ISSN 0027-1349, Moscow University Physics Bulletin, 2014, Vol. 69, No. 3, pp. 270–274. © Allerton Press, Inc., 2014.
Original Russian Text © A.A. Budnikov, Yu.D. Chashechkin, 2014, published in Vestnik Moskovskogo Universiteta. Fizika, 2014, No. 3, pp. 69–72.

PHYSICS OF EARTH, ATMOSPHERE, AND GYDROSPHERE

Marker Transfer in a Settled Composite Vortex

A. A. Budnikov[a] **and Yu. D. Chashechkin**[b]
[a] *Department of Physics, Moscow State University, Moscow, 119991 Russia*
[b] *Institute for Problems in Mechanics, Russian Academy of Sciences, Moscow, 119526 Russia*
e-mail: aa.budnikov@physics.msu.ru; chakin@ipmnet.ru

Received February 21, 2014; in final form, March 5, 2014

Abstract—The characteristics of the motion of solid-body markers over a settled composite vortex surface were studied using a laboratory apparatus. The vortex was generated in a cylindrical container filled with water using a rotating disc on the container bottom. The paths of solid-body markers were visualized. The radial distribution of the angular velocity of marker revolution around the container center was obtained. A relationship between eigenrotation frequencies and rotation around the container center occurred for two types of polypropylene markers (a flat square plate and a voluminous small tube).

Keywords: plastic island, composite vortex, solid-body marker paths.

DOI: 10.3103/S0027134914030047

INTRODUCTION

Compact vortices and vortex systems are often observed in the atmosphere and hydrosphere and are extensively used in industry.

Commonly accepted indicators of vortex currents in the ocean include spiral structures in the distribution patterns of algae, floating garbage, or ice [1]. During drifting, floating objects collide with each other and are destroyed. Fragments of floating materials that are trapped by sea currents are transported to large distances and concentrated in the centers of major oceanic gyres. In recent years, so-called "garbage islands" have been revealed in all oceans. These are extensive clusters of floating material that are millions of kilometers in area, consisting chiefly of plastic fragments ranging from few decometers to fractions of a millimeter in size. For large fragments, biological associations untypical for a region develop; a high concentration of fine particles is a hazard for all sea organisms [2].

The destructive actions of such intensive gyres in the atmosphere as tornadoes and hurricanes, which produce considerable material damage, are magnified by the impacts of trapped objects [3]. The short lifetime, unpredictable location, high speed, and spatial inhomogeneity of intensive vortex systems complicate the study of their properties under natural conditions.

The effect of particle distribution in a vortex flow in terms of size and composition is the basis of many industrial technologies: purification of liquids from admixtures and gases, substance separation, ore beneficiation, and drying of materials. In the recent years, vortex technologies for the fine grinding of solid materials are under development [4], as well as those for high-performance physical-chemical processes.

In addition to observations under natural conditions and at industrial facilities, vortex currents are studied theoretically and are modeled under laboratory conditions. The results of model studies of vortex dynamics in pure liquids or gases and those of mass transfer in different vortex currents have been given in a large number of original papers, reviews, and monographs [5]. In these experiments, currents produced by different bodies (inducers) revolve in free space or in the enclosed envelopes of cylindrical, spherical, ellipsoidal, toroidal, and more complex shapes. Due to their simplicity and universal character, devices where a vortex is produced by a rotary disc in a cylindrical container that is completely or partially filled with a liquid are the most widespread [5]. The calculated shape of the deformed free surface of the composite vortex in a container agrees satisfactorily with the measurements [6].

Such experiments have shown that the character of marked mass transfer over the surface of a composite vortex depends on many factors: the phase state (liquid or solid body), size, shape, and initial position of the marker, as well as the position and rate of the inducer of the rotation.

A spot of colored mixing liquid in a cavern on a vortex surface extends into spiral branches that consist of individual threads [7]. A rounded oil spot on a composite vortex surface also deforms into a body with a complex shape, with several spiral branches oriented towards the direction of the liquid rotation [8].

