DIRECT VORTICITY MEASUREMENT IN TURBULENCE

Huixuan Wu, Haitao Xu, & Eberhard Bodenschatz
Max Planck Institute for Dynamics and Self-Organization (MPIDS), Göttingen, Germany

Abstract Vorticity optical probing (VOP) is a direct vorticity measurement technique, which obtains the three-components of vorticity by measuring the rotation of micro-sized particles seeded in turbulent flows. Compared with other conventional vorticity measurement methods, a noticeable advantage of VOP is its high spatial resolution, which is given by the size of the seeding particles (20 μm in our experiments). Equipped with high-speed cameras, VOP can also reach high temporal resolution (down to 50 μs). We outline the principles of VOP and report the first direct measurement of vorticity in high-Reynolds-number turbulent flows.

INTRODUCTION

Vorticity plays a vital role in the dynamics of turbulent fluid flows. Conventionally vorticity is obtained experimentally from the finite difference of velocities measured at neighboring points using, e.g., hotwire arrays or particle image velocimetry (PIV) [1]. Besides from complications such as being intrusive (hotwire arrays based) or having access to only one or two components of the vorticity (PIV based), a major limitation of these indirect methods is the relatively low spatial resolution, which is set by the closest distance over which the velocity differences can be reliably measured. For typical experimental conditions, this resolution is approximately 0.2 – 1 mm. As a result, these low-resolution measurements would smooth out the sharp gradients, such as vortex filaments, which are important for energy dissipation and are tightly related to intermittency [2, 3]. Those sharp gradients are known to exist even at relatively low Reynolds numbers and their spatial scales become smaller and smaller as Reynolds number increases [2-5]. Therefore, it is necessary to develop a novel measurement technique possessing high spatial and temporal resolution, especially for the study of high-Reynolds number turbulent flows.

Frish and Webb [6] proposed the vorticity optical probe (VOP) method in 1980s, which was able to measure the vorticity directly without calculating the finite velocity differences. The principle relies on the fact vorticity is simply twice the rotation rate of a fluid element, which could then be measured by capturing the light beam reflected from a mirror embedded in a small, transparent and neutrally buoyant particle seeded in the flow. Frisch and Webb [6] demonstrated the feasibility by measuring the vorticity in a laminar channel flow. The optical sensing technology available at that time, however, did not allow the technique to be used in turbulence measurements. With state-of-the-art high speed imaging systems, high accuracy optics and control systems, we are constructing a prototype VOP setup that is suitable for turbulence measurement, and use it to study high Reynolds number turbulent water flows between counter-rotating baffled disks.

THE VORTICITY OPTICAL PROBE SETUP

The VOP setup is shown schematically in Figure 1. An illumination laser beam is reflected by mirrors in the measurement volume. Mirrors with different orientations reflect the incident beam to different directions. A large concave mirror (such as an elliptical mirror) is used to collect reflections to smaller divergence angle in order to increase the effective angular range. The reflections are then focused by a convex lens and recorded by a camera placed in the focal plane of the optics (plane AA in Figure 1). The position of the reflected light spot on the image plane is then directly related to the orientation of the mirror. Using a mirror array that is consisted of mirrors with distinct but known orientations as the calibration target, as shown in Figure 1, we can determine such a relationship between the image position and the mirror orientation. After that, the target mirror array is removed and the flow is seeded with special micro-sized tracer particles that are made by coating glass flakes (or crystal platelet) with poly-acrylamide hydrogel (see Figure 2). The coating has the same refractive index and density as those of water. Therefore, incident light will be reflected by the embedded flakes, but not by the outer coating. The high-speed recording of the reflected light spots, with the aid for the calibrated mapping between position and angle, gives the rotation of the flake, i.e., the particle. The small size of particles (less than 20 μm as shown in Figure 2) guarantees small inertia of rotation and faithful following of even the intense vorticity events [7].

The three-dimensional rotation rate of the particle can be calculated from the measured sequence of mirror orientation in the following way. Denote the orientations of the mirror over time by $\mathbf{n}_1$, $\mathbf{n}_2$, $\mathbf{n}_3$, and the rotation rate $\mathbf{\Omega}$. Obviously, $\mathbf{\Omega}$ is perpendicular to both $\Delta\mathbf{n}_2 = \mathbf{n}_3 - \mathbf{n}_2$ and $\Delta\mathbf{n}_1 = \mathbf{n}_2 - \mathbf{n}_1$. Therefore, $\mathbf{\Omega}$ is parallel to $\Delta\mathbf{n}_1 \times \Delta\mathbf{n}_2$. The magnitude can be calculated easily when the orientation is known. The vorticity of the flow is twice of $\mathbf{\Omega}$. With more than three successive samples of $\mathbf{n}$, $\mathbf{\Omega}$ can be evaluated by least square fitting to achieve higher accuracy.

