§2. Flow Visualizations by Reflective Flakes

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Reflective flakes (mica or aluminum flakes, commercial products such as Kalliroscope, etc) are widely used to visualize fluid motions in the laboratory. An example is shown in Fig. 1(a), which is a flake visualization of a steady flow in a precessing sphere (Fig. 2). In this experiment, a small amount (about 13 ppm) of TiO_2-coated mica, whose size is about $(10\ \mu\mathrm{m})^2 \times 0.1\ \mu\mathrm{m}$, is seeded to the water confined in the sphere. The incident rays are a thin laser sheet which runs through the centre of the sphere perpendicularly to the spin axis (see Fig. 2). Reflected light by the flakes is recorded by a digital camera from the perspective parallel to the spin axis. Since the visualized pattern is stationary, we may suppose that the flow is steady. However, can we extract the information of flow structures from the visualized pattern?

This fundamental problem has been investigated by quite a few authors (see the references in Ref. 1), but there is no clear answer. In order to investigate the mechanism of flake visualizations, we derive[1], under the assumption that flakes are infinitely thin elliptic disks without inertia, the governing equations of flakes:

$$\frac{\mathrm{d}\boldsymbol{X}}{\mathrm{d}t} = \boldsymbol{u}\big(\boldsymbol{X}(t), t\big) \tag{1}$$

for the translational motion of the position vector $\boldsymbol{X}(t)$, and

$$\frac{\mathrm{d}\boldsymbol{N}}{\mathrm{d}t} = -\big(\boldsymbol{N} \times \boldsymbol{\nabla}\big)\big(\boldsymbol{N} \cdot \boldsymbol{u}\big) \times \boldsymbol{N} \tag{2}$$

for the rotational motion of the normal vector $\boldsymbol{N}(t)$. Here, $\boldsymbol{u}(\boldsymbol{x}, t)$ denotes the fluid velocity at position $\boldsymbol{x}$ and time t. Note that (2) indicates that the temporal evolution of flake orientations is identical to that of the infinitesimal material surface elements.

Then, we may numerically reproduce the laboratory visualization (Fig. 1a) by tracking flakes according to (1) and (2) in the steady flow which is simulated by a spectral method in the precisely same flow conditions as in the experiment. Since (1) indicates that the spatial distribution of flakes in an incompressible fluid is uniform if it is initially so, the pattern observed in flake visualizations stems from their non-uniform orientations. Therefore, flake orientations at each point on the laser sheet are numerically determined to simulate the intensity of the observed light based on the probability for flakes to reflect the incident rays to the observer. Obtained result is shown in Fig. 1(b), which is in excellent agreement with the laboratory result in Fig. 1(a). We may, therefore, conclude that the motion of flakes is well described by (1) and (2).

By further detailed numerical investigations, it is shown that flake orientations are isotropic on the three concentric bright circles in Fig. 1, whereas those off the circles are strongly anisotropic. Hence, the three circles are always bright irrespective of the angles of incident rays and perspective, but the observed light intensity in the latter regions depends on the angles. It is confirmed both by laboratory experiments and numerical simulations that observed patterns are indeed different for different angles of the incident rays. This result implies that a visualized image by a single pair of incident rays and perspective cannot distinguish these essentially different regions, and we need to use multiple light sources or perspectives to determine flake orientations. The possibility of the identification of flow structures, especially coherent structures in turbulence, based on thus determined flake orientations is under investigation.

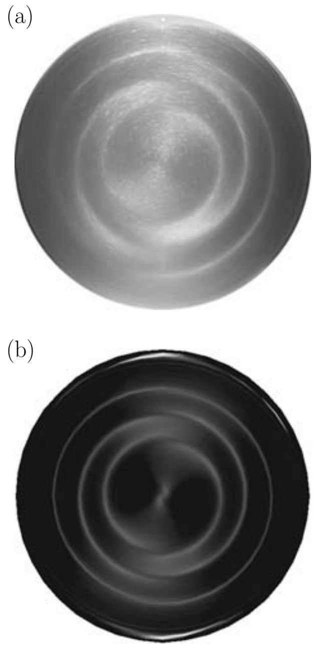

Fig. 1: Flake visualization of a steady flow in the precessing sphere (Fig. 2). (a) Laboratory experiment. (b) Numerical simulation based on (1) and (2).

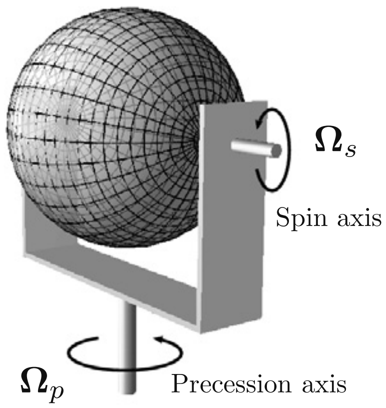

Fig. 2: Precessing sphere.

1) Goto, S., Kida, S., and Fujiwara, S.: J. Fluid Mech. (2011) in press.