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SHORT PAPER

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Visualization of hydrodynamic pilot-wave phenomena

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1 Introduction

The reflection of an object can be distorted by undulations of the reflector, be it a funhouse mirror or a fluid surface. Painters and photographers have long exploited this effect, for example, in imaging scenery distorted by ripples on a lake. Here, we use this phenomenon to visualize micrometric surface waves generated as a millimetric droplet bounces on the surface of a vibrating fluid bath (Bush 2015b). This system, discovered a decade ago (Couder et al. 2005), is of current interest as a hydrodynamic quantum analog; specifically, the walking droplets exhibit several features reminiscent of quantum particles (Bush 2015a).

2 Experiments

The experiment (Fig. 1) consists of a 4" wide Petri dish filled with 20 cSt Silicon oil (Sigma-Adrich), driven by a loudspeaker, which is connected to an amplifier, itself linked to a sine wave function generator on a smartphone (see Supplementary Information for details). In a typical experiment, the forcing frequency is fixed ($f = 80$ Hz), and the amplitude A of the forcing is varied, thereby changing the peak acceleration $\gamma = A(2\pi f)^2$ of the bath. Above a critical acceleration amplitude γ_B, a droplet of the same fluid (generated by swiftly removing a partially submerged needle from the bath) does not coalesce, but bounces indefinitely on the vibrating bath (Walker 1978). For $\gamma > \gamma_w$, this bouncing state destabilizes, giving way to a walking state in which the drop propels itself across the surface though a resonant interaction with its own wave. As the wave guides or pilots the bouncing drop, the walker system is referred to as a hydrodynamic pilot-wave system (Bush 2015a, b; Couder et al. 2005) (Fig.2d,e). When γ exceeds a critical value γ_F, the free surface becomes unstable to a field of Faraday waves (Faraday 1831) (Fig.2g). In such a case, a drop on the surface will move in an irregular fashion (Fig.2h,i). The optical method developed here offers a technique for visualizing the micrometric waves and millimetric droplets in all of these situations.

The lighting system consists of a high-intensity lamp (Victor-Smith, 650 W) directed toward the bath. A transparent film with colored patterns is mounted to a frosted diffuser and placed between the lamp and the bath. The simplest pattern consists of 6-mm-wide horizontal stripes, chosen so that the periodicity of the reflected pattern approximately matches the wavelength of the Faraday waves generated by the droplet, when suitably oriented. Other patterns can create various effects such as the square pattern used for Fig.2d. We image the surface of the bath with either a still camera (Canon Rebel T1i with a 60-mm macro lens and

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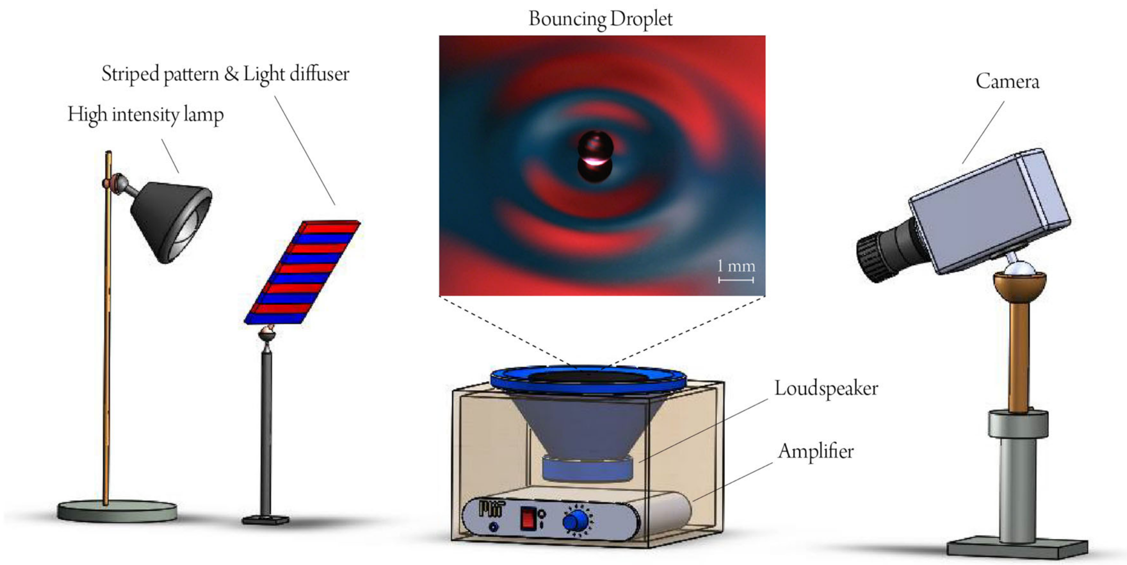

