turbulence universal?* and if not *is the interaction between large and small scales universal?*

2 Three dimensional experimental data

The universality of fine-scale turbulence, if it exists, will be visible in the interactions of the rate of strain and rotation fields[5]. The interaction between rate of strain (S_{ij}) and rotation (Ω_{ij}) is described as "intrinsic to the very nature of three-dimensional turbulence"[6]. The study of this interaction requires access to all nine components of the velocity gradient tensor at an extremely high spatial resolution. Experimentally this has become available through techniques such as hot wire probes[7], holographic particle image velocimetry (PIV)[8] and stereoscopic PIV[4,9].

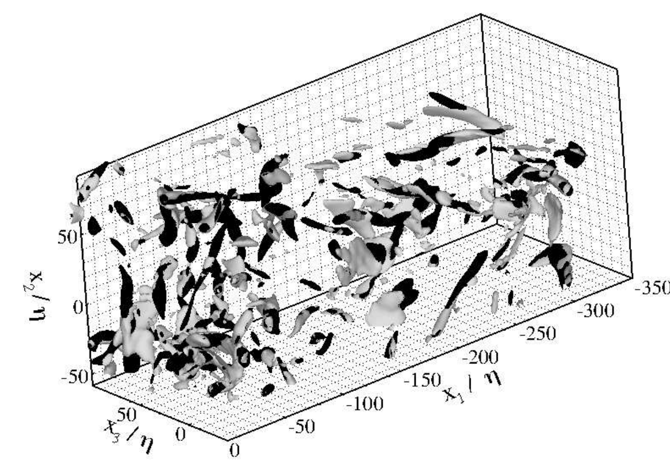


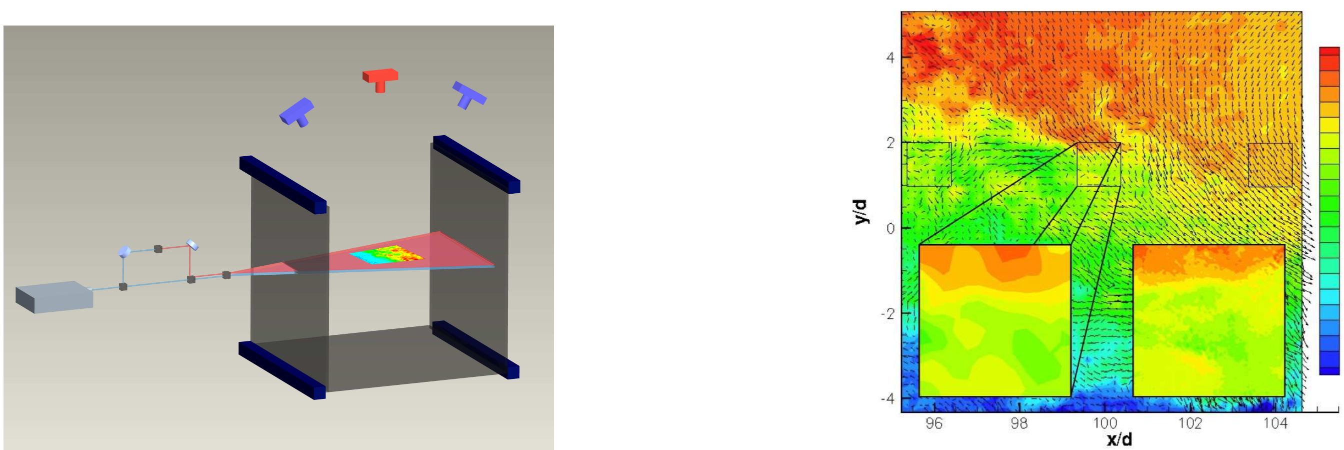
Figure 1: Isourfaces of $\omega_i S_{ij} \omega_j$ (white) and swirling strength (black) in the far field of an axisymmetric turbulent jet[4]. The axes are scaled by η.

