A SHADOW PTV TECHNIQUE FOR PARTICLE TRACKING IN AN INHOMOGENEOUS TURBULENT FLOW.

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Summary We use a Shadow Particle Tracking Velocimetry technique (S-PTV) with collimated light to investigate the dynamics of a turbulent von Kármán (VK) flow of water. Such a PTV technique, easy to calibrate as apparent particle position on the images do not depend on the camera-particle distance, allows to track small objects (100 μm particles, fibers, ...) with low power LEDs as light sources. Investigating the dynamics of Lagrangian tracers, we observe the flow produced in a square tank is bistable, the two states having a life time of several minutes so that the high speed recordings appear as snapshots of one of the two states that can be reconstructed from the particle trajectories. We show the two states topologies strongly differ from the one of the mean flow, and how the bistability affects the dispersion of tracers.

INTRODUCTION

Turbulent flows play a major role in mixing, chemical process in reactors, and transport of pollutants in the atmosphere. In this context, because the Lagrangian point of view which describes the fluid flow properties along the trajectories is the most natural, Particle Tracking Velocimetry has grown a lot in the past decade [1, 2, 3]. Using an ensemble of fast cameras, PTV allows to track 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 mass unit, and ν the fluid viscosity. However when developing a PTV setup with classical illumination, one has to face several difficulties: the quality of images strongly depends on the particles characteristics (refraction index, size), it needs a complex 3d calibration in order to achieve stereo-matching between the different views [4], and it requires powerful light sources (high power LEDs, or a high power laser) when tracking small objects. To overcome these difficulties we have developed a new optical setup inspired from [5] which allows to track particles' shadows produced when using parallel lighting.

EXPERIMENTAL SETUP AND RESULTS

The experimental apparatus is a von Kármán flow identical to the one used in [5]. The flow is produced in a cylinder with square section using two bladed discs, with radius $R = 7,1$ cm, which counter rotate at constant frequency Ω (figure 1 a)). Their spacing is equal to 15 cm, which is also the length of the tank section. Using a water-Ucon mixture 8 times more viscous than water, this setup produces an intense turbulence with a Taylor based Reynolds number $R_\lambda = 200$ and a dissipative length $\eta = 90$ microns. We perform particle tracking of Lagrangian tracers (200 μm polystyrene particles) in a large volume $8 \times 7.6 \times 7.6$ 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 $f_s = 12$ kHz. The camera arrangement, inspired from reference [5], is depicted in figure 1 b). It consist of 2 arms forming an angle $\theta = 90^\circ$ with parallel lighting. Both arms are identical and use a small LED imaged in the focus of a large parabolic mirror (15 cm diameter, 50 cm focal length). This large parallel ray of light then reflects on a beam splitter and intersects the flow volume before being collected onto the camera using a doublet consisting of a large lens (15 cm in diameter) and the camera objective. As this arrangement requires some precision in the mounting, all optical elements are aligned using large (home made) reticules also used to measure precisely the magnification in each arm. When placing an object in the field of view, it appears as a black shadow on a white background corresponding to the parallel projection of the object on the sensor. When particles are tracked, camera 1 will then provide their (x_1, z_1) 2d positions while camera 2 will measure their (y_2, z_2) positions, the z coordinate being perfectly redundant (we have $z_2 = az_1 + b$). 3d tracking is then performed by first tracking particles independently on the movies corresponding to the 2 views before trajectories with $z_1(t) \simeq z_2(t)$ are identified using the relation $z_2 = az_1 + b$ as shown in figure 1 c). This relation is obtained by self-calibration with a dilute ensemble of particles that is tracked within a pair of movies recorded by cam1 and cam2 (here the parameters are $a = 0.96$, $b = 2.7$ pixels). Together with the pixel to mm magnification of one of the cameras, it provides all informations about particle positions in world coordinates.

Because the measurement volume $8 \times 7.6 \times 7.6$ cm^3 is twice larger than the integral length-scale $L = 3$ cm of the turbulence, the flow properties are not homogeneous in space. We thus record 200 pairs of movies with duration 1.3 seconds per Reynolds number with $\mathcal{O}(100)$ particles in the measurement volume, leading to a very large ensemble of $\mathcal{O}(4.\ 10^5)$ trajectories with mean duration $\langle t \rangle \sim 0.25/\Omega$ so the Lagrangian statistics can be conditioned in space. However we discovered that whatever the number of movies randomly chosen, we always found that the x and y component of the velocity had

