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Off-axis PTV for 3-D visualization of rotating columnar flows

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ABSTRACT

A new simple optical method for visualizing flow structures generated in a rotating flow is presented. The method consists of planar PTV with sheet illumination slightly offset to the rotation axis and a geometric reconstruction of velocity vector field under the assumption of azimuthal periodicity. Two types of columnar flows intrinsically associated with rotating flows are investigated with the method. The two types of flow are a local columnar wake induced behind a moving sphere, and an asymmetrically precessing Taylor Column created below a spinning disk. By means of this new technique we obtain the first quantitative visualization of the columnar wake and the three-dimensional structure of the Taylor Column.

1. Introduction

Rotating flows are ubiquitous in science and engineering. In such flows Coriolis forces give rise to phenomena absent in non-rotating flows [6,22,4]. These phenomena can appear counterintuitive to anyone not familiar with the theoretical background of rotating flows. One example is, for instance, the Taylor-Proudman theorem derived from the geostrophic approximation of the full momentum equation [17,20,6,21,4]. For a fluid rotating with angular velocity Ω that is aligned with the x-axis of a Cartesian coordinate system (*cf.* Fig. 1) fixed in the rotating frame of reference the Taylor-Proudman theorem states that the effects of Coriolis forces are such that the derivatives $\partial v/\partial x$ and $\partial w/\partial x$ of the velocity components v and w in the y and z coordinate directions are identically zero. This means that when there exists a flow field $v(y,z)$, $w(y,z)$ at a plane $x = x_1$ then the flow field must be the same at any other plane $x = x_2$. This requirement gives rise to the formation of a cylindrical flow that is aligned with the axis of rotation referred to as a Taylor-Column. The phenomenon has received attention in the fields of geophysical flows and turbo machinery and represents one striking manifestation of the action of the Coriolis forces present in rotating fluids.

In this study two kinds of flow which display such a columnar structure are investigated. One is flow around a sphere that propagates along the axis of rotation. A Taylor-Column will develop ahead of the sphere and in its wake as first described by Maxworthy [12], Maxworthy [13]. The flow scenario is similar to that observed for vortex rings in a rotating fluid [3]. We investigate Reynolds numbers $O(10^3)$ as this is the regime where a single toroidal vortex is known to form behind the sphere in a non-rotating quiescent fluid during the phase immediately following an impulsive start of the sphere motion (see e.g. [10,18,11]). Experiments were conducted for a range of Rossby numbers to investigate the dynamics in the flow regime where the axial and the circumferential momentum compete with each other. The second flow structure considered is a Taylor-Column that is created with a disk rotating differentially to the background rotation. The present study focuses on how such a two-dimensional column departs into a three-dimensional structure as parameters change. The origin of such three-dimensionality is discussed in comparison with dye-visualization experiments of Hide and Titman [7].

Particle image velocimetry (PIV) has been a powerful tool for studying three-dimensional flows in rotating fluids. Norman et al. [16] showed various three-dimensional wake patterns of a sphere with a surface protrusion rotating in the azimuthal direction. Foster and Munro [5] visualized unique circulation structures in a stratified fluid inside a square container during the linear spin-up of the system. In the present study we introduce particle tracking velocimetry (PTV) as a new technique to reconstruct the three-component velocity-vector field from recordings made by a

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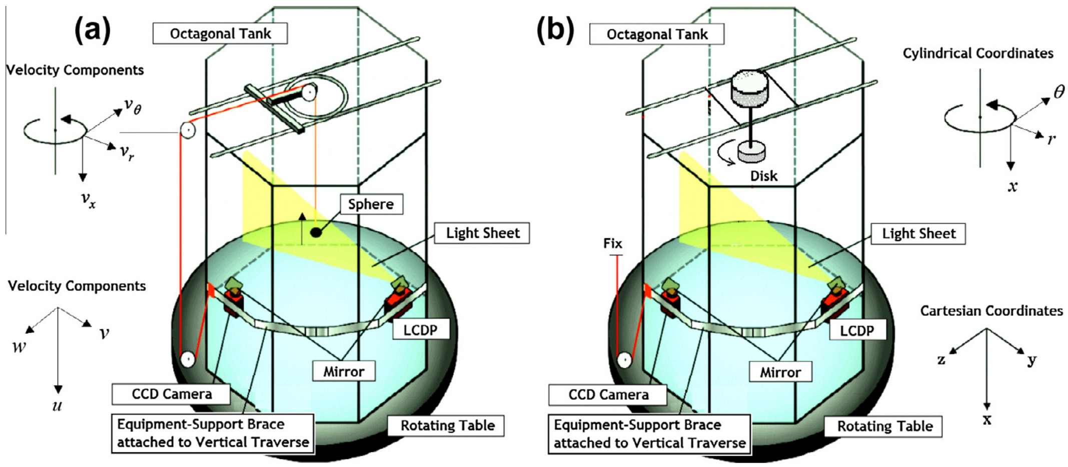