Detailed studies of solid-body marker behaviors in vortex currents that are used in many traditional and modern industrial technologies, including detonation ones, are of practical interest [9]. The commonly used methods of current-velocity measurements (in particular, laser Doppler anemometry (LDA) and particle-image velocimetry (PIV)) are based on the recording of the velocity of solid particles under the assumption of "passive" admixtures that follow a liquid without gliding. However, it is also known that free bodies in an offset vortex are affected by both forces (friction, drift, and ascentional) and torque that cause simultaneous offset and rotation [10]. The effects of intensive approach and collision are used in technologies for grinding solid particles in "vortex mills" [4].

The transfer of macroscopic bodies (whose speed depends on shape, the relative position of the center of mass, and buoyancy) in vortices has been studied in less detail [11]. The present work considers the motion dynamics of solid-body markers of two types (voluminous and flat) on a composite vortex surface in detail for the first time.

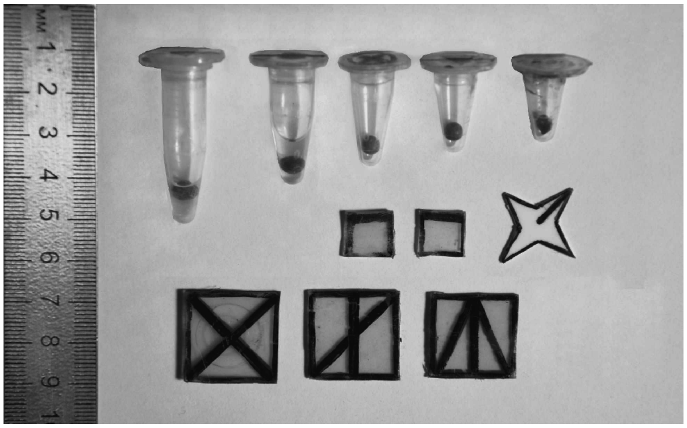

Fig. 1. Markers.

EXPERIMENTAL APPARATUS

A composite vortex was created in a cylindrical container that was 29.5 cm in diameter; in addition, to eliminate optical distortion of the current pattern, the container was placed in a transparent rectangular pool. The pool and container were partially filled with degassed running water. The composite vortex was produced by a uniformly rotating disc of 5.5 or 15 cm, with the upper plane coinciding with the basin's false bottom. The disc was attached to the motor axis, whose rotation rate was, according to an optical sensor, $\Omega_d = 3–5$ revolutions per second.

One or several markers were placed on the surface of the liquid with a settled vortex current. The markers were of two types: voluminous and flat (Fig. 1). Voluminous markers were small polypropylene tubes 2 to 5 cm long, with a conical rounded lower part. The cone diameter gently increased from 0.6 to 1 cm, and the height was 1.8 cm. The cylindrical part of tube joined the conic part and ended with a flat elliptic cap (1.6 cm in the major and 1.3 cm in the minor axis) that was 0.1 cm thick. Depending on the size of the tubes, the height of its cylindrical part was 0.1 to 2.9 cm.

A lead shot was put into a tube; the weight of the shot was selected based on the condition that the upper plane of a cap should be located on the water surface. The location of the mass center beneath the buoyancy center provided the stability of the vertical position for a tube in a vortex current.

The position of a neutral-buoyancy flat marker (a square plate with a side of 1 cm, or a quadrangular star of the same size, made of 1-mm thick polyethylene film) was stabilized by the effect of surface-tension forces (Fig. 1).

Video recording of the current pattern was performed using a Panasonic NV-MX500 digital camera installed vertically above the pond center. The digital viewfinder allowed the sight line position to be operatively corrected; the sight line was directed along the central axis of the container. The position of illumination devices was selected proceeding from the condition of stable recording of the marker position indicator. The experiment was managed and the data were recorded using a PC (see the more detailed description of the experiment technique in [7, 8]).

When processing the footage, the change of the marker position in time on the vortex surface was recorded with a spatial error of ±0.05 cm. The time error (0.04 s) was determined by the rate of recording with the camera.

DISCUSSION

Preliminary visual observations showed that all solid-body markers, independently of shape (both voluminous and flat), were moved in a spiral trajectory towards the center of the container. In addition to rotation around the vortex center, markers revolved around their inner axes. It was revealed during the experiments that the directions of the angular velocity of all the motion of the bodies coincided: they were the same for revolutions of a disc, square plate, and a tube around the container axis and for revolutions of markers relative to their axes. In the discussed experiments, the inducing disc, liquid, and markers revolved counter clockwise.

