ACCELERATION MEASUREMENT WITH A LASER DOPPLER SYSTEM

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Summary We discuss an experimental application of the laser Doppler technique for measuring particle acceleration. The basic principles of the technique follows closely those introduced in [12], although numerous improvements have been implemented in the signal processing to increase the reliability of individual estimates of particle acceleration. Following [8], the errors due to optical fringe divergence in the measurement volume and due to the signal processing could be identified and quantified using a dedicated experiment, in which a water flow is accelerated in a nozzle. The system then has been used to derive statistics of particle acceleration in a highly turbulent flow.

INTRODUCTION

The Lagrangian acceleration yields deep insights into turbulence as it describes the sum of all forces acting on a fluid element. The measurement of particle accelerations allows both the measurement of Lagrangian acceleration of the flow with the aid of small passive tracer particles as well as the Lagrangian acceleration of inertial particles. It has been shown that the probability density function (PDF) of a Lagrangian acceleration component in turbulent flows is strongly intermittent, i. e., the PDF exhibits wide tails [9, 20]. This has been also observed in direct numerical simulations of fully developed turbulence (see [16]).

The measurement methods used to date were particle tracking velocimetry (PTV) with high-speed cameras [15] or silicon strip detectors [9, 20, 21]. Further measurements of Lagrangian and Eulerian accelerations have been performed with particle image velocimetry (PIV) [1, 2, 4, 5, 6, 7, 13, 22]. However, the laser Doppler technique can also be used to measure fluid acceleration, as demonstrated in [10, 11, 12, 18, 19]. Here we use a commercial system and replace the usual signal processing by one, which extracts the particle velocity and acceleration instead of only the velocity. Using a commercial laser Doppler system, offering the advantages of a smaller measurement volume with high spatial and temporal resolution, requires to quantify the accuracy of this method and to compare it to other alternative methods.

The measurement volume of a usual laser Doppler system has a diameter of the order of $100\,\mu$ m. A particle crossing the measurement volume with 10 m/s needs $10\,\mu$ s to pass the volume. Assuming a particle acceleration of $1000\,\mathrm{m/s}^2$, the change of the particle velocity while passing the measurement volume is only 0.01 m/s which is a relative change of 0.1 %. To resolve this small change both the optical system and the signal processing must be highly accurate.

This paper uses a verification experiment to derive reliable information about systematic and random errors of the measurement system and introduces the application to a turbulent flow.

MEASUREMENT SYSTEM

One aim of this investigation was to demonstrate acceleration measurements with a commercial laser Doppler system, requiring no additional optical components. In such cases only the signal acquisition and processing must be modified. The standard signal processor provided the frequency shift signal of 40 MHz for the Bragg cell, but was otherwise only used for conditioning and down-mixing of the signal to a frequency of 2 MHz plus or minus the individual Doppler frequencies before its digital acquisition. These signals were digitized with a transient recorder card at a sampling frequency of 10 MHz. The amplitude resolution of the card was 14 bits. In addition the arrival times are recorded for all burst.

The signal processing and the estimation of particle velocity and acceleration follows the method given in [8]. The accuracy of the signal processing method has been investigated in [14] in comparison to the lower possible limit given by the Cramér Rao bound. However, the results of [8] show that the systematic and random errors are dominated by distortions of the optical system.

One origin of the fringe non-uniformity is the Gaussian nature of the laser beams and the curvature of their wavefronts away from the focused waist. Unfortunately, besides the Gaussian beam divergence there is another reason for fringe distortions, namely optical distortions of the beam. This is caused by optical devices with non-ideal optical transfer functions, like optical fibers, couplers, lenses and apertures. These influences lead to distortions of the fringe system because a non-Gaussian beam shape leads directly to deformations of the wave fronts. Furthermore, the distortions of the beam waists cause problems in aligning the beam waists, since the position of the minimum beam diameter may strongly differ from the position with minimum wave front curvature. In [8] the relevance of this effect for the commercial Laser Doppler system has been assessed empirically using a verification experiment.

EXPERIMENTS

An experiment was designed to validate the measurement procedure and the data processing. Its arrangement allows to verify whether the optical alignment is appropriate and to estimate the resolution and uncertainty of the acceleration measurement. In this experiment a water flow is accelerated through a contracting nozzle (Fig. 1).

It is a flat nozzle with a one-dimensional contraction from an rectangular cross-section of 11 mm×21.8 mm at the entrance to 0.3 mm×21.8 mm at the exit. The exact shape of the contraction zone is unknown. The side walls are transparent (plexiglass) and allow optical access to the flow through plane surfaces (air/plexiglass and plexiglass/water). The exit velocity of the water flow is about 1.7 m/s. The water flow was gravity driven and pressure controlled using a fill height regulation of the upper reservoir. The water reservoir was temperature controlled at 23±0.5 ^{0}C. From the centerline exit velocity, the half width of the nozzle exit and the viscosity of water at the given temperature, a Reynolds number of 267 can be estimated, indicating a laminar flow at the nozzle exit. Since the nozzle's contraction is one-dimensional this Reynolds number is constant within the entire contraction zone. Velocity components perpendicular to the vertical flow direction are not expected at the nozzle's centerline.

The identification of systematic and random errors of the signal processing and the optical system is possible by performing two experiments in the same flow. In the first measurement, the laser Doppler system measures particle velocities in the direction of the water flow (downstream), whereby the measured Doppler frequency, hence the velocity, is positive. In a second step, the laser Doppler probe is rotated by 180 ^{0}. A rotation of the measurement probe leads to a changed sign of all flow quantities, while the systematic errors caused by optical distortions "rotate" with the probe and don't change their sign.

In [8] systematic and random errors of the acceleration measurement of particles a_{bias} and a_{random} have been found to be proportional to the velocity v of the particle squared

$$a_{bias} = c_{bias} v^2 \qquad a_{random} = c_{random} v^2 \tag{1}$$

with $c_{bias} = -100\,\mathrm{m}^{-1}$ and c_{random} =220 m^{-1} for the particular measurement system.

We will report data obtained with this system as applied to highly turbulent flows with axial anisotropy.

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