Physics of Fluids

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Cite as: Phys. Fluids **27**, 091103 (2015); https://doi.org/10.1063/1.4930899
Submitted: 22 August 2015 . Published Online: 24 September 2015

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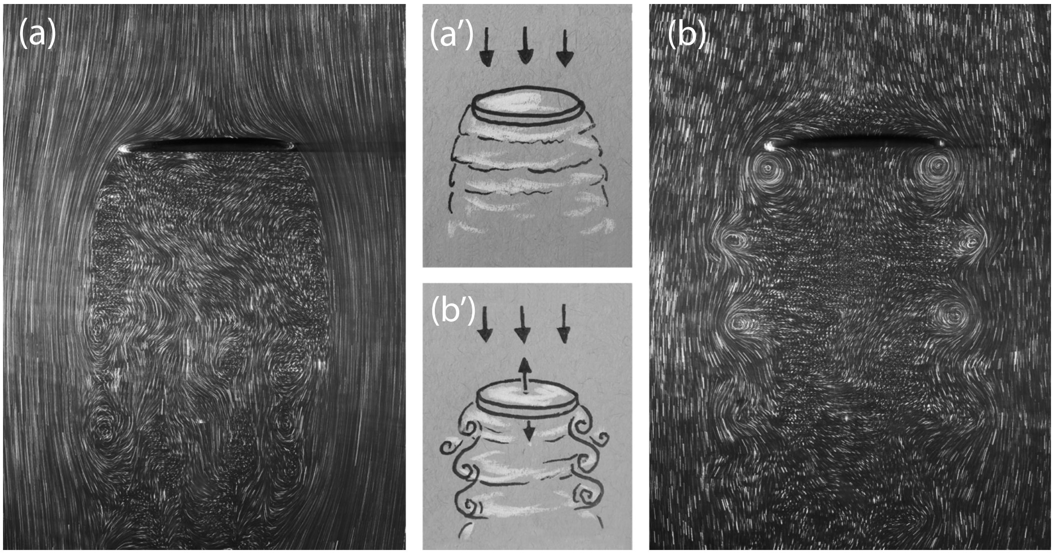

FIG. 1. Comparison of flow past (a′) a stationary disk and (b′) a disk undergoing in-line oscillations. (a) Pathline visualization using microparticles in water illuminated by a laser sheet: A stationary disk induces a relatively quiescent wake separated from a fast outer flow. (b) An oscillating disk, here captured in upstroke, emits successive vortex rings that travel downstream. Source: APS-DFD (http://dx.doi.org/10.1103/APS.DFD.2014.GFM.P0059).

Comparative flow visualization for steady and unsteady motions of a disk through a fluid

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(Received 22 August 2015; published online 24 September 2015)
[http://dx.doi.org/10.1063/1.4930899]

Flow visualization is indispensable for experiments related to unsteady fluid flows, as it can reveal the subtle fluid-structure interactions that lie behind complex phenomena. Visualization also serves as an instructive way to compare unsteady or time-dependent motions of a body through a fluid to the better-characterized case of steady motion. We explore this comparison in the context of high Reynolds number ($Re \sim 10^4$) flows past stationary and oscillating disks, as sketched in Figs. 1(a′) and 1(b′). A stationary disk generates an unsteady downstream wake where the flow has separated from the disk edge. By driving the disk to oscillate in-line with the oncoming current, we directly impose unsteadiness and strongly modify the separated flow.

While visualization techniques uncover the otherwise hidden nature of a flow, each method also contributes a distinct set of information that can influence our interpretation. Figs. 1(a) and 1(b) show *pathlines* revealed by glass microparticles immersed in water and illuminated by a laser sheet. Time-exposed photographs record particle paths that indicate the flow velocity field.[1] The images of Fig. 2 represent *streaklines* using fluorescent dye released from the front of the disk and entrained by the flow. Pathlines reveal the flow velocity over an entire 2D slice but only at a given instant in time. Streaklines represent the set of all fluid parcels that have passed near the sites of dye release at any time in the past.[1] This method tags the fluid involved in the interaction and highlights the vorticity shed from the edge of the oscillating disk.

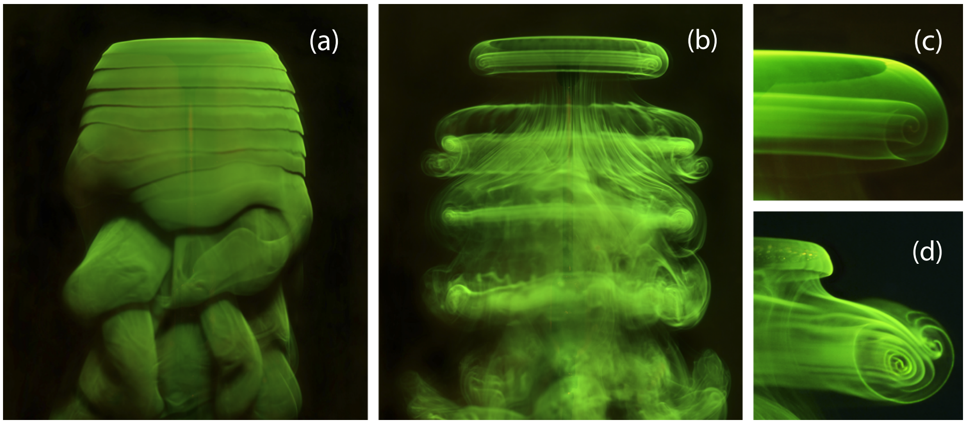

FIG. 2. Streakline flow visualization using fluorescein dye released from the front surface of a disk. Flow past (a) a stationary disk compared to that of (b) an oscillating disk. (c) For slow oscillations, a single vortex ring is shed from the disk edge with each forward stroke. (d) For faster oscillations, a pair of counter-rotating vortex rings, or dipole, is shed with each complete oscillation.

Taken together, these two sets of photographs demonstrate that multiple visualization methods applied to identical situations paint a richer picture of a given flow phenomenon. The pathlines of Fig. 1(a) seem to show that a stationary disk leaves behind a sharply defined wake just downstream of the body, whereas the streaklines in Fig. 2(a) reveal that the disk sheds thin, threadlike vortices that envelope this wake, which becomes unstable further downstream. Pathlines also reveal features of the outer and wake flows which are not seen with streaklines. For example, Fig. 1(b) captures a moment in which an off-body stagnation point is induced upstream of the disk during the forward stroke. Revealed by streaklines in Fig. 2(b), but not apparent in the corresponding pathlines of Fig. 1(b), is a vortex dipole that is shed during each oscillation.[2] In fact, for oscillations that are slow compared to the flow speed, the disk emits a single vortex ring per cycle, as shown in Fig. 2(c). Increasing the flapping speed leads to the formation of a dipole, or pair of counter-rotating vortices, as shown in Fig. 2(d).

[1] D. J. Tritton, *Physical Fluid Dynamics* (Clarendon Press, 1988).
[2] G. K. Batchelor, *An Introduction to Fluid Dynamics* (Cambridge University Press, 2000).