The typical trajectory of the motion of a square-shaped marker (side $l_m = 1$ cm) in a composite vortex (liquid depth $H = 40$ cm, disc diameter $D = 5.5.$ cm, angular rate of disc rotation $\Omega_d = 8$ revolutions per second) in the form of sequential positions of the marker center is given in Fig. 2a. One remarkable feature is the irregular position of some curls and the distances between the angular points, every of which had its own time of transition of the center of the square plate. The sequence of marker positions at the beginning of the trajectory illustrates self-rotation (revolution) and the dark arrow indicates the direction. The direction of

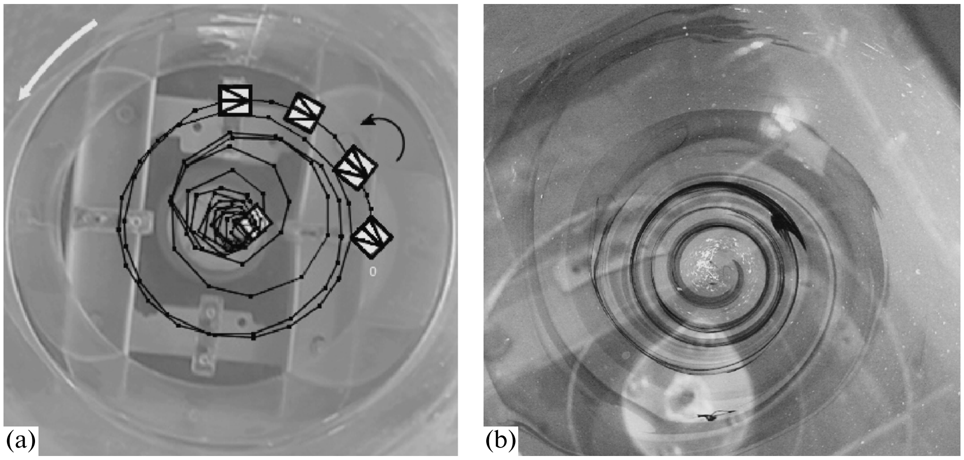

Fig. 2. Marker paths on the composite vortex surface ($H = 40$ cm): (a) the sequential positions of a flat square plate ($D = 5.5$ cm, $\Omega_d = 8$ revolutions per second, $l_m = 1$ cm); (b) the spiral branches from ink spot ($D = 15$ cm, $\Omega_d = 3$ revolutions per second) [7].

the rotation velocity of the liquid is indicated with a light arrow in the left corner of the figure.

A tube set into the settled current reached the center of the composite vortex in 1–3 min. During the experiment, tubes sometimes moved in an efferent direction and began to move away from the vortex center. In one to two turns, the general direction was restored; the markers reached the cavern center and then continued to revolve around the vortex center, while participating in the core precession. The radial component of the velocity was 0.2 cm/s at the beginning of the motion and increased to 0.6 cm/s as the marker approached the vortex center.

The flat markers moved more regularly. The velocity of their radial motion also increased from 0.2 to 0.6 cm/s, but due to the absence of return motion the markers reached the vortex center faster.

The rotational velocity of the marker center changed non-monotonously along the container radius. In the outer part of the vortex, at distances of 2 to 9 cm from the container axis, the rotation velocity of marker center v_φ was reduced with distance by a factor of $0.2\ \mathrm{s}^{-1}$. In the inner part of the current, the v_φ velocity rapidly grew by a factor of $1.5\ \mathrm{s}^{-1}$.

If several markers were put on the surface, they sometimes moved independently towards the center; they sometimes joined, forming clusters that revolved around the container axis and their own centers and they sometimes collided and moved in opposite directions.

In the vortex center, the markers revolved only around their axes.

Eigenrotation of a marker disturbs the smooth liquid flow in its vicinity; thus, a revolving marker is an additional source of the vortex. The disturbance produced by a revolving marker is of a complex character because some points of the upper margin of a marker simultaneously transited from zones of high rotational velocity to low-velocity zones, while other points did the opposite; therefore, due to the boundary-adhesion condition, these points transport liquid volumes that possess eigenvelocities.