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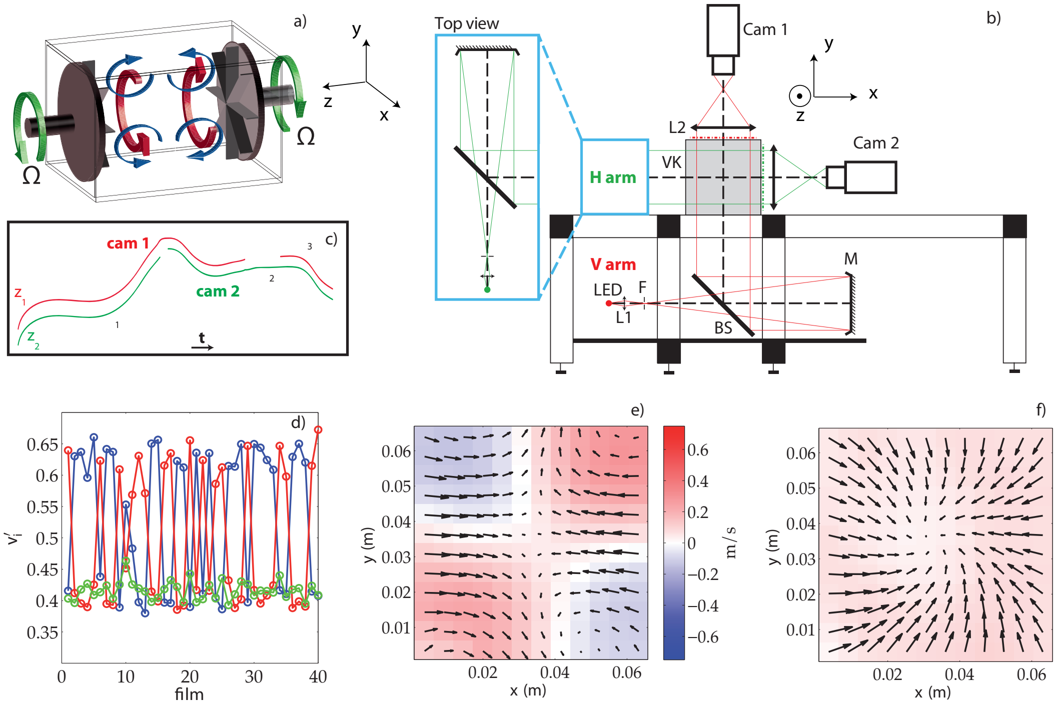

Figure 1: a) Sketch of the counter-rotating von Kármán flow. Arrows indicate the topology of the mean flow. b) Optical arrangement for S-PTV with 2 identical arms forming an angle $\theta = 90$ degrees (only the vertical arm is described).The 1W LED source is imaged in the focus of a parabolic mirror to form a large collimated beam. Light is propagating through the flow volume using 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. c) time evolution of the z (redundant) coordinate of the same particle as obtained with 2d tracking with cam1 and cam2. d) rms velocities of the averaged of the particles (v'_x, v'_y, v'_z) for 40 consecutive movies and a rotating frequency $\Omega = 5.5$ Hz, which corresponds to $Re_\lambda = 200$. (symbol, v'_x-blue, v'_y-red, v'_z-green). e,f) reconstructed mean flow in the plane $z = 0$. Arrows indicate $(\langle v_x\rangle(x, y, z = 0), \langle v_y\rangle(x, y, z = 0))$ while colors indicate $\langle v_z\rangle(x, y, z = 0)$. e) as obtained by conditioning on the v_x dominant state. f) as obtained with the same number of movies from each state.

different statistics, which is in contradiction with the symmetries of the setup. This can be observed in figure 1 d), which displays the changes of the rms value of the velocity components (v'_x, v'_y, v'_z) obtained using all the trajectories whitin one movie. Indeed one always find $v'_z \sim 0.4$ with very different values for v'_x and v'_y which take randomly the values 0.4 and 0.65 m/s. This behavior, observed whatever the frequency of rotation in the fully turbulent regime, indicates that the large scale flow is bistable with one transverse component dominating over the other. This is confirmed when investigating the mean flow conditioned on the x-dominant state (corresponding to $v'_x > 0.55$) measured in the mid-plane ($z = 0$) in figure 1 d). In the x-dominant state, $\langle v_x\rangle(x, y, z = 0)$ is much larger than $\langle v_y\rangle(x, y, z = 0)$ with a non zero component $\langle v_z\rangle(x, y, z = 0)$. The global symmetries of the flow are broken so that the mean flow is not invariant under a rotation of an angle $\pi/2$ around the z-axis. As shown in figure 1 f), the symmetries of the mean flow are only recovered when averaging over the same number of realizations of both x-dominant and y-dominant states. This type of bistability, for which the two states exchange under a discrete rotation on a time-scale of several minutes (estimated from flow visualization with bubbles), is different from the one already observed in von Kármán flows with circular section [6]. Indeed the present bistability, which has important consequences concerning the transport of particles in the flow, may be due to the interaction between corner vortices on the flat walls that can have complex interactions with the flow.

References

[1] Virant M., and Dracos T., 3D PTV and its application on Lagrangian motion, Measurement science and technology, **8**, (1997).
[2] Ouellette N. T., Xu H. , Bourgoin M., and Bodenschatz E., Small-scale anisotropy in Lagrangian turbulence, New J. Phys., **8**, (2006).
[3] Springer Handbook of Experimental Fluid Dynamics, ed. C. Tropea, A. L. Yarin, and J. F. Foss, pp. 789-799 (Springer-Verlag, 2007)
[4] Tsai, R., IEEE T. Robot. Autom., A versatile camera calibration technique for high accuracy 3d machine vision metrology, **RA-3**, (1987)
[5] Machicoane N., Bonaventure J., and Volk R.,, Melting dynamics of large ice balls in a turbulent swirling flow, Physics of fluids, , (2013)
[6] de la Torre, A. and Burguete, J., Slow Dynamics in a Turbulent von Kármán Swirling Flow, Physical Review Letters, **99**(5), (2007)