Fig. 1 Schematic of the experimental setup. The striped pattern, reflected from the oil bath, is captured by a camera as a droplet bounces on the interface

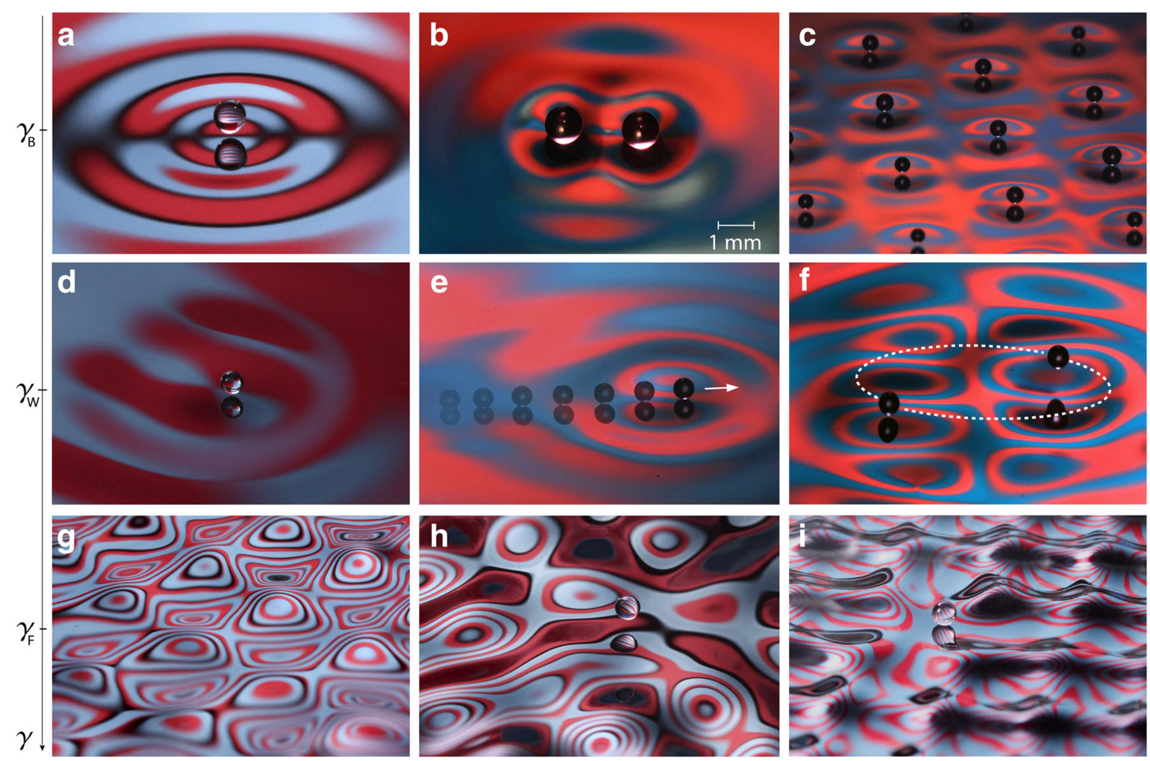

Fig. 2 **a** A bouncing droplet and its wave field. When positioned near one another, bouncing droplets may lock into stable geometrical patterns, creating: **b** bouncing pairs (Eddi et al. 2008), or **c** lattices (Eddi et al. 2009). As the driving amplitude of the bath is increased, the bouncer (**a**) destabilizes into a walker (**d**), which self-propels across the bath as shown in the time-lapse photograph (**e**). **f** Two walking droplets directed toward each other can spontaneously lock into orbit (Protiere et al. 2008). **g** Faraday waves arising when $\gamma > \gamma_F$. Above the Faraday threshold, drops traverse the wavy bath surface in an irregular fashion (Terwagne and Bush 2011) (**h**, **i**). All droplets are of approximately 1 mm diameter. **a**, **d**, **g**, **h**, **i**, were captured with the still camera and **b**, **c**, **e**, **f**, with the video camera

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an external flash) or video camera (Phantom V5.2 configured to 1000 frames per second, with a 1152×896 pixel resolution, a 105-mm lens with aperture set at f/8 and a Nikon 2X teleconverter). The colored stripes reflect on the bath surface, and the camera is focused on the bouncing droplet. The base of the dish is painted black to minimize reflections. A typical observation from the video camera is reported in Fig. 1, and several of our video or still images are presented in Fig. 2.

