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Harmonic resonance of acoustically levitated two-phase droplets

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***Abstract* — A droplet of a mixture of immiscible water and oil is levitated in a standing acoustic wave and is set into resonance. The in-situ recording of the resonating droplet allows one to determine the mode number (or number of equatorial lobes) at characteristic frequencies which depends on the fluid viscosity, surface tension, and droplet size. Since the mixture is immiscible, the surface wave is distinctly different from the pure liquid, and the resonance frequency falls in between the values of pure components.**

Keywords* — *droplet, acoustically levitated, harmonic resonance

I. INTRODUCTION

A standing acoustic wave is set up between two identical and symmetric hemispherical dishes with arrays of sonic transducers installed, generating alternating high antinodes and low-pressure nodes along the axis [1-5]. A pipette delivers a droplet to a low-pressure node at the center with its weight supported by the high-pressure antinode below. A modulated frequency is superimposed on the driving acoustics and is scanned over a range. At a threshold frequency, the levitated droplet resonates depending on the fundamental fluid properties such as viscosity, surface tension, and size. Droplets of low viscosity liquids (e.g. water) oscillate in the equatorial plane only. The integral number of lobes observed is referred to as the mode number hereafter. The higher the mode number, the higher the modulated frequency. Droplets of high-viscosity liquids (e.g. oil, glycerol) exhibit out-of-plane bending resonance resembling that of a circular solid plate.

This paper explores the resonance behavior of immiscible two-phase droplets comprised of water and vegetable oil with a range of volume ratios. Their distinct behavior will be compared using the levitation setup.

II. EXPERIMENTS

A. Equipment and setup

Figure 1 shows the experimental setup. The acoustic levitator with a 3-D printed base is equipped with the accessories of sonic transducers and control using an Arduino nano and a signal generator to generate the standing acoustic wave along the loading axis. Two high-speed cameras equipped with macro lenses monitor the top and side views of the levitated droplet, and a pipette delivers the droplet with precise control of volume. Illumination with high intensity white is installed to raise the optical contrast.

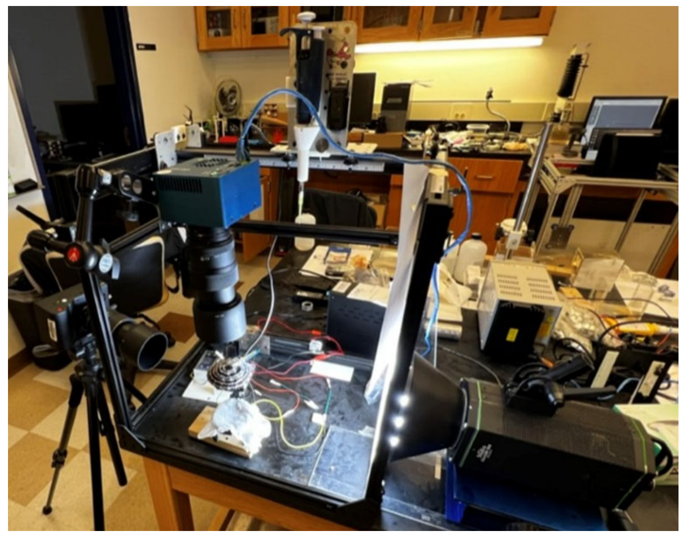

Figure 1. Experimental setup

B. Baseline behavior of fluid components

To establish the baseline behavior of pure liquid, 0.08 mL droplets of water and oil are characterized for their resonance modes and frequencies, as shown in Figure 2. Water droplet exhibits equatorial resonance with distinct lobes for each resonance frequency f. The standard deviation is in the range of Δf = 10-20 Hz. No out-of-plane bending mode is observed.

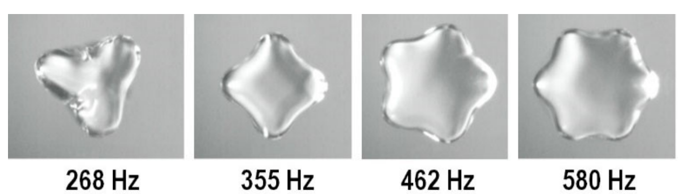

Figure 2 Top view of a 0.08mL water droplet in resonance modes 3-6 and the characteristic frequencies.

Figure 3 shows the resonance of oil droplets. The oil droplet exhibits planar oscillations of bending and reverting to a spherical shape. However, no oscillation modes were observed for frequencies beyond 180 Hz. At higher f, the oil droplet stays quiescent. No equatorial mode is observed, though Δf is significantly wider than that of pure water. Note that f_{water} and f_{oil} do not overlap in their distinct resonance frequencies.

