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DYNAMICAL PHENOMENA

Walking and orbiting droplets

Small drops can bounce indefinitely on a bath of the same liquid if the container is oscillated vertically at a sufficiently high acceleration[1]. Here we show that bouncing droplets can be made to 'walk' at constant horizontal velocity on the liquid surface by increasing this acceleration. This transition yields a new type of localized state[2–5] with particle–wave duality: surface capillary waves emanate from a bouncing drop, which self-propels by interaction with its own wave and becomes a walker. When two walkers come close, they interact through their waves and this 'collision' may cause the two walkers to orbit around each other[6–8].

The bouncer transition to walking is continuous and occurs when the vertical acceleration of the bath, γ_m, reaches a critical threshold, γ_m^c. Below γ_m^c, the drops bounce with no horizontal motion. Above γ_m^c, bouncing drops acquire a rectilinear motion along the surface of the bath (Fig. 1a–c). Their velocity V_w is constant (0–20 mm s^{-1}) and increases with γ_m.

Why do the drops start walking? This phenomenon occurs below, but near, the onset of the Faraday instability, a point at which the surface becomes spontaneously wavy. In this regime, the vertical motion of a drop becomes subharmonic, with a period that is double that of the forcing. As a result, it emits a damped Faraday wave. The drop undergoes successive identical parabolic jumps that are locked with its wave. Each jump brings the drop into collision with the side of the central bulge of the wave generated by the previous collision (Fig. 1a). This collision with an inclined surface generates a non-zero horizontal impulse, which can be translated as an equation for the drop's horizontal motion, averaged over a period π/ω_0 of the subharmonic vertical motion

$$m\,d^2x/dt^2 = a\sin\{(\pi k/\omega_0)\,dx/dt\} - b\,dx/dt \quad (1)$$

where m is the drop's mass, a is about 10^{-6} N, k is the wavenumber, and b is about 10^{-6} N m^{-1} s. The left-hand side of equation (1) represents the inertia of the drop; the first term on the right-hand side accounts for the effective force due to the inclined surface, and the second for viscous damping during the collision. Equation (1) predicts the observed continuous transition of the droplet from stationary to walking when $a > b\omega_0/(\pi k)$.

When walkers coexist in a cell, they inevitably collide. These 'collisions' do not involve any contact between the drops but only a deflection of their horizontal trajectories, when the wave generated by a drop affects the horizontal velocity of the other one. The main parameter characterizing this collision is d_c, the minimal distance of approach of the two drops; depending on the value of d_c, the walkers either attract or repel each other. Attraction leads to a twin-star-like orbiting motion of the drops (Fig. 1d, and see movie in supplementary information). The diameters of the orbits take discrete values d_n^{orb}, which self-adapt to the forcing frequency[9,10]. The orbital diameters are slightly smaller than an integer multiple of the Faraday wavelength (λ_F), or $d_n^{orb} = (n-\varepsilon)\lambda_F$ when the drops bounce in phase. They are $d_n^{orb'} = (n+1/2-\varepsilon)\lambda_F$ when the drops bounce in antiphase; the offset, $\varepsilon = 0.2 \pm 0.02$, is such that when a drop collides with the surface, it falls on the inward slope of the wave emitted by the other. This provides the centripetal force needed for the orbital motion. For other values of d_c, each drop falls on the outward slope of the wave of the other, which causes a repulsion.

We have shown that walkers can behave as billiard balls, undergo scattering collisions or form circular orbits, and can even display complex three-body motion (results not shown). The variety of these phenomena can be explained by interaction through waves and by generalizing equation (1) to two or more drops (the resulting equations yield the same quantification of orbits and numerical trajectories, which are very similar to the experimental collisions; S. P. *et al.*, manuscript in preparation). In this system, real particles experience the same non-local interaction as nonlinear waves.

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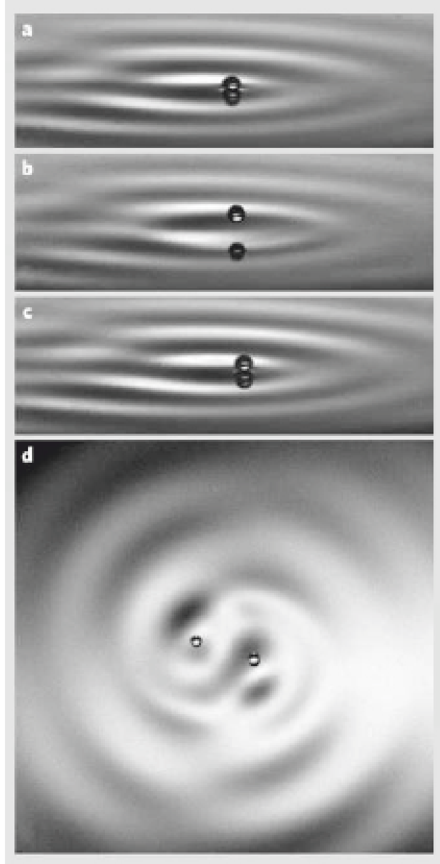

Figure 1 | Behaviour of silicon oil droplets on a bath of silicon oil when it is oscillated vertically. Experimental parameters: oil viscosity, 20×10^{-3} Pa s; forcing frequency, $\omega_0/2\pi = 80$ Hz, diameter of droplets $D\approx0.65$ mm; forcing acceleration, $\gamma_m/g \approx 3.9$ (where g is the acceleration due to gravity). **a–c,** Photographs showing the motion of a single drop in interaction with its own localized Faraday wave on the liquid surface. The drop's motion is composed of a series of identical parabolic jumps, each jump bringing the drop into collision with the forward side of the central bulge of the wave generated by the previous collision. **d,** Photograph of two orbiting drops and associated waves. The horizontal motion is in a twin-star-like orbit of diameter $d_n = 5.8$ mm. (For movies, see supplementary information.)

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