The error of rotation rate measurement was evaluated using a mirror mounted on an electronic rotary stage, and was found to be lower than 5%. We are now setting up a Taylor-Couette device running in the laminar regime to determine the error and a system to measure the high Reynolds number flow between counter-rotating disks. Recent simulations suggest an intriguing transition in vorticity statistics at around $Re_\lambda \sim 10^3$ [5, 8]. It is therefore very interesting to study that experimentally. In the near future, we plan to incorporate VOP into a Lagrangian particle tracking system so that both the orientations and the positions of the mirrors can be determined at the same time, i.e., simultaneous measurement of both velocity and vorticity, and their Lagrangian evolution. This will provide unprecedented information of high Reynolds number turbulence.

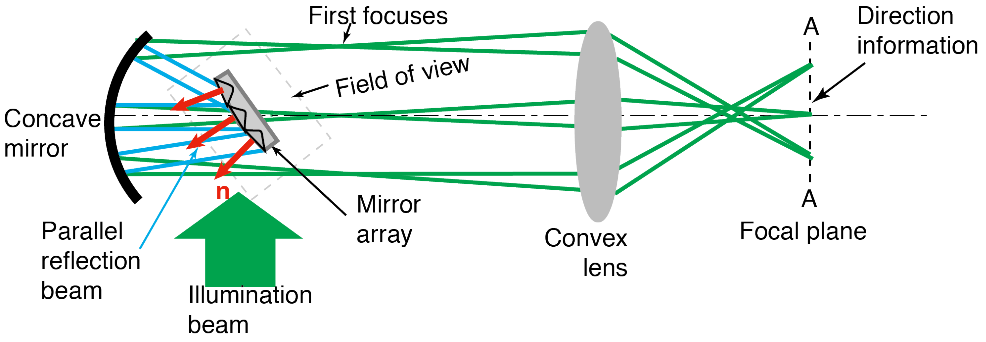

Figure 1. Sketch of the VOP setup. The actual target is much smaller than that shown in the plot and is placed slightly off the optical axis so the reflection from the center mirror is not blocked by the target itself.

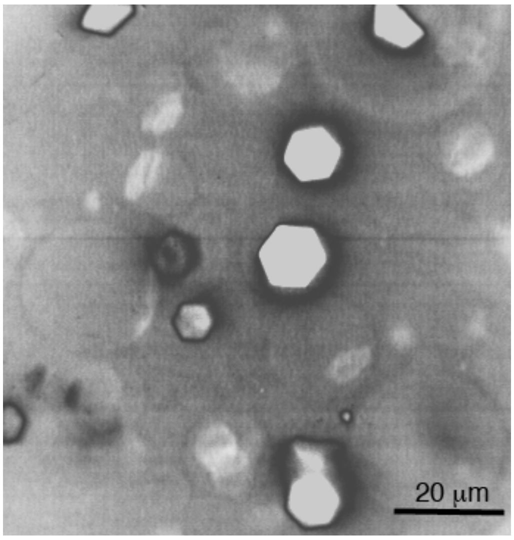

Figure 2. A photo of the sample VOP particles: reflective mirrors embedded in index matched polymer coating.

References

[1] J. M.,Wallace, and P. V. Vukoslavčević. Measurement of the Velocity Gradient Tensor in Turbulent Flows. *Annu. Rev. Fluid Mech.*, **42:**157-181, 2010

[2] U. Frisch. *Turbulence: The Legacy of A. N. Kolmogorov*. Cambridge University Press, 1995

[3] K. R. Sreenivasan and R. A. Antonia. The phenomenology of small-scale turbulence. *Annu. Rev. Fluid Mech.*, **29**:435-472, 1997

[4] J. Schumacher, K. R. Sreenivasan, and V. Yakhot. Asymptotic exponents from low-Reynolds-number flows. *New J. Phys.*, **9**:89, 2007

[5] T. Ishihara, T. Gotoh, and Y. Kaneda. Study of High–Reynolds Number Isotropic Turbulence by Direct Numerical Simulation. *Annu. Rev. Fluid Mech.*, **41**:165-180, 2009

[6] M. Frish and W. Webb. Direct Measurement of Vorticity by Optical Probe. *J. Fluid Mech.*, **107**:173-200, 1981

[7] A. T. Chwang and T. Y. Wu. Hydrodynamics of low-Reynolds-number flow. Part 1. Rotation of axisymmetric prolate bodies. *J. Fluid Mech.*, **63**:607-622, 1974

[8] P. K. Yeung, D. A. Donzis, and K. R. Sreenivasan. Dissipation, enstrophy and pressure statistics in turbulence simulations at high Reynolds numbers. *J. Fluid Mech.*, **700**:5-15, 2012