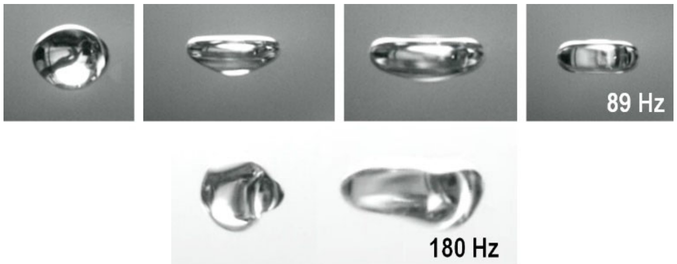

Figure 3 Side view of 0.08mL pure oil droplet at resonance.

C. *Creating the two-phase droplet*

The two-phase droplets are prepared by placing set proportions of water and vegetable oil into a conical centrifuge tube. The mixture is shaken vigorously to facilitate emulsification. The emulsified fluid is immediately dropped into the acoustic levitator, though phase segregation occurs almost instantly. The levitated droplet is left for roughly one minute to allow sufficient separation. Three mixtures are made for testing, namely, 25% water, 50% water, and 75% water, with oil as the complementary component. Each droplet in the test has the same volume of 0.08 mL. Figure shows an example of each two-phase droplet. For the 75% and 50% droplets, the oil does not float to the top but is pushed to the side, whereas the 25% droplet has water being encapsulated by oil.

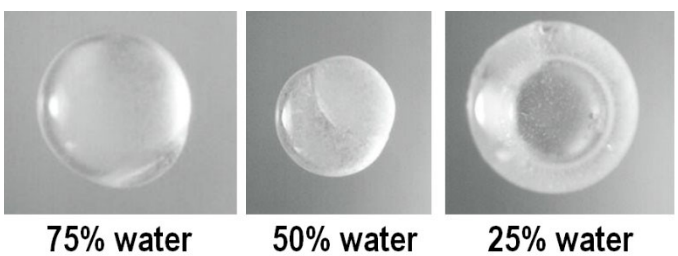

Figure 4 Top view of 0.08 mL two-phase droplets of water + oil mixture.

D. *Oscillation behavior of two-phase droplets*

Figure 5 shows the 75% droplet, showing mixed out-of-plane bending and equatorial resonance, i.e. behaviors of both of its constituent phases. Equatorial modes are observed up to mode 5. In general, f augments for the same mode, except $n = 3$ when f stays unchanged. No higher resonance mode beyond $n = 5$ at 510Hz is observed. At 268 Hz, the side view shows the same kind of triangular oscillation in a planar-bending fashion, which is a new phenomenon not reported in the literature. The 75% droplet also exhibits similar bending oscillation modes at 146 Hz to that of pure oil at 180 Hz, though the droplet fails to stay levitated below 100 Hz after many trials. It is worthwhile to mention that the 75% droplet, when undergoing equatorial oscillations, pushes the oil component to the side and exhibits blurred borders than pure water (c.f. Figure 1).

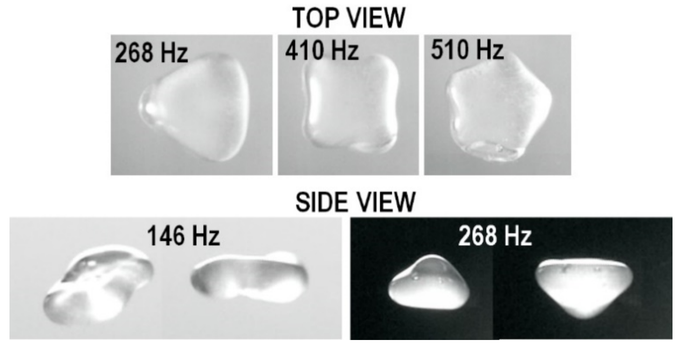

Figure 5. Resonance of a 0.08mL droplets of 75% water + 25% oil mixture

Figure 6 shows a 50% droplet exhibiting stable equatorial oscillation at 328 Hz in mode 3. Its silhouette has less defined edges and less pronounced lobes than that of pure water (c.f. Figure 2). No higher modes can be reached. It should be noted that the vibration mode may have been reached prior to the two liquids sufficiently separating from one another due to the lack of a clearly defined water-oil interface. Resonance is observed at 123 Hz, which is below the frequency spectrum of pure water, though the oscillations are highly unstable and do not follow patterns outlined in Figure 2. One mode of bending resonance is observed at 85 Hz through beyond 200 Hz, and the behavior matches that found for pure oil at that frequency (c.f. Figure 3). The water component pushed to the side has a different geometry than the oil droplet. It appears that at least in this situation, the main component of oil is influenced at 85 Hz while the water component lags behind.