Buxton & Ganapathisubramani[4] examined this interaction between rotation and strain by observing the rate of enstrophy amplification ($\omega_i S_{ij} \omega_j$, where $\omega_i = (-1)^i \cdot 2\Omega_{jk}$ is the i^{th} component of the vorticity vector) at the dissipative scales of turbulent jet flow. This quantity is dependent upon the alignment between the vorticity vector and the eigenvectors of the rate of strain tensor. The literature extensively reports the tendency of the vorticity vector ($\boldsymbol{\omega}$) to preferentially align itself with the intermediate strain-rate eigenvector ($\boldsymbol{e_2}$). It is also noted that there is no preferential alignment direction between $\boldsymbol{\omega}$ and the extensive strain-rate eigenvector, $\boldsymbol{e_1}$, resulting in a flat probability density function (*pdf*) for the cosine of this alignment angle. Buxton & Ganapathisubramani[4], however, reported that the nature of enstrophy amplification was dependent upon the alignment between $\boldsymbol{\omega}$ and $\boldsymbol{e_1}$. When these two vectors are aligned, such that they are parallel to one another, enstrophy is amplified by means of vortex stretching, that is to say $\omega_i S_{ij} \omega_j > 0$. However, when the two vectors are perpendicular to one another enstrophy is observed to be attenuated, that is to say the $\omega_i S_{ij} \omega_j < 0$. The effect of the alignment between $\boldsymbol{\omega}$ and the intermediate strain-rate $\boldsymbol{e_2}$ was found to be qualitatively similar for both enstrophy amplification and enstrophy attenuation. It was thus concluded that the alignment between the vorticity vector and the extensive strain-rate eigenvector was of much greater significance than the alignment with the intermediate eigenvector. In addition the "traditionally" flat *pdf* for this $\boldsymbol{\omega}$ - $\boldsymbol{e_1}$ alignment is the combination of two different physical processes, namely enstrophy amplification and enstrophy attenuation.

The initial part of this study[4] used cinematographic stereoscopic PIV, and enabled the visualisation of the fine scale features of a quasi-instantaneous volume of data. It was thus possible to observe the topology of regions of strong enstrophy amplification ($\omega_i S_{ij} \omega_j > 0$) and enstrophy attenuation ($\omega_i S_{ij} \omega_j < 0$). It was observed that whilst enstrophy amplifying regions were found in coherent "sheet-like" topologies enstrophy attenuating regions displayed a spatial coherence over a much smaller distance in all directions and were described as "spotty". Additionally, enstrophy amplifying "sheets" were observed filling the spaces surrounding the intensely swirling "worm-like" regions of the flow and can be observed in figure 1, displaying isosurfaces of strong enstrophy amplification (white) and strong swirling (black). This reflects statistical observations that high positive enstrophy amplification rates are observed to occur in rotationally dominated regions of the flow[4].

In order to attempt to address the question of *"universality"* of fine scale turbulence in shear flows it is necessary to gather three-dimensional data from different flows. This study also examines the fine scales of the self similar region of a planar mixing layer. The three-dimensional data is provided by two state of the art techniques at Reynolds numbers beyond the reaches of modern simulations ($Re_\lambda \approx 400$). Firstly, volumetric three-dimensional velocimetry (V3V) is employed to provide all three velocity components within an interrogation volume, in a turbulent flow **for the first time**. Figure 2(a) shows dual plane stereoscopic PIV which is also used to provide all nine components of the velocity gradient tensor in a plane.

3 New and novel multi-scale experimental technique



(a) (b)

Figure 2: (a) The dual plane stereoscopic PIV experimental setup. Red corresponds to vertically polarised light and blue corresponds to horizontally polarised light. (b) Instantaneous PIV streamwise velocity fields (u_1) for all four cameras. The contour levels are in ms^{-1} and velocity vectors of ($u_1 - U_C$), where $U_C = \frac{1}{2}(U_h + U_l)$ is the convection velocity and u_2, the cross-stream velocity component, are superimposed. For clarity only alternate vectors are shown. The insets show the close up of the large scale (left) and fine-scale (right) velocity data of the middle field of view.