The difference between the motions of the solid and liquid markers is illustrated by the pattern of the distribution of the colored liquid (ink) from an initially circular spot (Fig. 2b). The liquid with ink was dragged by the flow and elongated into the shape of a growing spiral branch. The zone of primary contact between the liquid and ink marker simultaneously glided over the liquid surface and left a colored trace, whose outer margin slowly moved towards the main direction (Fig. 2b). The liquid marker colors the entire trajectory and its different points in Fig. 2b correspond to the same time.

A three-dimensional character of the current in every point of the flow was displayed by the ink-spot transformation into a system of colored spiral threads divided by pure liquid bands. These elongated smooth spiral threads, which are typical patterns of admixture distribution in vortex currents both under laboratory [7] and marine conditions [1, 2], did not exhibit signs of revolution around the line center, in contrast to the trajectories drawn by margins of solid-body markers.

The distribution of the angular velocities of the rotation motion Ω of the center for the two types of markers (tube and square plate) around the vortex axis is shown in Fig. 3. The minimal value of the angular velocity Ω was observed at the periphery of the vortex, while the maximal one was in the vortex center (vortex core).

These data for the tubes are approximated by the following dependences: $\Omega_p = A_p R^\beta$, $A_p = 2.9 \pm 0.2$, $\beta = -1.24 \pm 0.06$, $[\Omega_p] = \mathrm{c}^{-1}$, and $[R] = \mathrm{cm}$; those for flat markers are as follows: $\Omega_s = A_s e^{-\gamma R} + C_s$, $A_s = 2.26 \pm$

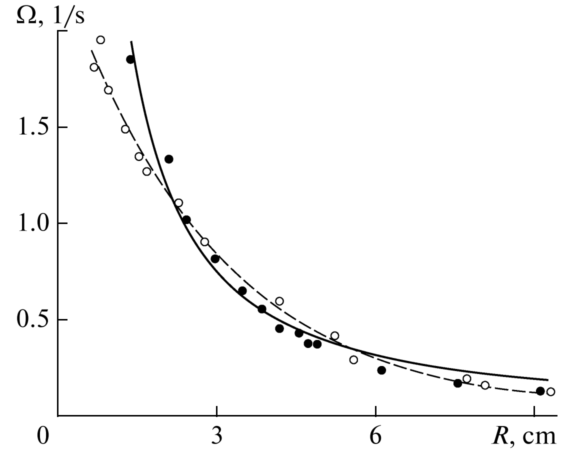

Fig. 3. The radial distribution of the angular velocity of marker revolution around the container center (H = 40 cm, D = 5.5 cm, Ω_d = 8 revolutions per second); the empty circles denote tubes, the filled circles denote flat square plates.

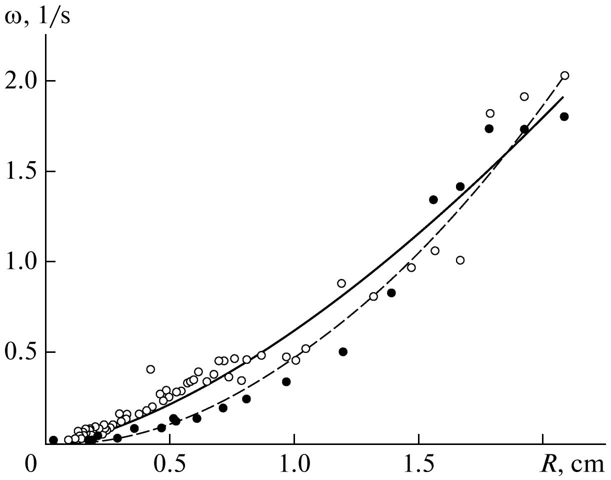

Fig. 4. The relationship between marker eigenrotation frequencies and rotation around the container center (H = 40 cm, D = 5.5 cm, Ω_d = 8 revolutions per second); the empty circles denote tubes, the filled circles denote flat square plates.

