

Drops on architected elastic substrates: A repertoire of regimes at the turn of a knob

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Drops on a vibrating substrate can experience a variety of motion regimes, including directional motion and climbing. The key ingredient to elicit these regimes is simultaneously activating the in-plane and out-of-plane degrees of freedom of the substrate with the proper phase difference. This is typically achieved by imposing a prescribed rigid-body motion of the entire substrate. However, this framework is unable to establish different motion conditions in different regions of the substrate, thus lacking the precious spatial selectivity necessary to elicit complex drop control patterns. Challenging this paradigm, we leverage the inherent elasticity of the substrate to provide the required in-plane and out-of-plane modal characteristics and spatial diversity. To this end, we design architected substrates exhibiting a rich landscape of deformation modes, and we exploit their multimodal response to switch between drop motion regimes and select desired spatial patterns, using the excitation frequency as our tuning parameter.

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I. INTRODUCTION

The ability to control confined amounts of liquids has applications in microfluidics [1–4], coating and printing processes [5,6], particle suspension [7], electric generators [8,9], and biological processes [10–13]. Of particular interest is the problem of controlling the movement of sessile drops placed on a surface. Here, to promote drop motion, one must overcome the pinning forces [comprehensively described by contact angle hysteresis (CAH)] generated by physical or chemical interactions with the surface [14–17]. Drop motion can be controlled through a variety of strategies, including surface chemical treatment [18–20] or structural modifications [21–23], and mechanical vibrations of the substrates [7,14,24–34].

In the context of vibration-induced drop control, achieving *net* drop motion requires breaking the problem symmetry, which is accomplished by overcoming CAH in a predominant biased direction over each excitation cycle. Canonically, drops are moved under vibration by rigidly translating the entire substrate [14,27–29,32]. This is attained by simultaneously controlling the in-plane (IP) and out-of-plane (OOP) degrees of freedom of the plate, either by prescribing an excitation along a given direction or by using independent, dedicated actuators for the IP and OOP components [28]. Previous studies [28,35] have demonstrated that the relative amplitude and phase between IP and OOP dictate the direction of motion for a given droplet volume. A major drawback of working with

rigid substrates is a lack of spatial tuning and local control: since every point on the plate experiences the same kinematics, drops deposited on different regions inevitably experience the same motion conditions. Our goal is to inject an additional *spatial selectivity* into the substrate, thus promoting its ability to subject different subsets of drops to different motion regimes, according to a variety of spatial patterns.

One avenue to achieve spatial selectivity is to work with *elastic* substrates, where a spatial diversity of the mechanical response stems naturally from the internal deformability that is inherent to all elastic media. An additional diversity of deformation profiles is encoded in the spectrum of mode shapes that elastic structures can experience even under a single, fixed source of excitation. This consideration inspires the development of a parsimonious experimental framework that relies exclusively on the elastic response of the substrates to achieve all the desired drop motion control patterns without unnecessary proliferation of actuation sources. The potential of elastic substrates for spatially selective control was initially explored in [36] using thin metaplates as vibrating substrates. However, while this approach was successful at programming depinning and the onset of sliding, other useful regimes, such as net motion on a horizontal surface [14,28] or climbing [29], remained unattainable. To realize these conditions, a substrate must experience appreciable IP deformation. Unfortunately, classical plates are significantly stiffer IP than OOP, making their IP response negligible. To fully unleash the potential of elastic substrates, it is imperative to design special substrates that display comparable IP and OOP compliance. In this paper, we present a strategy to achieve this goal.

II. DROP MOTION CONTROL ON SINGLE-CELL FLEXIBLE SUBSTRATE

The inspiration comes from the design philosophy of elastic metamaterials, whose archetypal architecture often

