Gallery of Fluid Motion

Traveling Faraday waves

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(Received 17 March 2023; published 16 November 2023)

This paper is associated with a video winner of a 2022 American Physical Society's Division of Fluids Dynamics (DFD) Milton van Dyke Award for work presented at the DFD Gallery of Fluid Motion. The original video is available online at the Gallery of Fluid Motion, https://doi.org/10.1103/APS.DFD.2022.GFM.V0040

DOI: 10.1103/PhysRevFluids.8.110501

When a liquid layer is subjected to a sinusoidal vertical vibration, there exists a critical driving acceleration, known as the Faraday threshold, above which the entire free surface becomes unstable to a standing field of waves [1]. These so-called "Faraday waves" are subharmonic, oscillating at half the frequency of the imposed vibration, and monochromatic, with a wavelength λ prescribed by the standard capillary-gravity wave dispersion relation [2] [Fig. 1(a)]. As the forcing amplitude is further increased, there is a second threshold, known as the order-disorder threshold [3,4], beyond which a secondary instability triggers a transition to a spatiotemporally chaotic state in which the wave pattern is in continuous erratic motion [Fig. 1(b)]. Notably, the surface Faraday dynamics is coupled to flows in the bulk of the liquid layer: Standing Faraday patterns generate relatively well-ordered oscillatory flows [5–7], while chaotic waves lead to a self-sustained state of spontaneous nucleation, irregular motion, and sudden annihilation of defects (dislocations of pattern lines) known as "defect-mediated turbulence" [8–11]. Faraday waves thus provide an excellent platform to study nonlinear dynamics and pattern formation driven far from equilibrium [12].

The transition from standing [Fig. 1(a)] to chaotic [Fig. 1(b)] Faraday dynamics is significantly affected by the shape and size of the fluid bath [3]. When the bath is large relative to the Faraday wavelength λ, the transition to the spatiotemporal chaotic state is characterized by a sharp decline in the translational correlation and long-range orientation order of the pattern, and the emergence of temporal fluctuations with frequency increasing with the driving amplitude [3,4]. When the Faraday waves are confined to small domains, however, the pattern remains ordered at higher forcing accelerations, and secondary instabilities may lead to coherent motion before chaos sets in and dominates the dynamics. In particular, Faraday waves inside a narrow annular channel may exhibit the nucleation/annihilation of one wavelength, the development of a secondary frequency, and a "drift" instability wherein the pattern begins to rotate slowly at a constant speed [13,14]. The mechanism responsible for this drift instability was rationalized theoretically by Martín *et al.* [15]

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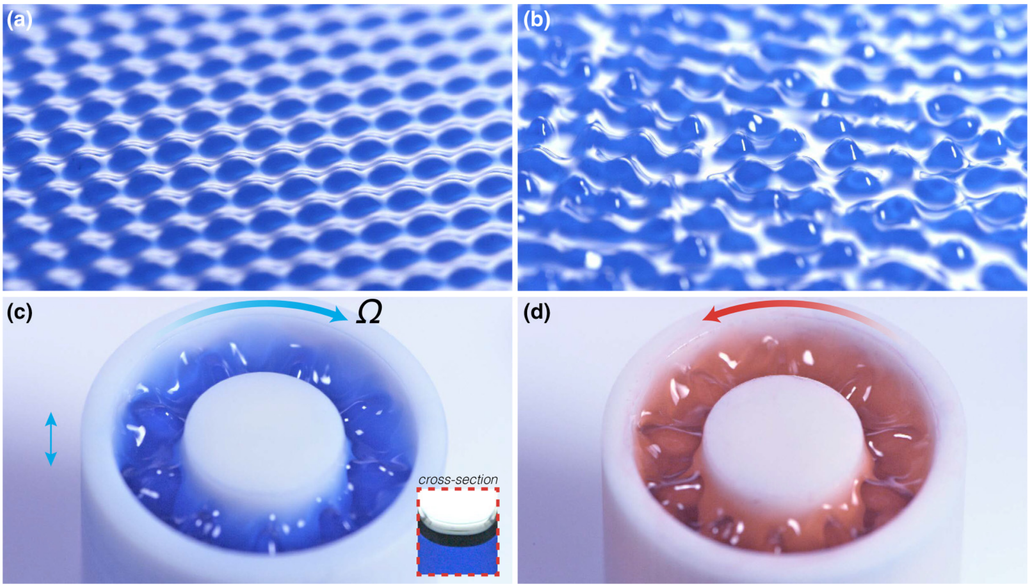

