Investigation of Ultrasonically Levitated Droplets for Sonochemistry with High-Speed Camera Observations

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***Abstract*— Ultrasonic levitation is a non-contact method of manipulating samples in mid-air that has drawn significant interest in the fields of biochemistry and pharmaceutical science. In these fields, the stability of levitated droplets is crucial for effective applications. This study aims to investigate the droplet levitation while focusing on their oscillation dynamics and levitation stability using an ultrasonic levitator with multiple nodes. A high-speed camera was used to observe the behavior of the droplets, and the results showed that the number and position of levitating droplets are critical factors affecting the stability of the levitation. By exploring the high-speed camera observations, we seek to understand the dynamic interactions between ultrasonic waves and these levitated droplets, which could induce oscillation and can be used for sonochemistry.**

Keywords*— *Ultrasonic levitation, airborne ultrasound, droplet manipulation, sonochemistry

I. INTRODUCTION

The manipulation and precise control of matter at millimeter and micrometer scales have witnessed significant advancements in recent years. Several researchers developed ultrasonic/acoustic levitation methods working in air **[1-7]** and ultrasonic/acoustic tweezers for particle manipulation in fluids or in human body **[8-15]**. These studies have demonstrated several use cases in handling and analysis of particles for biomedical, chemistry, and pharmaceutical industries, such as multi-functional droplet manipulation **[16]**, detection of viral RNSs **[17]** and morphological and thermal analysis of multiple droplets **[18]**. Among these applications, this study focuses on the potential uses of ultrasonic levitators for sonochemistry, where it can provide a tool to conduct reactions in isolation without a container or stirrer. The non-contact characteristic of ultrasonic levitation minimizes pollution, enables zero-waste chemistry and reduces the risk of damage to delicate materials, including biological specimens and fragile particles.

Tinylev system is one of the most affordable and compact ultrasonic levitation designs used by many researchers **[1-3]**. The system used in this work is based on the Tinylev architecture and it can achieve non-contact manipulation of liquid droplets by utilizing the pressure exerted by opposing ultrasonic waves. The suspension and non-contact manipulation of droplet in mid-air are achieved by generating standing waves that create pressure nodes and anti-nodes resulting in an acoustic radiation force that can levitate tiny particles, droplets, or even small organisms. Although this concept is demonstrated by countless researchers, the stability of ultrasonic levitation is mostly overlooked, where only several studies investigated the dynamics and stability of levitated objects **[2, 19-21]**.

The phenomenon of oscillation-induced instability occurs when a levitated object experiences small perturbations that increase its amplitude exponentially **[2]**. This unstable state of acoustic levitation is caused by the convergence of acoustic radiation forces acting as a spring and the surrounding air generating a drag force, resulting in a damped oscillation that pulls the particle toward its equilibrium position. There is no oscillation when the object is displaced from its equilibrium point, so there is no instability in the levitation. There are, however, some cases in which the perturbations are large enough to cause the object to oscillate with an increasing amplitude until it is ejected from the levitated trap. Motivated by this instability phenomenon, this study performs a set of high-speed camera observations to evaluate the stability of ultrasonic levitation.

II. METHODS

To conduct the experiments, an ultrasonic levitator was built by placing 72 Multicomp transducers (Premier Farnell Ltd, UK) operating at 40 kHz on two opposing domes that are 10 cm apart, following the design in **[1]**.

Fig. 1. Experimental setup.