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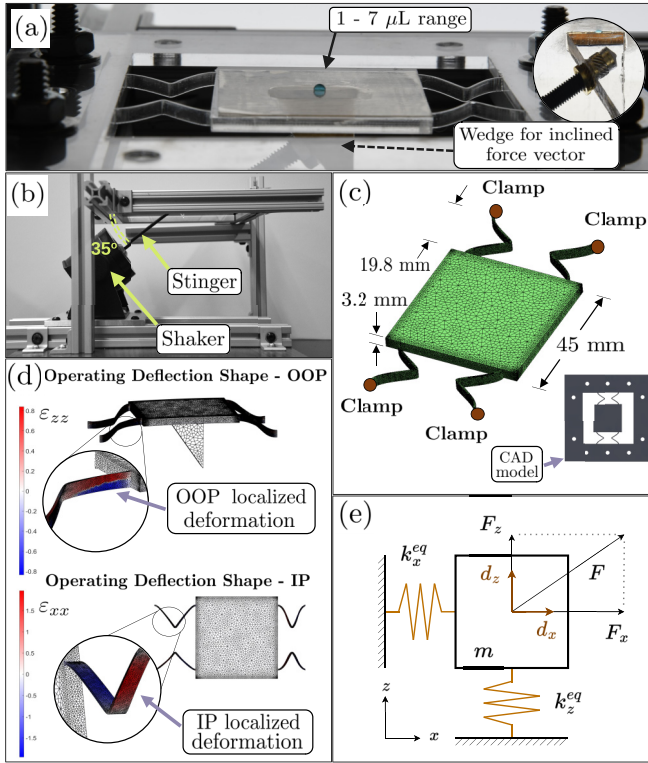


FIG. 1. (a) Single-cell prototype, with inclined excitation prescribed through an actuation wedge. (b) Experimental setup showing the support frame and shaker. (c) Meshed model used in finite element (FE) simulations. (d) Operating deflection shapes for OOP and IP motion, providing evidence of deformation localizing at the ligaments. (e) Equivalent lumped-parameter single-body system with mass m and equivalent springs. The system is excited by harmonic force F and undergoes IP d_x and OOP d_z displacements.

consists of a discrete network of masses joined by structural objects that serve as elastic connections. Accordingly, we envision our substrate as a discrete set of one or more plates (referred to as *cells*), which can be considered locally rigid, supported by structural ligaments designed to localize the deformation and maximize the global IP compliance. Following this idea, we assemble the prototype shown in Fig. 1(a), made by laser cutting a thin acrylic sheet (Young's modulus $E = 3.1$ GPa, Poisson ratio $\nu = 0.35$, thickness 3.2 mm), and the setup depicted in Fig. 1(b). The cell is a 45 mm $\times$ 45 mm plate connected to a fixed frame by doubly curved thin ligaments. An acrylic wedge is attached to the bottom surface to exert a force at a prescribed angle (here 35° from the horizontal) via the stinger of a shaker (Brüel & Kjær Type 4810 Mini). Given the contrast in stiffness between plate and ligaments, we can assume that the deformability is concentrated in the ligaments and the plate undergoes rigid-body motion. This assumption is validated via finite element (FE) simulations [mesh shown in Fig. 1(c)], which confirm that the IP and OOP response is indeed localized in the ligaments [see Fig. 1(d)]. Accordingly, the ligaments can be functionally interpreted as a pair of equivalent springs (one for IP, one for OOP) and the system can be conceptually reduced to the lumped-parameter single-body model in Fig. 1(e), featuring two displacement degrees of freedom (IP d_x and OOP d_z). This reduced-order descrip-

tion emphasizes the mechanistic role played by the prototype parts and would qualitatively capture the low-frequency dynamics of the substrate in our excitation band of interest, e.g., the resonance modes in Fig. 1(d). Nevertheless, for additional quantitative accuracy and generality, we will use the FE model for all calculations in the remainder of the paper.

Throughout the study, we deposit on the cell surface water drops with volume in the 1–7 μ L range [see Fig. 1(a)]. To make the surface slightly hydrophobic to promote drop motion [14], we apply a low-friction tape with measured equilibrium contact angle $94^\circ \pm 3^\circ$, advancing angle $92^\circ \pm 4^\circ$, and receding angle $73^\circ \pm 3^\circ$. The key physical mechanism behind vibration-assisted droplet motion consists of simultaneously actuating the first (rocking, i.e., lateral) and second (pumping, i.e., out of plane) modes of the drop [28] (see the detailed description in the Appendix), whose respective resonant frequencies can be computed using the semianalytical sessile drop eigenfrequency criteria provided in [27,31,37,38]. For our drop volume interval of interest, we estimate the following resonant frequency ranges: 38–92 Hz for rocking mode and 76–184 Hz for pumping mode [see Fig. 1 in the Supplemental Material (SM) [39]]. In our experiments, we carefully target the interval between these two modes, which ensures that drops in our prescribed volume range will be in their ideal frequency range for controlled motion. To this end, we deliberately design the structural features of the substrate to yield a rich and well-defined modal response in this interval, as we will substantiate below.