FIG. 1. Symmetry-breaking of Faraday waves. (a) Standing surface waves emerging when a liquid layer is vibrated vertically at a driving acceleration just above the so-called Faraday threshold. (b) The uniform Faraday pattern becomes chaotic as the driving acceleration is increased further due to a secondary order-disorder instability. (c), (d) Faraday waves in an annular channel start to rotate at rate Ω when the channel width W, the Faraday wavelength λ, and the capillary length l_c are all comparable. The symmetry is spontaneously broken; the direction of motion, (c) clockwise or (d) counterclockwise, is random, but persistent once one direction is selected.

in terms of the coupling between the oscillatory surface waves and the underlying streaming flows [16–18] generated near the bottom boundary, which become unstable for sufficiently high driving leading to the development of a direct-current (dc) flow [15]. The study of Faraday waves in quasi-one-dimensional channels has mainly focused on large waves (low frequencies) confined to narrow channels to minimize three-dimensional (3D) effects [19,20]. In this gravity-dominated regime, the drift instability has been largely considered a secondary effect owing to its relatively insignificant magnitude, typically below 0.01 mm/s [13,14].

Here, we present a new Faraday instability arising in annular pools when the Faraday wavelength λ, channel width W, and capillary length l_c are all comparable. We generate this instability by vertically vibrating 3D-printed channels filled with either water or silicone oils mounted on an electromagnetic shaker, which we imaged from either an oblique or top view with a color high-speed camera. In this capillary-dominated regime, for which the interface shape is dominated by the menisci at the vertical walls [Fig. 1(c)], the Faraday pattern starts to translate as the driving acceleration is increased, with translation speeds ($\approx$10 mm/s) up to three orders of magnitude higher than that of the drift instability [Fig. 1(c)]. The sense of rotation, either clockwise or counterclockwise [Figs. 1(c) and 1(d)], is random but persistent once a direction is selected. We refer to this spontaneous symmetry-breaking instability as the "traveling" Faraday instability by virtue of its unprecedented translational speeds. Moreover, we note that our experiments are performed in the deep-fluid limit, when the channel depth H is large relative to λ, thus distinguishing the traveling instability from the drift instability. In so doing, the interaction between the Faraday waves and the bottom boundary is removed, and the lateral walls of the channel thus emerge as the main source of streaming flows. Our experiments, along with simulations, collectively show that the magnitude of the streaming flows generated by the Faraday waves is significantly amplified by capillary effects,