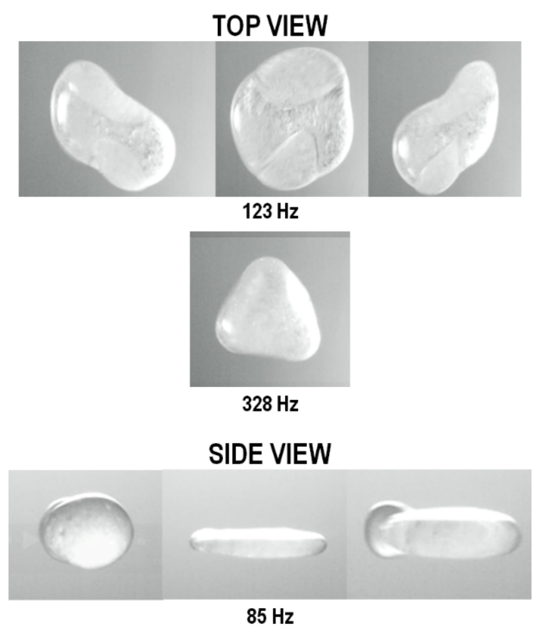

Figure 6 Oscillation modes from both viewing angles of 50% water, 50% oil droplet, 0.08 mL

Figures 7-8 show the behavior of a 25 % droplet. Figure 8 shows bending similar to pure oil with the water component being pushed to the side whereas the oil component shows independent behavior (c.f. Figure 3). The water component shows a slightly different geometry than the oil. Similar to the 50% droplet, only one oscillation mode is observed with a large Δf. The equatorial oscillations, however, exhibit uniquely different behavior. Figure 7 shows the water component being encapsulated by oil. The two-phase droplet still exhibits planar oscillations with events observed up to 429 Hz. However, instead of pronounced lobes, the water component contracts and expands. The largest difference between the minimum and maximum inner ring size is observed at 164 Hz, a frequency that is out of range for water droplets, and the smallest difference is found at 429 Hz. No bending mode is observed for the frequencies where the equatorial oscillations were found.

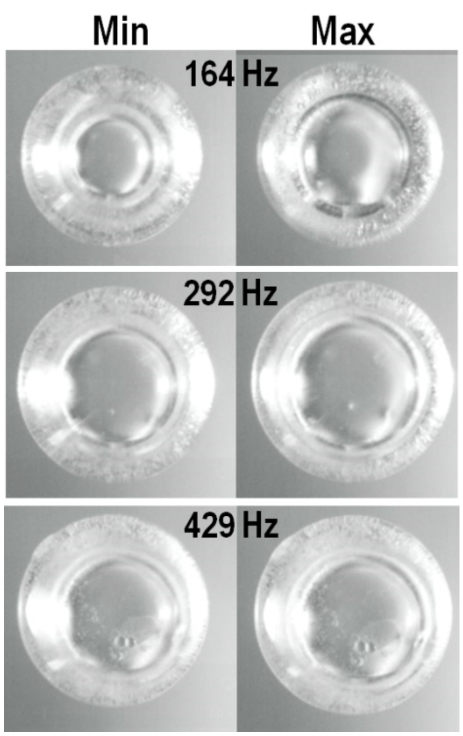

Figure 7. Top view of a 0.08mL resonating droplets of 25% water + 75% oil

III. Conclusion

A two-phase immiscible droplet exhibits resonating behavior from both components and both components act relatively independently from each other in terms of oscillation. In most cases, when one component enters its corresponding oscillation mode, the other gets pushed aside. The viscous forces between the droplets likely cause the component that is typically not affected by the oscillation to react. The composition level likely influences the likelihood for one component to lead while the other lags. It is quite evident that all two-phase droplets exhibit at least one form of oscillatory behavior from each component.

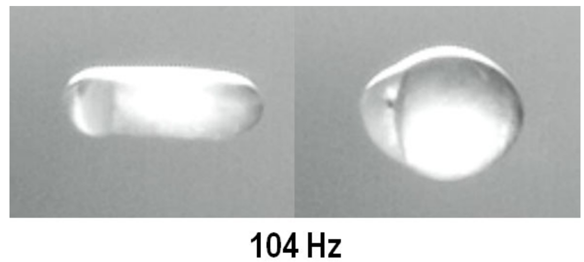

Figure 8. Side view of a 0.08mL resonating droplets of 25% water + 75% oil

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