We characterize the dynamics of the cell in Fig. 1 using finite element simulations under a harmonic point excitation mimicking the stinger inclination. This was done by prescribing a sine function [$\sin(2\pi ft)$] to the center node of the mesh. The two curves in Fig. 2(a) show the spectral amplitudes A_x (IP) and A_z (OOP), computed at the central node of the mesh, as a function of frequency f . We observe two distinct natural frequencies, one at ≈ 90 Hz, associated with IP motion, and the other at ≈ 135 Hz, associated with OOP, which subdivide the domain into three frequency intervals. We corroborate this trend experimentally with a few laser-vibrometer measurements (insets denoted by laser head icons) that by and large confirm the ratios between IP and OOP displacements predicted by FE simulations at the sampled frequencies. Here we expect that, for each degree of freedom, every resonance peak induces an abrupt shift by π in the phase between the displacement and the force that causes it. Indeed, in Fig. 2(b) the phase components φ_x (IP) and φ_z (OOP) jump at their respective resonance frequencies, again marking the three characteristic frequency regimes mentioned above. Note that a small amount of viscoelastic damping is introduced in the FE model, which smoothens the jumps in the phase curve. The insets in Fig. 2(b) show laser-acquired plate velocity time histories at three representative frequencies (selected within our three regions of interest), which experimentally confirm the expected phase switches.

The quantities plotted in Fig. 2(b) are phase differences between each displacement component (d_x or d_z) and their corresponding force component (F_x or F_z). Since the force is prescribed by a single actuator, F_x and F_z are naturally in phase with respect to each other. In light of this, we can define a relative phase metric $\Delta\varphi \triangleq |\varphi_x| - |\varphi_z|$, plotted in Fig. 2(c), to

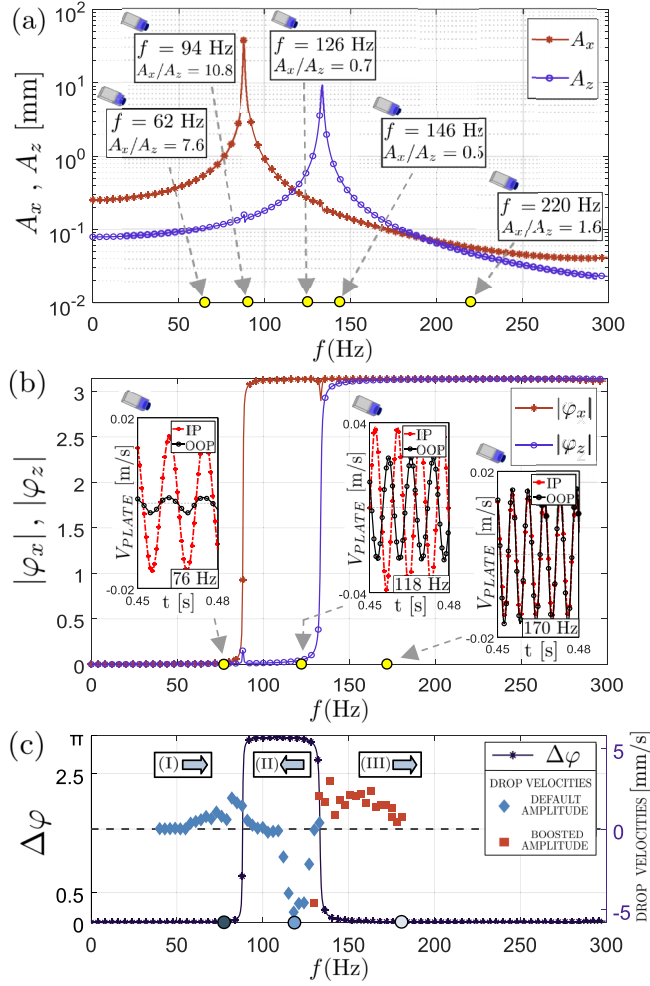


FIG. 2. (a) FE-computed spectral amplitudes A_x and A_z for d_x and d_z displacements, respectively. The laser head icons denote laser vibrometer readings at sampled frequencies. (b) Displacement-force phases $|\varphi_x|$ and $|\varphi_z|$, featuring jumps at natural frequencies. The insets show substrate velocity time histories acquired from laser measurements, confirming phase switches at resonances and antiresonances. (c) Relative phase metric $\Delta\varphi = ||\varphi_x| - |\varphi_z||$ responsible for selection of drop motion direction, plotted vs f and experimentally measured drop velocities [mm/s] at sampled frequencies. (d) High-speed camera captures of drop motion at frequencies 76, 112, and 180 Hz confirming predictions of drop directions.