3 Results and perspective

Detailing the entire physical landscape of this pilot-wave hydrodynamical system is beyond the scope of this letter. In Fig. 2, we provide examples of what may be observed in the laboratory when varying the driving of the bath and the number of droplets, respectively. Accompanying movies are provided in Supplementary Information and labeled in a similar fashion. Strobed movies are recorded at $f = 40$ Hz with a phase such that the droplet is captured either when impacting the bath (Fig. 2e) or at its peak height (Fig. 2f). Note that the method enables us to assess qualitatively the form of the micrometric waves piloting the droplets. In principle, this technique could be adapted to produce quantitative measurements by adopting the surface synthetic Schlieren of Moisy et al. (2009).

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References

Bush JWM (2015a) The new wave of pilot-wave theory. Phys Today 68(8):47–53

Bush JWM (2015b) Pilot-wave hydrodynamics. Ann Rev Fluid Mech 47:269–292

Couder Y, Protiere S, Fort E, Boudaoud A (2005) Dynamical phenomena: walking and orbiting droplets. Nature 437(7056):208–208

Eddi A, Terwagne D, Fort E, Couder Y (2008) Wave propelled ratchets and drifting rafts. Europhys Lett 82(4):44001

Eddi A, Decelle A, Fort E, Couder Y (2009) Archimedean lattices in the bound states of wave interacting particles. Europhys Lett 87(5):56002

Faraday M (1831) On the forms and states assumed by fluids in contact with vibrating elastic surfaces. Philos Trans R Soc London 121(319):1831

Moisy F, Rabaud M, Salsac K (2009) A synthetic Schlieren method for the measurement of the topography of a liquid interface. Exp Fluids 46(6):1021–1036

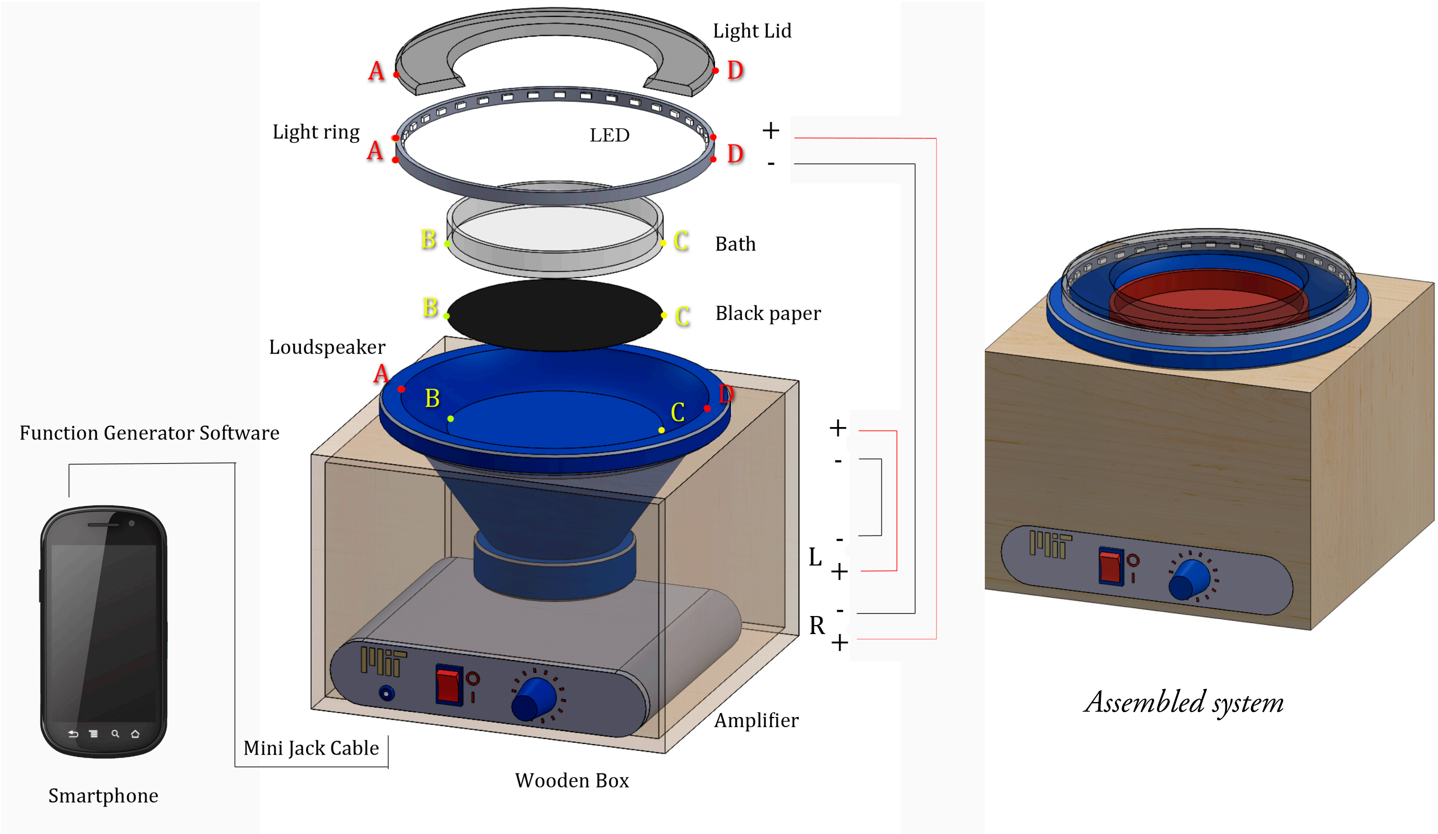
Protiere S, Bohn S, Couder Y (2008) Exotic orbits of two interacting wave sources. Phys Rev E 78(3):036204