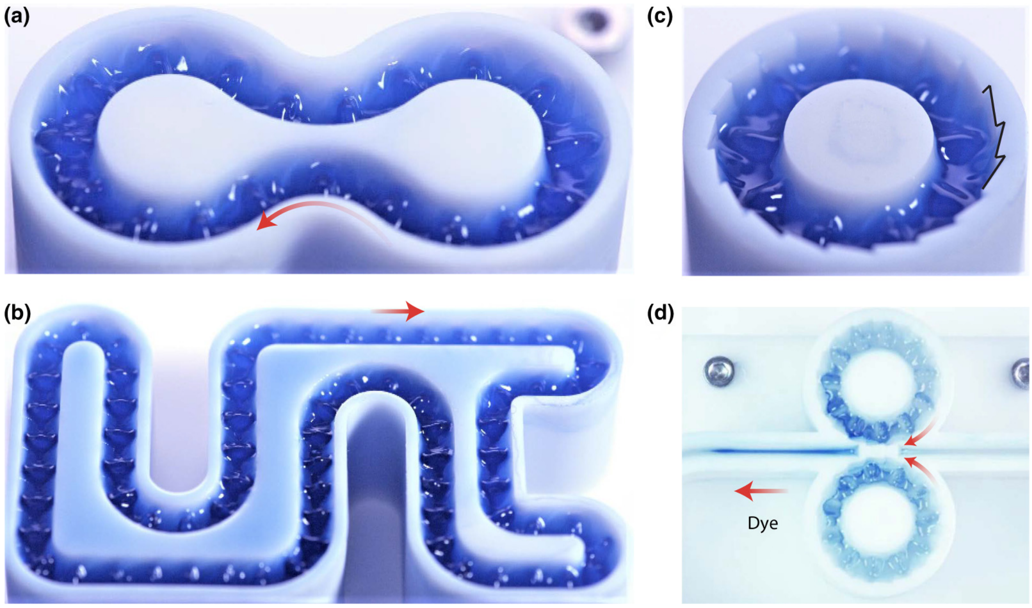

FIG. 2. Traveling Faraday waves in complex geometries. Traveling Faraday waves may also move along (a) channels with variable curvature, and (b) more complicated networks including both straight and curved sections. (c) The direction of motion can be fixed by including ratchets on the channel's vertical walls. (d) Small-scale fluid pumps may be created by connecting channels with ratcheted walls to a secondary fluid channel. Drops of blue dye have been added in (d) to demonstrate the fluid's unidirectional transport.

including wettability and contact-line dynamics. We extend our investigation to demonstrate that the traveling instability is a robust effect that arises for different channel geometries, including channels of various curvatures [Fig. 2(a)], and more complex flow networks with straight and

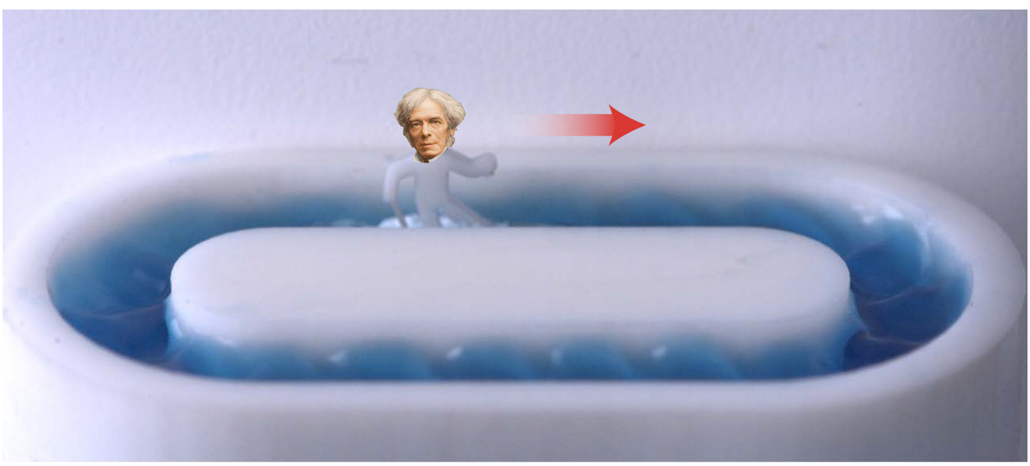

FIG. 3. Transport of floating objects. A 3D-printed figurine suspended on the liquid-gas interface is transported along the channel by traveling Faraday waves, illustrating the potential of this instability as a new mechanism for the transport of granular materials floating on interfaces. The speed of the object is proportional to the wave speed. An image of Michael Faraday was digitally added in reference to the title of the video, "Run, Faraday, run," and the playful reference to the famous line "Run, Forrest, run" from the movie *Forrest Gump*.

curved sections [Fig. 2(b)]. Across the various channel shapes, we found the wave speed remained of the same order of magnitude, provided the channel width was unaltered. We also demonstrate that the direction of motion may be enforced through physical biases in the confining channels, such as ratchet walls, which force the Faraday waves and underlying streaming flows to move in a prescribed direction [Fig. 2(c)]. Exploiting this ratchet concept, we create small-scale fluid pumps by connecting two ratcheted annular channels to a secondary linear channel in which fluid is transported in a particular direction [Fig. 2(d)]. Furthermore, the traveling Faraday instability may be also harnessed to transport solid objects suspended on the free surface (Fig. 3).

The authors gratefully acknowledge financial support from the National Science Foundation, under Grants No. CBET-2144180 (CAREER, P.J.S.), No. CMMI-2321357 (P.J.S. and J.H.G.), and No. DMS-1910824 (R.C.), the Alfred P. Sloan Foundation (Sloan Research Fellowships, P.J.S.), and the Office of Naval Research under Grant No. N00014-18-1-2490 (R.C.).

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