capture, with a single curve, the effective difference in phase between the displacement components d_x and d_z . Since it has been shown that the key ingredient to control (and possibly invert) the direction of drop motion on a horizontal surface is precisely the ability to control the phase between IP and OOP displacements, a simple inspection of the frequency regions emerging in the $\Delta\varphi$ curve is sufficient to predict all attainable motion regimes. Specifically, we appreciate that regions I (low frequencies) and III (high frequencies), where $\Delta\varphi \approx 0$, feature in-phase motion between IP and OOP displacements; in contrast, in region II between resonances (mid frequencies), where $\Delta\varphi \approx \pi$, we achieve opposition of phase. Accordingly, in Fig. 2(c), the boxed arrows indicate the three drop motion directions [right (R), left (L), and again right (R)] predicted for the three phase regimes, respectively. Let us emphasize

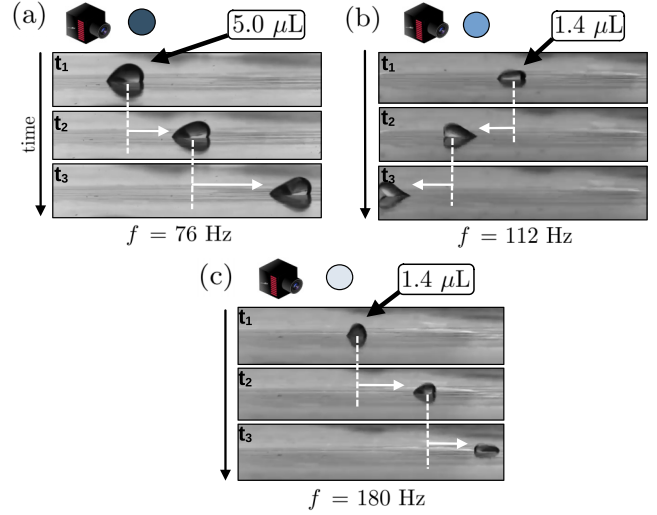


FIG. 3. High-speed camera captures of drop motion at frequencies (a) 76, (b) 112, and (c) 180 Hz confirming predictions of drop directions. Color-coded labels represent the frequencies denoted by the small circles in Fig. 2(c).

an important departure from the canonical paradigm involving a perfectly rigid substrate and distinct actuators for IP and OOP (see, for instance, the benchmark results in [28]), where inversion of the direction of drop motion is obtained by controlling the relative phase of the two actuators. Here, we achieve the same result with a single actuator, by only changing the frequency and relying on the inherent structural dynamics of the cells to provide the necessary amplitude and phase conditions.

In Fig. 3, we substantiate this claim experimentally through three sets of snapshots from high-speed videos for each regime. The cases correspond to frequencies 76, 112, and 180 Hz, marked by color-coded dots on the f axis in Fig. 2(c). The snapshots over three time instants document drop motion directions (L or R) consistent with the predictions (Movies 1–3 in the SM). Note that the drop volume is varied across the set, within the above-mentioned range, in order for the drop to be ideally tuned for resonance at each frequency (i.e., featuring an interval between rocking and pumping modes falling across the excitation frequency). While we only show snapshots for one representative frequency per region, we do measure drop velocities for a host of other frequencies. We superimpose the measured drop velocities on the $\Delta\varphi$ curve in Fig. 2(c). The reported velocity values further quantify the observed drop motion scenarios. Note that, in order to ensure that drops receive enough input energy as the IP response naturally decreases at high frequencies, we have to increase the amplitude of the excitation prescribed to the system (labeled “boosted amplitude” in the legend) above ≈ 140 Hz (details in Table 1 in the SM).