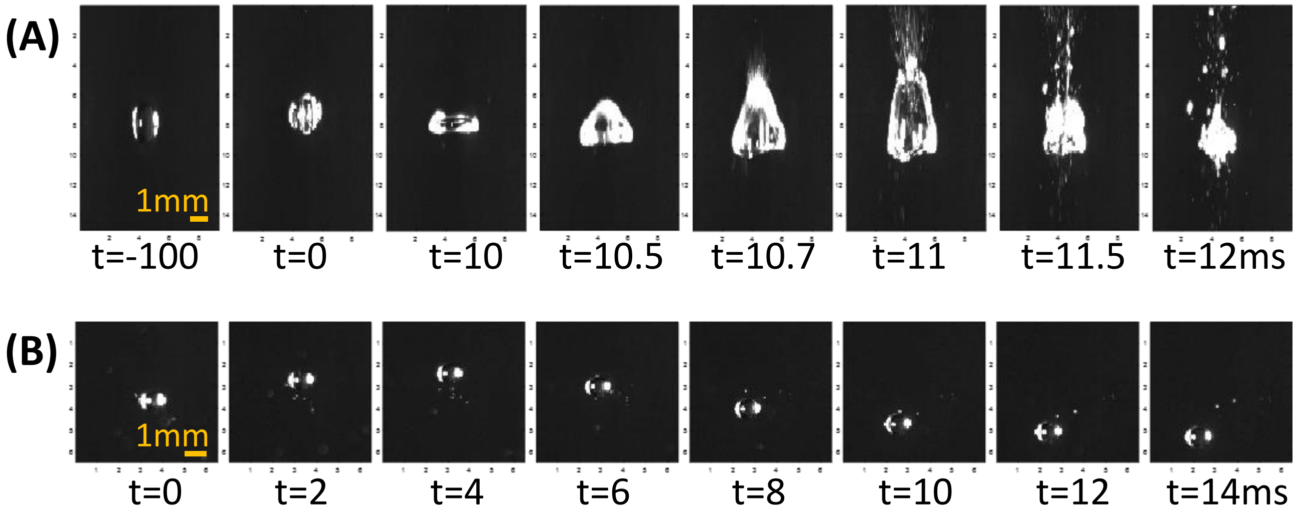

Fig. 2. High-speed camera images of the trapped water droplets recorded at 10,000 fps. (A) Exploding droplet (8.8 mm3) due to high trapping force. Voltage is increased from 12 Volts to 18 Volts at t=0. (B) Vibrating droplet (5.3 mm^3) due to unstable trapping.

This ultrasonic levitator generates standing waves with multiple zero-displacement points, known as nodes, which can trap solids and liquids. The behavior of levitated water droplets was observed using a Fastcam Mini AX50 camera (Photron Ltd, Japan) at 10,000 fps, and several droplets were trapped in mid-air at 24°C. The video was analyzed in Matlab to determine the size of droplets with respect to a calibration measurement done with a caliper. Fig. 1 shows the ultrasonic trapping setup with varying voltage levels between 9-20 Volts, which corresponds to trapping densities of 0.75-3 g/cm^3 at the Rayleigh regime.

III. RESULTS & DISCUSSION

The setup begins with positioning the ultrasonic levitator, The power supply is then connected to the levitator, and the initial voltage is set to 12 Volts. A camera is positioned to capture the droplet and the power supply values simultaneously. A caliper is also placed in the camera's field of view to determine the droplet's size. The water is dyed with a contrasting color to make it easier for the camera to identify the droplet. The power supply is then gradually increased, and the camera records the behavior of the droplet at each voltage level. As the voltage increases, the droplet begins to expand, and if the voltage is raised too high, the droplet explodes due to the force exerted by the ultrasonic waves. On the other hand, if the voltage is decreased, the droplet becomes unstable and may be ejected from the levitator.

Our observations are consistent with **[1]**, where the minimum voltage level required to trap water droplets effectively is 11 Volts, which is generated an acoustic radiation force of 110±50 mN. Increasing the voltage would narrow the trapping zone, eventually causing the water droplet to explode above 16 to 18 Volts, as shown in Fig. 2(A) for the tested droplet size range of 5-10 mm^3. Fig. 2(B) footage revealed that a 5.3 mm^3 droplet underwent axial oscillations at 20 Volts, where the stable region is shown in Fig. 3.