Terwagne D, Bush JWM (2011) Tibetan singing bowls. Nonlinearity 24(8):R51–R66

Walker J (1978) Drops of liquid can be made to float on the liquid. Sci Am 238:151–158

Supplementary Information

We here present the design of a low-cost bouncing-droplet demonstration device suitable for exploratory and educational purposes. It consists of seven main components: a loudspeaker, an audio amplifier, an LED strip, two petri dishes, 20cSt silicon oil and a signal generator in the form of a smartphone or computer.



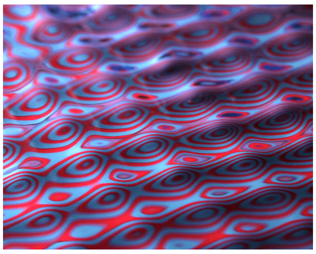
Assembly Procedure

1. *Vibrating Bath* : Paste a black sheet of paper to the base of the 6.5" diameter petri dish in order to optimize visualization. Glue the petri dish to the cone of the loudspeaker, being sure to level the system. (Connect B and C)
2. *Light ring* : Cut off the base of the Petri dish and glue the LED strip to the remaining plastic ring's inner surface. Add an optional light lid (made of cardboard) to optimize visualization. (Connect A and D)
3. *Power* : Using DC wires, connect the two electrical pins of the loudspeaker to the Left channel of the amplifier. Connect the two pins of the LED strip to the Right channel of the amplifier.
4. *Fill the bath* : Pour 20cSt silicon oil into the inner Petri dish, creating a fluid layer of approximately 3mm depth. *Optional*: a substitute for silicon oil is *Linseed oil,* easily found in stores.
5. *Signal generator* : Connect the smartphone or computer with the mini-Jack cable. Start and configure the Function Generator App. Click on OUT so the system starts emitting, and adjust the smartphone volume to the maximum. Configure Channel 1 to Left and Channel 2 to Right. The correct parameters are:

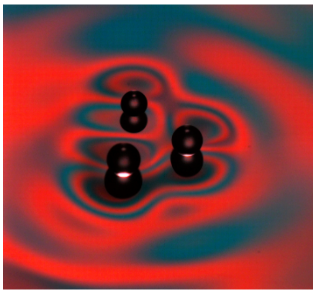
Channel	Left	Right
Wave type	Sine	Square
Duty	-	20%
Amplitude	15%	100%
Frequency for 20 cSt Silicon oil / Linseed oil	80 Hz / 60Hz	40 Hz / 30Hz

   Turn on the amplifier and slowly increase the Bass up to 75% of the maximum. Turn the Volume on. The system should start making a low noise. Increase the Volume to initiate the vibration. Faraday waves should arise at high volume. The system is now ready to operate.
6. *Mounting (Optional)* : Affix amplifier and loudspeaker in a box.

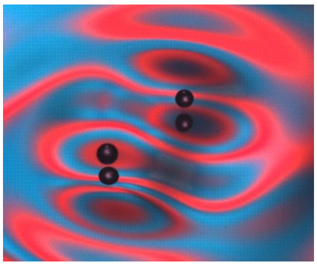
Some experiments



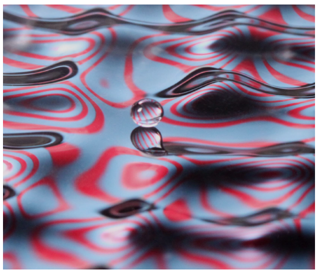
1. *Faraday waves:*
   Play with the Volume and the Bass in order to find the Faraday threshold, above which waves are excited.