III. DROP MOTION CONTROL ON MULTICELL FLEXIBLE SUBSTRATE

So far, we have shown that we can select the direction for drop motion on a single vibrating substrate by using the excitation frequency as the tuning parameter. The next

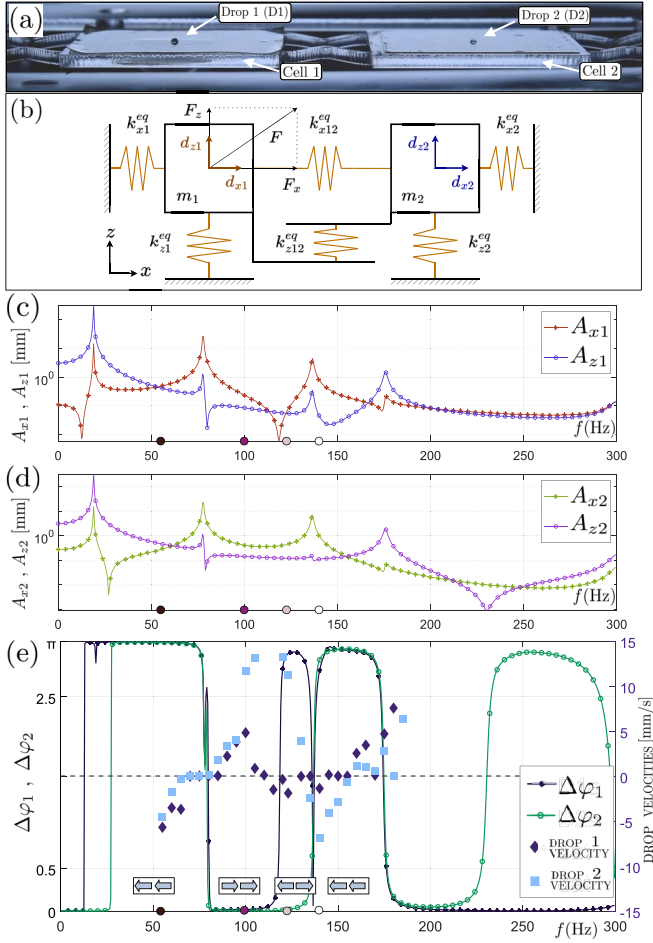


FIG. 4. (a) Two-cell prototype. (b) Equivalent lumped-parameter model. A harmonic force is applied to cell 1. (c), (d) Spectral amplitudes A_{x1} (IP) and A_{z1} (OOP) for cell 1 and A_{x2} (IP) and A_{z2} (OOP) for cell 2, from FE. (e) Relative phases $\Delta\phi_1$ and $\Delta\phi_2$ determining the R vs L motion of their respective drops. Drop velocities experimentally acquired at sampled frequencies are overlaid to the plot, showing good correlation with the $\Delta\phi$ curves.

natural question is does this capability hold for more complex structures? If so, what additional drop motion regimes can be elicited? One way to add geometric complexity is by adding masses (and degrees of freedom) to the vibrating system. To this end, we design the two-cell prototype shown in Fig. 4(a) by doubling the cells and connecting them through intercell ligaments identical to the external ones. The goal is to activate the motion of both cells through a single excitation applied to cell 1, relying exclusively on the elasticity of the system to transfer the excitation to cell 2. This augmented system can be interpreted as the two-body lumped-parameter model shown in Fig. 4(b), featuring 4 degrees of freedom, one IP, and one OOP per cell. To characterize the system, we can extend the analysis for the single cell. The results in Figs. 4(c) and 4(d) show the spectral amplitudes for cells 1 and 2, respectively. The phase is reported in Fig. 4(e) where, for each cell $i = 1, 2$, the $\Delta\phi_i$ curve captures the phase between IP and OOP components. By treating $\Delta\phi_i$ as a predictor of the direction of drop motion on the i cell, we deduce that we can achieve up to four possible scenarios in the 50–175 Hz interval: (i) both drops

move left (LL), (ii) both move right (RR), (iii) the drops move away from each other (LR or divergent pattern), and (iv) the drops move towards each other (RL or convergent pattern).