0.04, $\gamma = 0.29 \pm 0.03$, and $C_s = -0.08 \pm 0.06$. Thus, the values of angular velocity in the same current for different markers revolving around the vortex center and the eigenrotation (revolution) rates of these markers depended on the marker shape and size.

The individual peculiarities of marker motions are expressed in the curves that depict the dependence of the revolution rate ω on the marker rotation rate around the vortex center Ω (Fig. 4); these curves are approximated by the following power-law dependences: $\omega_p = A_p\Omega_p^{\beta_1}$, $A_p = 0.64 \pm 0.02$, $\beta_1 = 1.46 \pm 0.06$ for tubes; $\omega_s = A_s\Omega_s^{\beta_2}$, $A_s = 0.48 \pm 0.3$, and $\beta_2 = 2 \pm 0.1$ for flat markers.

The universal character of the simultaneous rotation of a solid body around a vortex center and around its own axis was noticed for the first time by René Decartes and was described in his *Principles of Philosophy* (Part III, paragraph 46): "Thus, for example, {we may think that God divided} all matter... {into a very great number of particles} which He transported {not only around its center but also} all together around the center S; and that, similarly, He transported all the parts of the matter that occupies the space AEV around the center F, and so on; so that, [these] the parts formed as many vortices {from now on, I shall use this word to denote all the matter that thus revolves around each of these centers} as there are now heavenly bodies in the world" [12].

CONCLUSIONS

The simultaneous revolution of a solid-body marker around its axis and vortex center can both stabilize its trajectory and cause unexpected shifts, acceleration, and deceleration, even in a settled vortex current. Inhomogeneities of motion in the considered experiments were more expressed for the voluminous marker.

ACKNOWLEDGMENTS

This work was supported in part by the Presidium of the Russian Academy of Sciences (Program no. P-23 Fundamental problems of oceanology: physics, chemistry, biology, and geology) and by the Russian Foundation for Basic Research (project no. 12-01-00128). The VTK apparatus of the USU complex (Institute for Problems in Mechanics, Russian Academy of Sciences) was used.

REFERENCES

1. M. Eriksen, Report Algalita Marine Research Foundation **148**, 1 (2012). http://www.algalita.org/uploads/2012_asia_pacific_expedition_report.pdf
2. Thin sea ice make swirls in East Greenland, 2012. http://earthobservatory.nasa.gOv/IOTD/view.php?id=79521
3. D. V. Nalivkin, *Hurricanes, Storms, Windspouts* (Leningrad, 1969) [in Russian].
4. F. A. Bykovskii and E. F. Vedernikov, J. Appl. Mech. Techn. Phys. **41**, 351 (2000). http://link.springer.com/article/10.1007%2FBF02465234#page-1
5. S. V. Alekseenko, P. A. Kuibin, and V. L. Okulov, *Introduction into Theory of Concentrated Swirls* (Sibir. Otd. Ross. Akad. Nauk, Novosibirsk, 2003) [in Russian].

6. Yu. D. Chashechkin and A. V. Kistovich, Dokl. Phys. **55**, 43 (210).
7. E. V. Stepanova and Yu. D. Chashechkin, Dokl. Phys. **53**, 634 (2008). http://link.springer.com/article/ 10.1134%2FS1028335808120069
8. T. O. Chaplina, Yu. D. Chashechkin, and E. V. Stepanova, Dokl.-Phys. **55**, 238 (2010). http://link.springer.com/ article/ 10.1134%2FS1028335810050083
9. F. A. Bykovskii, S. A. Zhdan, E. F. Vedernikov, and Yu. A. Zholobov, Burning of solid fuel, *Proc. 8th All-Russ. Conf. with Int. Particip.* (Novosibirsk, Sibir. Otd. Ross. Akad. Nauk, 2012); http://www.itp.nsc.ru/conferences/ gtt8/files/26Bykovskiy.pdf
10. S. S. Sadhal, P. S. Ayyaswamy, and J. N. Chung, *Transport Phenomena with Drops and Bubbles* (Springer-Verlag, New York, 1997).
11. T. E. Faber, *Fluid Dynamics for Physicists* (Cambridge, 1997).
12. R. Descartes, *Principles of Philosophy* (Gardners Books, 2013).

Translated by N. Astafiev