2. *Bouncing droplets:*
   a. Increase the Volume and the Bass but stay well below the Faraday threshold. (The surface of the water should remain planar in the absence of drops).
   b. Use a toothpick or needle to create drops by dipping it into the bath and then extracting it swiftly.
   c. The bouncing drop should appear to be stationary if you synchronize the LED lights and the loudspeaker. Altering the phase of the LED lights will change the apparent height of the drop. To see the bouncing, detune the LED lights to 41Hz.
   d. Create several droplets and observe their interactions.



3. *Walking droplets:*
   a. Create a small bouncing droplet (~1mm diameter).
   b. Increase the Volume and the Bass until the droplet starts to walk. If you cross the Faraday threshold prior to the onset of walking, try a smaller drop.
   c. Create multiple walkers to observe bound states: orbiting pairs [1], ratcheting pairs [2], the promenade mode [3], crystal lattices [4] etc…
   d. Alter the phase of the LED to see a detuned walker [5].



4. *Breaking the interface:*
   Increase the Volume and the Bass in order to cross the Faraday threshold. Continue until the interface breaks, creating a multitude of droplets. Visualization of the large amplitude waves may be improved by placing a mirror beneath the bath.

[1] Protiere, S., Bohn, S., & Couder, Y. (2008). Exotic orbits of two interacting wave sources. *Physical Review E*, *78*(3), 036204.

[2] Eddi, A., Terwagne, D., Fort, E., & Couder, Y. (2008). Wave propelled ratchets and drifting rafts. *EPL (Europhysics Letters)*, *82*(4), 44001.

[3] Borghesi, C., Moukhtar, J., Labousse, M., Eddi, A., Fort, E., & Couder, Y. (2014). Interaction of two walkers: Wave-mediated energy and force. *Physical Review E*, *90*(6), 063017.

[4] A Eddi, A Decelle, E Fort, and Y Couder. Archimedean lattices in the bound states of wave interacting particles. EPL (Europhysics Letters), 87(5):56002, 2009.

[5] See additional references in: Bush, J. W. M. (2015). Pilot-wave hydrodynamics. *Annual Review of Fluid Mechanics*, *47*, 269-292.

Purchasing Details

Loudspeaker ($21.78) is a commercially available woofer (6.5" diameter, 50 watts, 8Ω impedance, available at Dayton Audio DC160-8): http://www.parts-express.com/dayton-audio-dc160-8-6-1-2-classic-woofer--295-305

Male to Male 3.5mm mini-Jack Cable ($1.59): http://www.amazon.com/niceeshop-3-5mm-Stereo-Audio-Cable/dp/B00HIDEE22/ref=sr_1_26?s=audio-video-accessories&ie=UTF8&qid=1430855605&sr=1-26

Amplifier ($13.95) is a radio booster MP3 stereo (200W max power output at 2Ω impedance - 50W@8Ω): http://www.amazon.com/Hi-Fi-Amplifier-Booster-Stereo-Motorcycle/dp/B00M0XSJX0

Amplifier power supply cable ($7.48): http://www.amazon.com/Replacement-Adapter-Charger-Benq-Monitors/dp/B003Z6ZR5O

LED strips ($13.25) are 5050 SMD LED lights (6600 Lumen, dimmable LED available at NFLS): http://ledlightscompare.com/led-light-strips-led-tape-light-with-18-smdsft-3-chip-smd-led-5050-p-544.html

4" (or 10cm) diameter petri dish ($0.5) for the oil bath: http://www.amazon.com/SEOH-Petri-Dishes-20-pk/dp/B0007656QA

6.5"diameter petri dish ($1) to be used as a frame for the LED lights: http://www.amazon.com/Karter-Scientific-Plastic-150x15mm-Sterile/dp/B005Z4QV4U

2 Channel function generator App /Software (Free) : https://play.google.com/store/apps/details?id=com.keuwl.functiongenerator

Smartphone/ Computer to be used as a 2 channel function generator using the above app to drive the loudspeaker through the amplifier.

Silicon oil (20ctS): http://www.sigmaaldrich.com/catalog/product/aldrich/378348?lang=en&region=US

Linseed oil : http://www.amazon.com/SUNNYSIDE-CORPORATION-87232-1-Quart-Linseed/dp/B000C016PG/

DC wires for applications in electronics.

Glue (e.g. McMaster Acrylics glue).

Black paper.

Total Cost: ~$60