Gallery of Fluid Motion

Multiple vortex tornadoes in a bucket

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(Received 19 May 2023; published 16 November 2023)

This paper is associated with a poster winner of a 2022 American Physical Society's Division of Fluid Dynamics (DFD) Milton van Dyke Award for work presented at the DFD Gallery of Fluid Motion. The original poster is available online at the Gallery of Fluid Motion, https://doi.org/10.1103/APS.DFD.2022.GFM.P0005

DOI: 10.1103/PhysRevFluids.8.110504

A shallow water layer in an open cylindrical tank is set into rotation by spinning a disk at its base. What do you expect to observe? A simple axisymmetric swirling flow perhaps? While this is true for low speeds of rotation, higher speeds result in interesting symmetry-breaking patterns of the parent axisymmetric swirling flow through the formation of subvortices [1].

These subvortices are equally distributed on a circular ring and revolve around the center of rotation of the parent swirling flow. Each subvortex possesses a smaller diameter and a larger angular momentum than the parent vortex. The number of subvortices that form and their physical characteristics ultimately depend on the speed of rotation of the disk at the bottom of the cylindrical tank. The higher the speed, the more subvortices appear. The surrounding flow forms a regular polygonlike pattern with the subvortices occupying the vertices of the polygon. Refer to Fig. 1 for the experimental setup and schematics of the two and three subvortex systems.

Subvortices created from such a simple laboratory experiment bear a striking resemblance to the subvortices observed in multiple vortex tornadoes. In nature, powerful subvortices can form within the outer shear layer of a tornado [2]. These subvortices rotate rapidly and revolve around the main tornado, causing extreme destruction as they lift and entrain debris in their path [2]. Subvortices within a multiple vortex tornado are not to be confused with another meteorological phenomenon known as satellite tornadoes. A satellite tornado is a distinct tornado that revolves around another often larger (primary) tornado [3]. In other words, a subvortex resides entirely within the shear layer of its parent tornado, whereas a satellite tornado is clearly separated (resides outside the shear layer).

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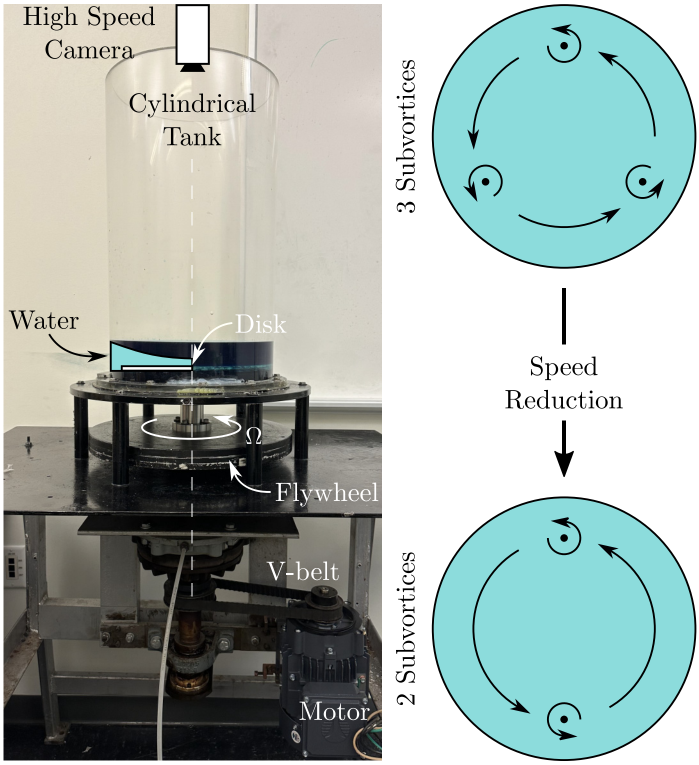

FIG. 1. Experimental apparatus (left). A motor drives the rotation of a disk (light gray sketch) within a cylindrical tank containing a shallow water layer. The black band at the base of the cylindrical tank, added for contrast purposes during image acquisition, hides the disk and water layer from view in the image. The disk and water layer are therefore provided schematically for half the tank. The shallow water layer within the tank (light blue sketch) is set into rotation purely as a result of the rotating disk. A flywheel is used to smooth out fluctuations in the disk rotation speed. With increasing rotation speed, more subvortices appear.

In this work, we investigate the transition from a stable system of three to two subvortices initiated by an abrupt reduction in the rotation speed of the disk. The start of the recording then coincides with the disk speed being set to its critical value for a system of two subvortices, thus triggering the transition process from an initially stable three-subvortex system. The dynamics of the transition process may provide insight on the decay of multiple vortex tornadoes resulting from a loss of rotation speed. In the laboratory model, the surface velocity fields are captured at 400 Hz via particle image velocimetry (PIV) measurements using white spherical polystyrene particles (250 µm) spread over the free surface of the shallow water layer. The diameter of the circular disk is 252 mm and is positioned 20 mm above the bottom of the cylindrical container, the internal diameter of which is 284 mm. To better observe the subvortices, a reduced-order model is then constructed from the leading eight modes of a space-only proper orthogonal decomposition (POD) [4] performed on the acquired velocity fields [5].