By recording the droplet's behavior at different voltage levels, the experiment can determine the voltage range within which the droplet remains stable. This data can then calculate the critical voltage level beyond which the droplet becomes unstable or explodes. These oscillations generate mechanical vibrations that can improve mixing within droplets, leading to enhanced reaction efficiency and selectivity, reduced reaction times, and potentially improved product quality. Ultrasonic waves can also be used to induce sonochemical effects to promote reactions that are otherwise difficult to achieve under normal conditions.

IV. CONCLUSIONS

Oscillation-induced instability can disrupt measurements, compromising experiments and sample integrity. Therefore, comprehending conditions for stable levitation or vertical oscillations in acoustic levitation systems is crucial. Initial work by Rudnick and Barmatz **[22]** theorised that object impact on resonance frequency and phase difference with driving frequency leads to damping factors influencing instability. For frequencies above resonance, an additional detrimental damping term drives exponential amplitude increase. Experimental studies validated this theory, revealing that stability depends on transducer distances. Closer transducer-opposite pairs yield stability, with higher resonance frequencies and favorable damping. However, increased distances can trigger instability, especially with higher driving frequencies.

In summary, oscillation-induced instability is an essential issue in acoustic levitation. It is necessary to understand the conditions that lead to stable levitation or vertical oscillations to avoid damaging the levitated object or losing valuable samples. Further investigations aimed at optimizing levitation conditions

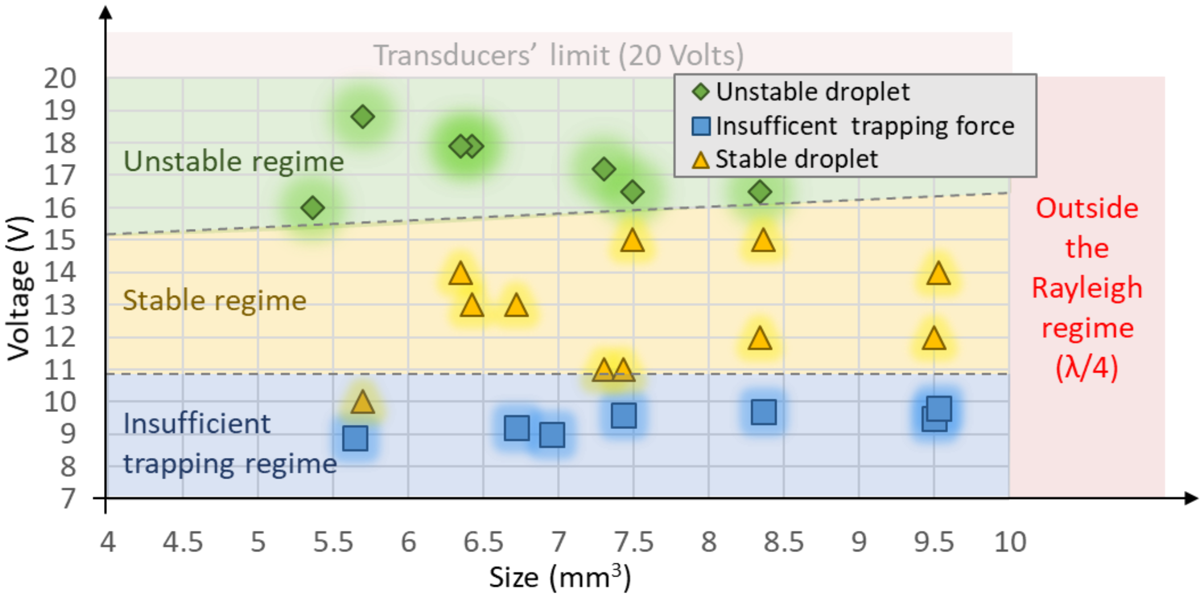

Fig. 3. Result of the high-speed camera observations of the trapped water droplets recorded at 10,000 fps by increasing or decreasing the voltage levels to determine the stable regimes. Droplet trapping regimes (*i.e.*, stable, unstable and insufficient trapping) are shown based on 25 different droplet measurements.

and comprehending the fundamental principles of oscillation-induced instability.

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