Three-dimensional imaging of a turbulent jet using shearing interferometry and optical tomography

B. J. Pelliccia-Kraft, D. W. Watt

Abstract The 3-D density field of a round, neutrally buoyant turbulent jet is obtained using a finite-fringe, shearing interferometer. A He–Ne laser beam ($\lambda = 632.8$ nm) is subdivided into six beams of equal intensity, which intersect a helium–argon jet flowing from a vertical nozzle. Two-dimensional projection data of the jet are captured simultaneously from six viewing directions distributed over 140°. The desired phase is removed from the spatial carrier using the Fourier transform method. A tomographic reconstruction technique, using a truncated Fourier–Bessel expansion is performed to obtain the complete 3-D density field. The Reynolds number, based on the exit mean velocity and the nozzle diameter, is 5890.

1 Introduction

It is known that large-scale organized structures play an important role in the dynamics of turbulence. One method researchers have used to better understand the physical processes that create and maintain turbulent flows, e.g., laminar to turbulent transition, entrainment, and mixing, is to identify and classify the organized structures which exist in such flows. The concept of organized structures in turbulent flows was introduced by Townsend (1956), who noted the existence of large-scale motions in shear flows.

The first experimental evidence was by Brown and Roshko (1974), who observed the large-scale structures present in a mixing layer using a flow visualization technique.

The technique used to extract the coherent structures from the background (incoherent) turbulence and the method of analysis depends upon which coherent structure definition (Cantwell 1981; Hussain 1986; Robinson 1991) is used. Experimental and numerical studies have been completed which extract structures in turbulent flows in one- or two-dimensions using either a scalar concentration (e.g., Sirovich and Kirby 1990), or a vectorial velocity field (e.g., Glauser et al. 1987; Delville 1994; Rajaee et al. 1994). The velocity may be measured using mechanical probes, which can disrupt the downstream evolution of the flow and offer limited spatial resolution.

Although many studies have been completed, there remains a need for experiments that characterize the flow structures in 3-D space. In prior work, tomographic reconstruction from holographic interferograms has been demonstrated as a technique for obtaining 3-D scalar fields (Timmerman and Watt 1997). The primary limitation of this technique has been the inability to record a large ensemble of data, which are required for meaningful statistical analysis. The experiment described below allows the acquisition of a large number of instantaneous flow realizations of a turbulent flow using a multiple-beam shearing interferometer. A tomographic reconstruction method is applied to determine the 3-D density field using the 2-D projection data from each viewing direction.

2 Experiment

In the present experiment, 200 realizations of an axisymmetric turbulent jet are obtained at both upstream and downstream locations. The jet is comprised of a mixture containing 24.9% helium in a base of argon. This mixture is used to reduce the effects of buoyancy on the jet dynamics. The turbulent flow is generated using a nozzle consisting of a settling chamber which contracts smoothly into a circular pipe with a 6.5-mm inner diameter and a length of 60 mm. The settling chamber is supplied with the helium–argon mixture using high-pressure plastic hose from a 1.97-m$^3$ gas cylinder. The settling chamber pressure is monitored over the duration of the experiment using a Dwyer Instruments micromanometer attached to a small pitot tube (outer diameter 2 mm). The jet velocity at the nozzle exit, estimated using the settling chamber stagnation pressure, is 20.75 m/s. Additional measurements to determine the velocity profile at the nozzle exit were not obtained.

2.1 Tomographic experimental set-up

The optical configuration of the experimental set-up is shown in Fig. 1. A 30-mW helium–neon continuous wave laser is used as the light source. Mirrors M$_1$, M$_2$, M$_3$, and M$_4$ raise and direct the laser beam. The beam is spatially filtered and expanded. After passing through lens L$_1$, the
beam is collimated. Mirrors $M_5$ and $M_6$ direct the ~40-mm-diameter plane wave to a 50–50 beam splitter, which divides the beam. The surface of the beam splitter is an axis of symmetry for the remainder of the experimental set-up. Each diffraction grating produces three beams of equal intensity. DG$_1$ produces beams for viewing directions 0°, 26.45°, and 51.30°. DG$_2$ produces beams for viewing directions 80.78°, 105.63°, and 132.08°. The optical path length of each beam from the diffraction grating to the flow field is nearly the same (±6.5 mm).

The flow field is located in a 305-mm space between two pneumatically supported optical tables which have been rigidly connected. All optics near the flow field are mounted to prevent disturbance of the flow. The nozzle is mounted to an optical jack so that the flow is directed vertically upwards and normal to the incident probe beams. The jack provides vertical displacement of the nozzle so that upstream and downstream measurements can be obtained.

After traversing the flow field, the field of view of each beam is reduced to ~22 mm by ~22 mm by placing a square aperture in the path of each view. This is required to eliminate interference between overlapping views on the camera. The beams are then directed towards an array of mirrors located at the opposite end of the optical table. The array consists of six mirrors arranged in two rows, each with three mirrors. The optical path length from the flow field to the mirror array is the same for each beam (±3.5 mm). To maximize the spatial resolution of each view on the camera, the mirrors on this array are mounted as close to one another as possible. Collection of the beams on the mirror array also allows the beams to be redirected along the same optical axis, i.e., the beams are parallel to one another. This is important because all views are imaged simultaneously on one CCD camera. A 203-mm-diameter parabolic mirror is used to reduce the overall size of the views. A small mirror is placed near the focal point of the parabolic mirror and used to redirect the beams towards lens $L_2$ of the shearing interferometer.

2.2 Shearing interferometer

In traditional interferometry, a fringe pattern results from the interference between two different wavefronts, i.e., a reference beam and an object beam. In shearing interferometry, the reference beam is eliminated and a fringe pattern is produced by the interference of two identical wavefronts which have been displaced with respect to one another. Several factors can induce phase errors in the traditional interferometer, especially when the light beam travels over long distances. Disruption of the ambient air, acoustic noise, and mechanical vibrations associated with the mounting of the optical components can all produce motion of the fringes. The elimination of the reference beam in the shearing interferometer greatly reduces the phase error because the total distance over which the wavefront is separated and recombined is very small (~30 mm) compared with the optical path length of the probe beam (~11.5 m).

The shearing interferometer, shown in Fig. 2, comprises a Michelson interferometer and a pair of matched imaging lenses. The amount of lateral shear and the number of carrier fringes in the interferogram are determined by the placement of the imaging lenses $L_2$ and $L_3$. The lateral shear is increased with increasing distance between the image plane of lens $L_2$ and the front surface of the mirrors in the Michelson interferometer. The number of fringes $N_I$ is the width of the image field $W$ divided by the fringe spacing $d$. The fringe spacing is obtained from the relative tilt angle $\varepsilon/2$ of the Michelson mirrors using

$$d = \frac{\lambda}{2 \sin(\varepsilon/2)}$$

![Fig. 1. Tomographic set-up: M, mirror; SF, spatial filter; $L_0$, lens; BS, beam splitter; DG, diffraction grating; F, flow field; PM, parabolic mirror; MA, mirror array; BSC, beam splitter cube; C, CCD camera](image1)

![Fig. 2. Shearing interferometer: M, mirror; BSC, beam splitter cube; L, lens](image2)