In Fig. 5, we show experimental results for three drop motion scenarios. We monitor the drop velocity time histories captured at selected frequencies falling in four characteristic frequency intervals (indicated by the color-coded dots). Here, we also adjust the drop size for each frequency interval (details in Table 2 in the SM). The snapshots document the establishment of the regimes expected in these intervals based on the vibration regimes of the substrates calculated above: LL, RR, LR, and again LL (Movies 4–7 in the SM). These results by and large confirm that we can establish a multitude of drop motion scenarios with a single actuator, relying on frequency selection as our tuning parameter. This said, many factors contribute to how easily we can trigger the predicted regimes, and some scenarios are especially challenging to obtain. For example, we can see that the low OOP amplitude A_{z1} predicted by FE simulations between 100 and 150 Hz penalizes drop 1 movement in this range. This is confirmed by the low experimental drop velocities measured in this region. We also report a discrepancy between the $\Delta\phi$ curves and the trend of the measured drop velocities above 150 Hz. This suggests some mismatch between model and prototype, with the former predicting a resonance at ≈ 175 Hz and the drops indicating one at ≈ 160 Hz. For completeness, in the SM we present an alternative prototype design that also realizes the fourth scenario (RL), not achieved in the system of Fig. 4.

IV. FREQUENCY-TUNED SIZE-SELECTIVE DROP PATTERN FORMATIONS

The fact that drop motion depends on both frequency and drop size allows us to create a variety of logic scenarios even operating with a single cell. Here we discuss two of them. For this task, we need to introduce some structural modifications to the first prototype: (i) we increase the cell size to grant the drops more space to move, and (ii) to lower the frequency spectrum, we add weights to the cell [Fig. 6(a); details in the SM]. The first scenario realizes a *size-selective drop filter* [Fig. 6(b)]. Four 1.5- μL and two 10- μL drops are deposited at the same axial coordinate. As the cell is vibrated (116 Hz), the two sets of drops move in opposite directions, segregating from each other (Movie 8 in the SM). This follows from the fact that drops of different sizes have different internal resonance dynamics [14,30,35,40] and thus respond differently to the same excitation frequency. Here, the smaller drops move right, since they respond in their first resonance range. At the same frequency, larger drops experience a higher mode, and it has been shown that, when this occurs, the dependence of the directionality upon the substrate phase is inverted [14,30]. This case exemplifies how drop motion depends on a complex interplay between the resonant dynamics of both the substrate and the drop. The second system is a *coalescence, growth, and path inversion* device [Fig. 6(c)]. Here, a heterogeneous array of drops is placed along a line. All drops, but the rightmost one, are small. At 116 Hz, the small drops move to the right, colliding, merging, and growing in volume. Eventually, the volume of the aggregate drop exceeds the threshold above

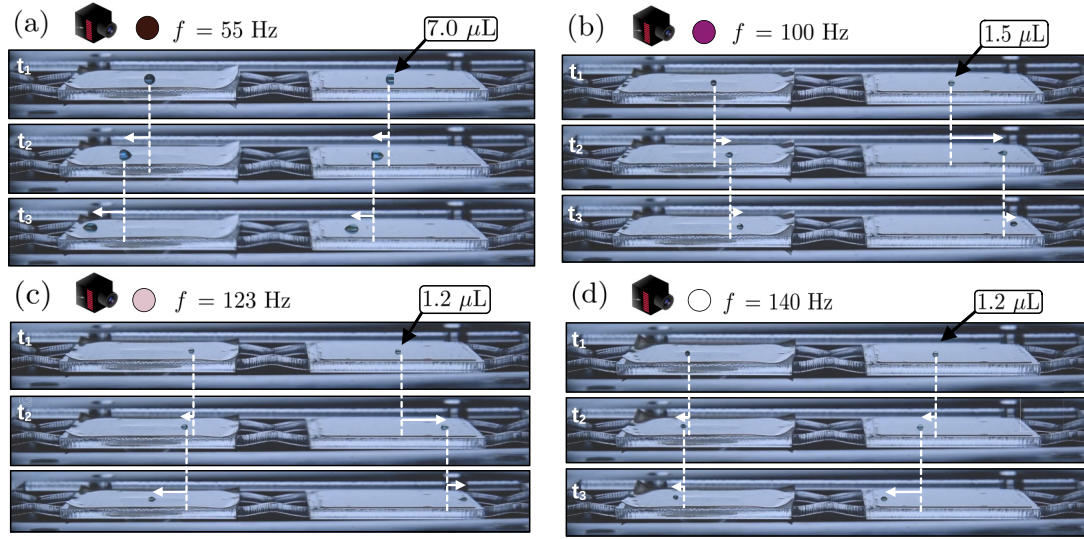


FIG. 5. High-speed camera snapshots revealing activation of LL, RR, LR (divergent), and again LL drop motion at (a) 55, (b) 95, (c) 123, and (d) 140 Hz. Color-coded labels represent the frequencies denoted by the small circles in Fig. 4(e).

