

MEASUREMENT OF FINE SCALE STRUCTURE IN TURBULENCE BY QUAD-PLANE STEREOSCOPIC PIV

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Abstract To investigate fine scale structure of turbulent flows, quad-plane stereoscopic particle image velocimetry (QPSPIV) has been developed. QPSPIV provides three-dimensional distribution of three components of velocity and nine components of velocity gradient with a high spatial resolution. The QPSPIV system was applied to measurements in a turbulent jet for two different conditions: $Re_\lambda = 76.8$ and 128.9 . Probability density functions (PDFs) of velocity gradients agree with DNS data. Fine scale structures of turbulence are investigated based on an eddy identification scheme used for the analysis of DNS data which requires full velocity gradient tensor. PDFs of the diameter and maximum azimuthal velocity of the detected eddies show peaks at $D/\eta \approx 8$ and $u_{\theta,max}/u_k \approx 1.5$ for both Reynolds numbers, and this coincides with the results obtained from DNS. The present study gives experimental evidence of the existence of the coherent fine scale eddy in turbulence.

INTRODUCTION

In our previous studies on fine scale structure of turbulence by direct numerical simulation (DNS)[1][2][3], the existence of universal fine scale structure, which is independent on Reynolds number and type of flow field, has been revealed. The diameter and the maximum azimuthal velocity of coherent fine scale eddies can be scaled by Kolmogorov length (η) and Kolmogorov velocity (u_k). Except for near wall turbulence[3], the most expected diameter and maximum azimuthal velocity are 8η and $1.2u_k$. To investigate these fine scale structure experimentally, simultaneous measurement of three velocity components and nine velocity gradients is needed. As a method to provide three velocity components and nine velocity gradients, dual-plane stereoscopic PIV (DPSPIV)[4] has been developed. In those DPSPIV measurements, velocity gradients in the in-plane directions ($\partial u_i/\partial x$ and $\partial u_i/\partial y$) can be calculated by a central finite difference scheme of higher than 4th-order, but calculation of velocity gradients in the out-of-plane direction ($\partial u_i/\partial z$) is limited to the 2nd-order central finite difference scheme. Furthermore, the separation between laser sheets is restricted by laser sheet thickness. For these reasons, higher accuracy in calculating out-of-plane velocity gradient components is desired in turbulence measurement under high Reynolds number conditions. In this study, quad-plane stereoscopic PIV (QPSPIV), which can introduce a 4th-order finite difference scheme in calculating the out-of-plane velocity gradient components, has been developed, and fine scale structures in a turbulent jet are measured.

EXPERIMENTAL DETAILS

Figure 1(a) shows a schematic of the QPSPIV system. This system consists of two Nd:YAG lasers, two dye lasers with Rhodamine6G dye, eight 2048×2048 pixels CCD cameras and several optics. QPSPIV can be accomplished by utilizing the difference of laser wavelength and polarization. The scattered light from tracer particles in four laser sheets is separated by the polarizing beam splitters and band-pass filters, particle images in respective measurement planes are obtained with eight CCD cameras. The lenses are located with an inclination angle of 24° , and the Scheimpflug condition is applied. Figure 1(b) shows the experimental apparatus of a turbulent jet. Air from a compressor is regulated to a constant pressure and constant flow rate, and is seeded with droplets generated by an atomizer. Then, the air is led to a nozzle to form a jet. In this study, DOS (dioctyl sebacate) was used as tracer particles (SMD approx $1 \mu\text{m}$).

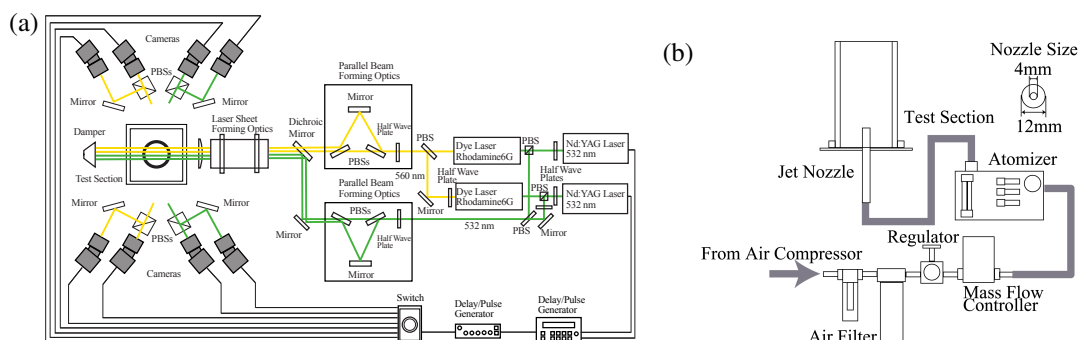


Figure 1. Schematic of QPSPIV system (a) and experimental apparatus of a turbulent jet (b).