Fig. 1. The experimental setup: (a) for sphere wake measurement, (b) for Taylor Column measurement.

single camera together with a light sheet that is slightly offset from the axis of the rotation. The technique is suitable for detecting, for instance, columnar swirling flow structures arising from the Coriolis forces associated with the background rotation. In comparison with multi-camera 3D PTV or PIV methods our new methodology is substantially less technologically challenging to integrate into any experimental configuration. This is in particular the case when the entire experimental arrangement has to be mounted, for instance, on a rotating turntable. The first half of the present study outlines the principle of our new off-axis PTV methodology by summarizing the relevant underlying theoretical issues. Thereafter we illustrate two typical applications of the method by discussing results obtained with our new method for flow around a sphere and within a Taylor Colum in a rotating flow.

2. Experimental facility

Experiments were conducted using the large rotating-tank facility at the University of Warwick. Fig. 1 displays an overview of the experimental rig. The setup consists of a large water-filled tank of 2.5 m height with octagonal horizontal cross section of 1 m wide. The tank is mounted on top of a computer-controlled rotating turntable[1].

For experiments of sphere's wake, a test sphere is mounted such that its centre coincides with the central axis of the tank as illustrated in Fig. 1(a). The sphere has a diameter of 50 mm and is supported by a thin thread, by means of which it can be pulled upwards along the central, vertical axis of the tank. A computer-controlled vertical traverse on the outside of the tank enabled mounting the required PTV equipment such as a CCD camera (Panasonic, HDC-SD1-S) and an illumination device (liquid crystal display projector, Panasonic, TH-LB10NT) to generate a suitable light sheet inside the tank via an arrangement of tilted mirrors. The thickness of the light sheet is computer-controlled, and the width was 5 pixels of the whole image size of 1024 × 768 pixels, which is equivalent to about 5 mm thickness in the flow. The total power of the light source is 200 W, of which a small portion is contained as useful power in the measurement plane. The light sheet thickens with the distance from the source due to diverging effect of the light projection. However, this thickening effect is negligible on the scale of the measurement window relative to the characteristic length scale of the flow. Moreover, a slightly-out-of-focus condition of the projected light at the measurement plane, was adopted to avoid particle flickering that results from the interference of light originating from individual pixels of pixel ensembles.

The thread supporting the sphere is mechanically connected to the equipment-support brace on the vertical traverse by means of a system of pulleys as shown in the figure. This ensures that the sphere and the light sheet and camera move in phase. Hence, the PTV system captured data within the rotating and linearly traversing frame of reference. The seeding material used for our PTV measurements is Talisman 30 which is a polymer powder with specific gravity 0.99 and diameters in the range of 100–200 µm. Following the initial spin-up of the turntable the water inside the tank was allowed to settle for at least 12 h, to reach a state of rigid-body rotation, before experiments commenced.

For the experiments on the long Taylor-Column, the disk is set at the center coaxially with the rotating water tank as shown in Fig. 1(b). The rotational speed of the disk is independently controlled to investigate the influence of the magnitude and sign of the differential rotation. By traversing the equipment-support brace, similar to the experiments using the sphere, we visualize and measure the whole 3-D structure of Taylor-Column with the off-axis PTV.

3. Wake of moving sphere in background rotation

A moving sphere induces a wake behind it, and its flow structure can be described with a Reynolds number as reported by numerous papers to date (see for example [1,19]). When it moves in a rotating fluid, the wake structure changes completely due to presence of Coriolis forces, as governed by the Rossby and Reynolds numbers. These are defined by

$$Re = \frac{UD}{\nu}, \quad Ro = \frac{U}{2\Omega D} \tag{1}$$

where U and D represent, respectively, the translational velocity and the diameter of the sphere, Ω is the angular velocity of the background rotation, and ν is the kinematic viscosity of the water inside the tank. We use the inverse of the Rossby number, Ro^{-1}, to enable characterizing data for the non-rotating flow ($\Omega = 0$) by the finite value $Ro^{-1} = 0$. The detailed experimental conditions are summarized in Table 1.

At low Ro number or high Ro^{-1} number, the wake forms an axisymmetric columnar structure which has a significant velocity component in the azimuthal direction. We measure such a flow structure positioning the light sheet of the PTV system slightly offset from the rotational axis of the tank as elaborated below.

[1] Photographs of the facility can be accessed at www.eng.warwick.ac.uk/staff/pjt/turntabpics/voriskt.html.