One of the stated aims of this study is to examine whether the multi-scale interactions of turbulence are universal, thereby requiring data at different spatial scales. This led to the development of the brand new experimental technique: synchronised multi-scale PIV. Figure 2 (b) shows results that have been generated using synchronised multi-scale PIV in the far field of a nominally two-dimensional turbulent mixing layer with Reynolds number based on Taylor micro-scale (Re_λ) of 390. The mixing layer is generated in a water channel by means of placing a blockage (50% open area perforated plate) on one side of a splitter plate (width h), thereby creating a high speed (U_h) and low speed (U_l) stream, and corresponding turbulent boundary layers. The technique, developed by the author, involves placing three cameras beneath the water channel capturing a small, highly spatially resolved field of view and one camera above the channel with a larger less well spatially resolved field of view. All four cameras are synchronised to capture particle images generated by the same laser pulses. Three small-scale velocity fields (successive vectors are separated by 0.18 mm $= 0.56\eta$, where η is the Kolmogorov length scale) are thus captured at the same time instant as a large scale field (successive vectors separated by 1.63 mm), incorporating the three small-scale fields of view. Thus multi-scale velocity fields, incorporating Kolmogorov scale spatial resolution, are captured at the same instant in time as fields of view incorporating integral range length scales. This data is unique and will, for the first time, facilitate the examination of multi-scale interactions in shear flow turbulence at relatively high Reynolds numbers. An example can be seen in figure 2(b), showing a typical instantaneous velocity field from the synchronised multi-scale PIV experiments.

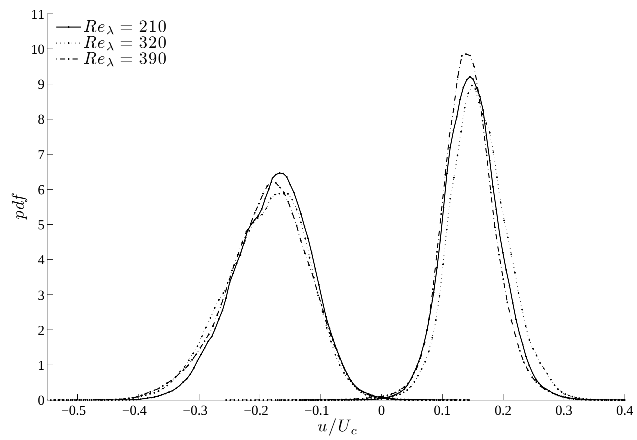


Figure 3: Probability density functions (pdfs) of small scale fluctuations conditioned on the large scale fluctuations. Fine-scale data from fields of view for which proportion $(1-e^{-2})$ of the large-scale fluctuations have a magnitude greater than the r.m.s. are included in the pdfs of the figure.

Figure 3 shows pdfs of the fine-scale fluctuations conditioned on the large scale fluctuations. The finesale data from high resolution PIV fields of view are included in the statistics only if large-scale positive or negative fluctuations are detected in the low resolution data, corresponding to the area bounded by the high resolution field of view. A proportion of $(1-e^{-2})$ of the large-scale fluctuations within the field of view must have $|u^{'}| > \sqrt{\langle u'^2 \rangle}$, i.e. the magnitude of the large scale fluctuations must be larger than the r.m.s. value. The fluctuations are scaled by the convection velocity, U_c and probability density functions are produced for three different Reynolds numbers. It can be seen that the pdfs for negative and positive fluctuations are fundamentally different with much longer tails for the negative fluctuations. A skew favouring larger magnitude fluctuations is also observed on the negative fluctuation pdfs, suggesting some large scale amplification of the negative fine-scale fluctuations. These results would seem to suggest that different physical interactions take place between the large and fine-scales of positive and negative turbulent fluctuations in shear flows.

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