Figure 2 depicts the flow patterns throughout the attenuation of a stable system of three to two subvortices (the figures arranged along an ellipse). The flow patterns are depicted using their finite-time Lyapunov exponent (FTLE) fields computed through forward time integration [6,7]. The FTLE fields reveal the repelling material lines or transport barriers in the flow (white lines). The attenuation begins with a stable system of three subvortices in the first subfigure (following the black arrow). The stable system possesses rather closed transport barriers, indicating that material

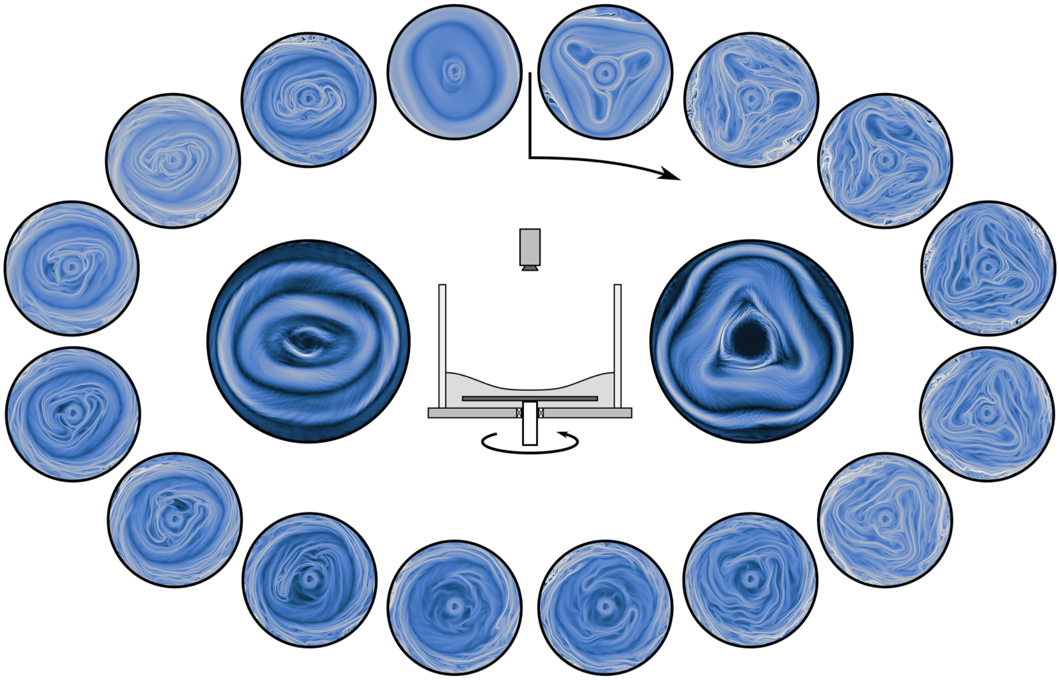

FIG. 2. Finite-time Lyapunov exponent (FTLE, forward time integration) fields resulting from the transition between a system of three to two subvortices in a cylindrical tank (arranged along an ellipse). The FTLE fields of the stable two and three vortex systems with the background flow removed are shown in the center. The brighter colored lines (white) correspond to repelling material lines in the flow. The original image is available online at https://doi.org/10.1103/APS.DFD.2022.GFM.P0005

contained within are transported as a collective mass. As the flow evolves, the transport barriers destabilize and completely unravel by the sixth subfigure. Material previously trapped by the subvortices have been released and now rotate with the background swirling flow (subfigures 7 to 11). An attracting material line (dark blue) begins to emerge and becomes increasingly regular and ellipsoidal until a stable system of two subvortices is attained (subfigure 16). Being a transport barrier, materials are once again trapped within the ellipsoid. In the context of multiple vortex tornadoes, the regions enclosed by these transport barriers may represent debris being trapped and carried by the subvortices as the main tornado travels. The decay of the system from three to two subvortices demonstrates an “unravelling” of these material lines which suggests that a multiple vortex tornado may rather suddenly shed debris if it exhibits a sufficient loss of angular momentum.

The two figures in the center of Fig. 2 show the FTLE fields in the stable two and three subvortex systems with the parent swirling flow removed. In other words, there is no longer a parent vortex to the subvortices and they act as individual satellite vortices revolving around each other. We observe that the satellite vortices alone are not sufficient to create regions isolated by strongly repelling material lines. This result may highlight an important difference between satellite tornado systems and multiple vortex tornadoes. Our results suggest that systems of two and three satellite tornadoes cannot trap debris to the same extent that equal-strength subvortices can in a multiple vortex tornado.

H.A.A. wishes to acknowledge the support of Khalifa University. This work was funded through Khalifa University Grant CIRA-2021-77.

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