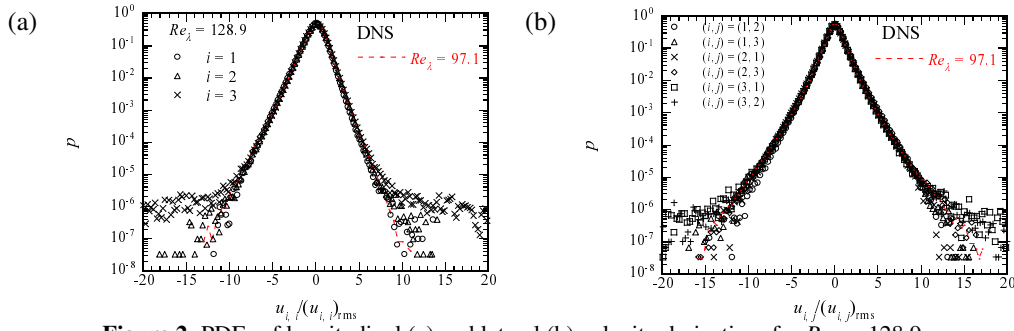


Figure 2. PDFs of longitudinal (a) and lateral (b) velocity derivatives for $Re_\lambda = 128.9$.

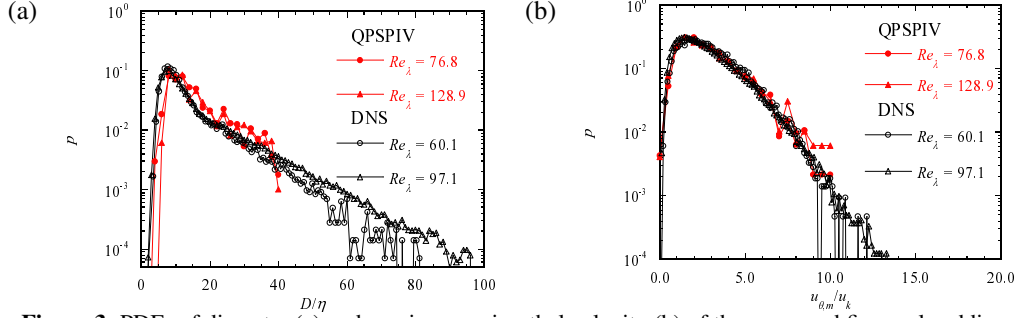


Figure 3. PDFs of diameter (a) and maximum azimuthal velocity (b) of the measured fine scale eddies.

The measurements were carried out for two different conditions: $U_0 = 19.9$ and 30 m/s at $x/D = 60$, $r/D = 0$, where U_0 is mean axial velocity at the jet exit, and D is the nozzle diameter. x is distance from the jet exit and r denotes the radial coordinate. Preliminary measurements in this position by a hotwire show that Kolmogorov length scale $\eta = 137$ μm and Reynolds number based on Taylor microscale $Re_\lambda = 76.8$ for $U_0 = 19.9$ m/s and that $\eta = 105$ μm and $Re_\lambda = 128.9$ for $U_0 = 30$ m/s. The FWHM (full width half maximum) of laser sheet thicknesses are about 200 to 300 μm , and the separations between each laser sheet are about 350 to 400 μm . The size of measurement region is 15.1 mm \times 15.1 mm. The PIV interrogation window size is 48×48 pixels with overlap of 75% . The present experimental settings provide the spatial resolutions of $2.6\eta \times 2.6\eta \times 2.4\eta$ for $Re_\lambda = 76.8$ and $3.3\eta \times 3.3\eta \times 3.1\eta$ for $Re_\lambda = 128.9$. These spatial resolutions are the same order of that of general DNS of turbulent flows.

FINE SCALE STRUCTURE IN A TURBULENT JET

Probability density functions (PDFs) of longitudinal and lateral derivatives of velocity components at the middle of the measurement planes for $Re_\lambda = 128.9$ are shown in Fig. 2(a) and (b). The results obtained from the QPSPIV are compared with those from DNS of homogeneous isotropic turbulence with $Re_\lambda = 97.1$. The longitudinal and lateral derivatives obtained by the QPSPIV agree very well with those by DNS.

From the nine-component velocity gradients obtained by QPSPIV, vorticity vectors (ω), strain rate (S_{ij}) and second invariant (Q) of velocity gradient tensor can be calculated by their exact definition. In our DNS studies [1, 2, 3], coherent fine scale eddies were educed without any threshold by using an identification scheme based on the local flow pattern. From the distribution of Q , cross sections of the coherent fine scale eddies are identified. The educed section includes a local maximum of Q along the axis of a coherent fine scale eddy and a center point of swirling motion is identified. Here, eddies nearly perpendicular to measurement planes are identified. As the spatial distribution of rotating axis is random for fully-developed turbulent flow, this does not affect the results. Figure 3(a) and (b) show the PDFs of the diameter and maximum azimuthal velocity of the detected fine scale eddies. The diameter and maximum azimuthal velocity are normalized by η and u_k calculated from the PIV data. The PDFs of the diameter and maximum azimuthal velocity show peaks at $D/\eta \approx 8$ and $u_{\theta,max}/u_k \approx 1.5$ for both Reynolds numbers. The characteristics of the fine scale eddies obtained in the present study are consistent with those of coherent fine scale eddy which has been shown by detailed analyses of DNS. These results give experimental support for the existence of the coherent fine scale eddy in turbulence.

References

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