which the directionality switches, and the drop starts moving to the left (Movie 9 in the SM).

V. CONCLUSION

Ultimately, the two-cell prototype represents a first step toward a powerful generalization, where a prototype of n

cells (effectively a *metachain*) could generate, in principle, up to 2^n combinations of relative drop motions. In this case, the problem can be described in terms of dispersion, and the appearance of band gaps in the spectrum can potentially be leveraged to suppress drop motion at selected locations. In addition, we have shown that even a single-cell substrate has significant potential for drop control in scenarios involving multiple drops activated simultaneously or sequentially. Extending this idea to problems involving large and heterogeneous families of drops promises to further enhance the pattern formation and control capabilities described in Fig. 6(b). Future efforts will assess the practical feasibility of these concepts.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX: MECHANISM OF NET DROPLET MOTION

There are two conditions that need to be met for a partially wetting droplet to achieve net motion under periodic vibrations: (i) depinning of the contact line (CL) by overcoming the contact angle hysteresis and (ii) breaking spatial symmetry over the period of vibration. The CL depinning is enabled by a sufficiently large amplitude of vibration, while symmetry breaking is achieved via simultaneous actuation of the first (rocking) and second (pumping) modes of the drop [28]. If the pumping mode is actuated by the OOP motion of the plate (with the phase difference $\Delta\phi$) while the droplet is rocking

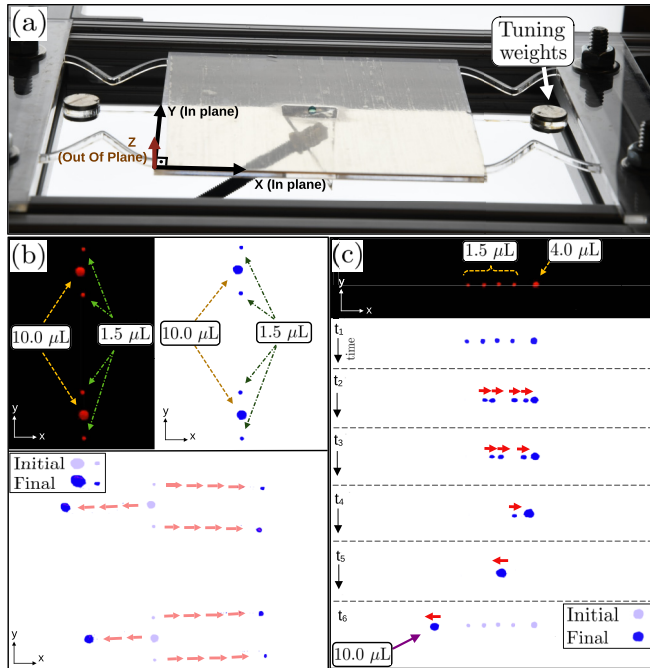


FIG. 6. (a) Experiment with a modified single-cell prototype. Tuning weights added to the cell in detail. (b) Size-selective filter achieving drop segregation by size. Dark picture shows the original acquisition with fluorescent drops; light images are postprocessed for enhanced visual clarity. Movement is shown by red arrows. (c) Coalescence, growth, and path inversion device, featuring drop motion inversion due to variable size triggered by controlled coalescence of a train of drops.

laterally via the IP motion, the droplet deformations as the droplet rocks to the right will differ from those as it rocks back to the left, due to the imposition of the OOP motion. This asymmetry in the droplet deformations can generate a net force on the droplet, which cannot be otherwise achieved

with the actuation of individual modes separately. As the resonance frequencies depend on the droplet volume, the resultant droplet motion (i.e., speed, direction) depends nonlinearly on the droplet volume, as well as $\Delta\phi$ and the amplitudes of the plate motion.

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