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A cost-efficient Shadow Particle Tracking Velocimetry setup suitable for tracking small objects in a large volume

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Abstract

We use a Shadow Particle Tracking Velocimetry technique (S-PTV) with collimated light to investigate the dynamics of a turbulent von Kármán (VK) flow in water. Such a PTV technique permits easy calibration since the apparent particle positions on the images do not depend on the camera-particle distance and tracking of small objects (100 μm particles, fibers, ...) with low power LEDs light sources is made possible in a large volume (approximately (6 cm)^3). This technique provides an ensemble of Lagrangian trajectories which are conditioned in space on a grid in order to reconstruct the 3d Eulerian mean flow together with its fluctuations. Typical Lagrangian statistics can also be obtained with this technique, such as velocity and acceleration auto-correlation functions.

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1. Introduction

Turbulent flows play a major role in mixing, chemical process in reactors, and has received much attention over the years. In the field of experimental fluid dynamics research, significant progress has been made during the last decade with the advent of space and time resolved optical techniques based on high-speed imaging[13]. However, classical techniques such as Particle Image Velocimetry reduces the available information (2 or 3 components in a plane) which may impede or complicate a direct resolution of the Eulerian flow, especially when the flow is created in a complex geometry. In this context, Lagrangian techniques such as Particle Tracking Velocimetry, offer the possibility for a full 3d characterization of the flow properties at a modest computational cost[15,10,13]. By using an ensemble of fast cameras, PTV permits tracking of small particles ($10 - 100$ μm large) in turbulent flows with Reynolds numbers $R_\lambda > 100$ with a temporal resolution of the order of the Kolmogorov frequency $f_K = \sqrt{\epsilon/\nu} \sim 1 - 10$ kHz, ϵ being the injected power per unit mass, and ν the fluid viscosity. However when developing a PTV setup with classical illumination, one confronts several difficulties: the quality of images depends strongly on the particle characteristics (refraction index, size), a complex 3d calibration is required in order to achieve stereo-matching between the different camera views[14], and powerful light sources (high power LEDs, or a high power laser) are requisite when tracking

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small objects. To overcome these difficulties we have developed a new optical setup inspired from previous works[3] which tracks particles' shadows produced when using parallel lighting.

2. Shadow Particle Tracking setup

2.1. Experimental setup

The experimental apparatus is a von Kármán flow that has been used previously[3] with a square cross-section of 15 cm on each side. Two bladed discs of radius $R = 7.1$ cm counter-rotate at constant frequency Ω (figure 1 (a)) and are 20 cm apart. The flow has a strong mean spatial structure arising from the counter rotation of the disks. The azimuthal component resulting from this forcing is of order $2\pi R\Omega$ near the disks' edge and zero in the mid-plane ($z = 0$), creating a strong axial gradient (figure 1 (a)). The disks also act as centrifugal pumps ejecting the fluid radially in their vicinity, resulting in a large-scale poloidal recirculation with a stagnation point in the geometrical centre of the cylinder (figure 1 (b)). Using water to dilute an industrial lubricant, Ucon^{TM}, a mixture with a viscosity of 8.2 m^{2}s^{-1} and a density of $\rho = 1000$ kg.m^{-3} allows the production of an intense turbulence with a Taylor-based Reynolds number $R_\lambda = 200$ and a dissipative length $\eta = 130$ microns (see table 1 for more details on the flow parameters). We perform particle tracking of Lagrangian tracers (250 μm polystyrene particles with density $\rho_p = 1060$kg.m^{-3}) in a large volume $6 \times 6 \times 5.5$ cm^3 centered around the geometrical centre $((x, y, z) = (0, 0, 0))$ of the flow with 2 high-speed video cameras (Phantom V.12, Vision Research, 1Mpix@7kHz) with a resolution 800×768 pixels, and a frame rate up to $f_s = 12$ kHz. Such a sampling frequency is sufficient for resolving particle acceleration, calculated by taking the second derivative of the trajectories.

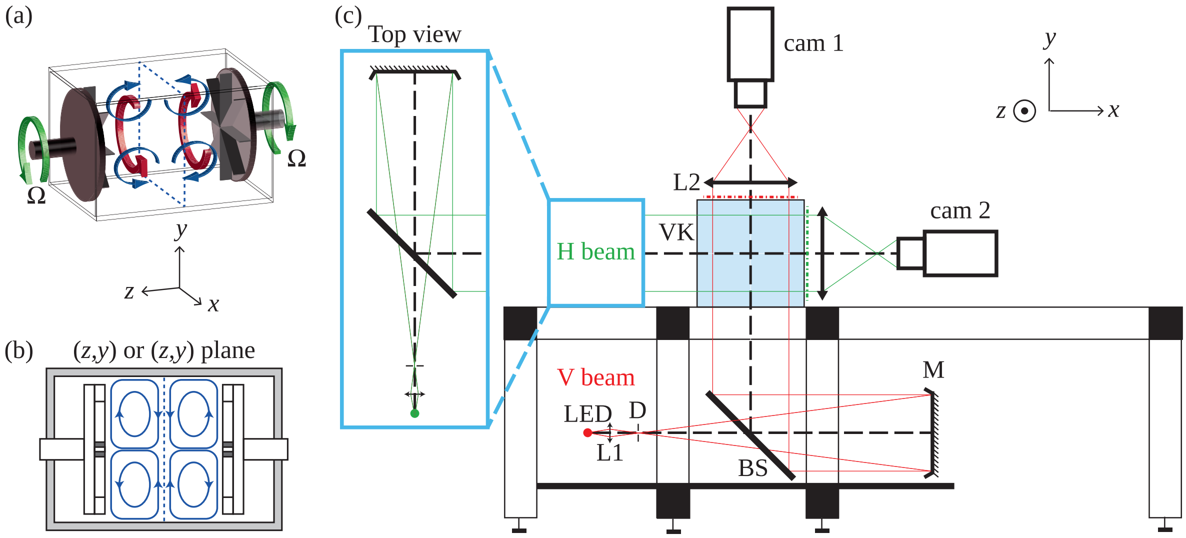

Fig. 1. (a) Sketch of the counter-rotating von Kármán flow. Arrows indicate the topology of the mean flow, the dashed line indicates the mid-plane of the vessel. (b) Schematic cut of the vessel along the (z, x) or (z, y) plane. (c) Optical setup for S-PTV with 2 identical optical arrangements forming an angle $\theta = 90$ degrees (only the vertical arm is described). The 1W LED source is imaged in the focus of a parabolic mirror to form a large collimated beam. A converging lens and a diaphragm are used to make the LED a better point-like source of light. Light is propagating through the flow volume using a beam splitter (BS) before being collected using a 15 cm large lens whose function is to redirect the light into the camera objective of the camera. The optical system [L_2+objective] is focussed on the output face of the vessel marked with a dashed-dotted line.

The camera setup is inspired from a previous work[3] and is depicted in figure 1 (c). It consists of 2 identical optical configurations with a small LED located at the focal point of a large parabolic mirror (15 cm diameter, 50 cm focal length) forming 2 collimated beams which are perpendicular to each other in the measurement volume. A converging lens and a diaphragm are used to make the LED a better point-like source of light. This large parallel ray of light then reflects on a beam splitter and intersects the flow volume before being collected by the camera sensor using a doublet