Conference of the Japan Society of Microgravity Application

PS17

音響場で浮遊する泡沫の浮遊安定性

Stability of levitated foam in acoustic field

大西一希 [1]，長谷川浩司 [2]
Kazuki ONISHI[1], Koji HASEGAWA[2]
[1] 工学院大学大学院，Graduate School of Kogakuin University #1
[2] 工学院大学，Kougakuin University #2

1. Introduction

In recent years, non-contact fluid manipulation technologies without using containers have been attracting great attention in various fields, including materials science, analytical chemistry, biology and medicine, and combustion science[1,2]. One of the promising technology used in this study is the acoustic levitation method. The acoustic levitation method utilizes ultrasound to levitate samples regardless the properties of the levitated sample[3]. However, due to the principle of ultrasound-induced levitation, the levitated samples exhibit nonlinear and complex behaviors, such as interfacial instability (interfacial deformation and atomization) and internal/external acoustic streaming[4]. In particular, the interfacial behavior plays a vital role in the levitation stability of the samples. While theoretical and numerical insights have been developed for linear regions in acoustics, to gain the insightful experimental understanding of the nonlinear and dynamic phenomena is the key to succeed the stable sample levitation. Although many researchers investigated on the levitated droplet and bubble in acoustic levitation, to the best of our knowledge, the levitated foam hasn't been studied yet. Therefore, this study aims to identify the interfacial stability of foams (sodium dodecyl sulfate (SDS) aqueous solution) levitated in an acoustic field.

2. Experimental setup

Figure 1 shows a schematic diagram of the experimental apparatus used in this study. The experimental procedure involves generating a sine wave signal with a function generator, which is then amplified by an amplifier and fed into an ultrasonic transducer. The sound waves emitted from the tip of the lower horn, connected to the ultrasonic transducer, are reflected by a reflector positioned at a predetermined distance. This reflection forms an acoustic standing wave between the horn and the reflector. The foam was introduced near the pressure nodes of the acoustic standing wave using a syringe for the levitation. The dynamic motion of the foam was captured using a high-speed camera with a backlight method, and the resulting images were processed on a computer.

Furthermore, the pressure gradient and changes in the pressure distribution caused by an increase in acoustic pressure within the test section of the experimental apparatus have a significant impact on the dynamic behavior of the levitated sample. Therefore, measuring the acoustic pressure and understanding its distribution within the test section are considered critical parameters when analyzing the dynamic behavior of levitated droplets. To achieve this, a probe microphone was mounted on a traverse device and moved in 1 mm increments. The acoustic pressure at each measurement point was recorded based on the waveform displayed on the oscilloscope. Since the oscilloscope displays voltage waveforms, it is necessary to convert the voltage values to acoustic pressure. The oscilloscope was calibrated so that a waveform of 1.0 mV corresponds to 1.0 Pa. Additionally, the measurement region assumed axial symmetry of the acoustic standing wave, with the horn center set as the origin (0), and measurements were conducted only on the right half of the horn.

The acoustic radiation force of the acoustic field enables the sample to be levitated by counteracting the gravitational force exerted on the sample. The levitation characteristics vary significantly depending on the competition between the acoustic field and the properties of the levitated fluid, such as surface tension. For insufficient acoustic pressure, the sample cannot be levitated, while excessive acoustic pressure may lead to atomization due to the inability to maintain the interfacial shape.

Table 1 lists the experimental conditions used in this study. A reflector with a curvature radius of 36 mm (R36) was used to enhance the levitation stability of the sample in acoustic field. The frequency of input sound wave was approximately 19.3 kHz, resulting in a wavelength of the sound wave λ of approximately 17.9 mm. The applied voltage was 750 mV. The levitated sample used was foam (sodium dodecyl sulfate (SDS) aqueous solution). A 0.5% aqueous solution was prepared by mixing SDS with purified water, and air was injected into the solution using a commercial hand soap dispenser.

In the acoustic levitation method, droplets levitated in the sound field become flattened and take on an elliptical shape due to the relationship between acoustic radiation pressure and gravity. Therefore, in this study, the equivalent diameter used for the foam is based on the volume-equivalent diameter, assuming the shape of a spheroid. The volume-equivalent diameter can be calculated using the following equation.

$$d = \sqrt[3]{ab^2} \tag{1}$$

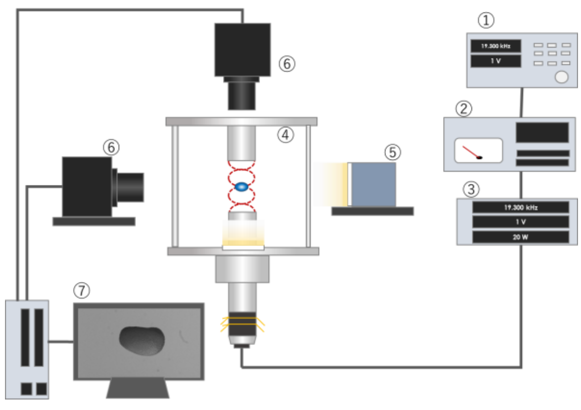


Figure 1. Schematic diagram of the experimental apparatus: 1.function generator, 2. power amplifier, 3. power meter, 4. acoustic levitator, 5. LED light, 6. high-speed video camera, and 7. PC

Table 1. Experimental conditions

Reflector type	Input frequency *f* [kHz]	Input voltage [V]	Wave length of input frequency λ [mm]	Temperature [℃]	Humidity [%]	Test sample	Equivalent diameter *d* [mm]
R36, R∞	19.3	0.2	17.9	25±2	50±10	Foam,SDS aqueous solution	4.3-7.2

3. Experimental result and discussion

3.1 Levitation stability of foam

Figure 2 shows the levitation range of the foam. In the figure, the horizontal axis represents the dimensionless diameter d, where d is the volume-equivalent diameter of the foam and λ is the wavelength of the acoustic field. The vertical axis represents the sound pressure P in the test section. The blue line and orange triangle plots represent for the stable foam levitation and unstable fell down due to insufficient applied acoustic pressure. To determine the stable levitation conditions for the levitated samples, the acoustic pressure around the foam was gradually reduced from a constant pressure when the foam was stably levitated until the foam was no longer levitated and fell. The dimensionless diameter of the levitated foam was found to be within the range $0.24 < d/\lambda < 0.4$. Regarding the lower limit of levitation sound pressure, it was observed that foam often fell around 0.6 kPa, and the minimum levitation threshold pressure being 0.34 kPa.

To compare with the dimensionless diameter of water, the dimensionless diameter will be calculated based on the levitation conditions of water. Water, with its higher density compared to foam, is considered a representative levitation sample in acoustic levitation methods. The levitation conditions for water include the minimum levitation sound pressure P_{min}[5] as described by King and the maximum levitation sound pressure P_{max}[6] as described by Danilov et al., as shown below.

$$P_{\min} = \sqrt{\frac{1.6\rho_1\rho_0 g c^2}{k}} \tag{2}$$

$$P_{\max} = \sqrt{\frac{6.8\sigma\rho_0 c^2}{d}} \tag{3}$$

The diameter at which the minimum and maximum levitation sound pressures coincide, as derived from these theoretical formulas, represents the theoretical maximum levitation diameter. Upon calculation, the maximum diameter was found to be d=5.5 mm, and the maximum dimensionless diameter was d/λ=0.31. Since a typical water droplet has a dimensionless diameter greater than 0.31, it can be inferred that the diameter of the levitated foam is approximately 1.3 times larger compared to that of the water droplet.

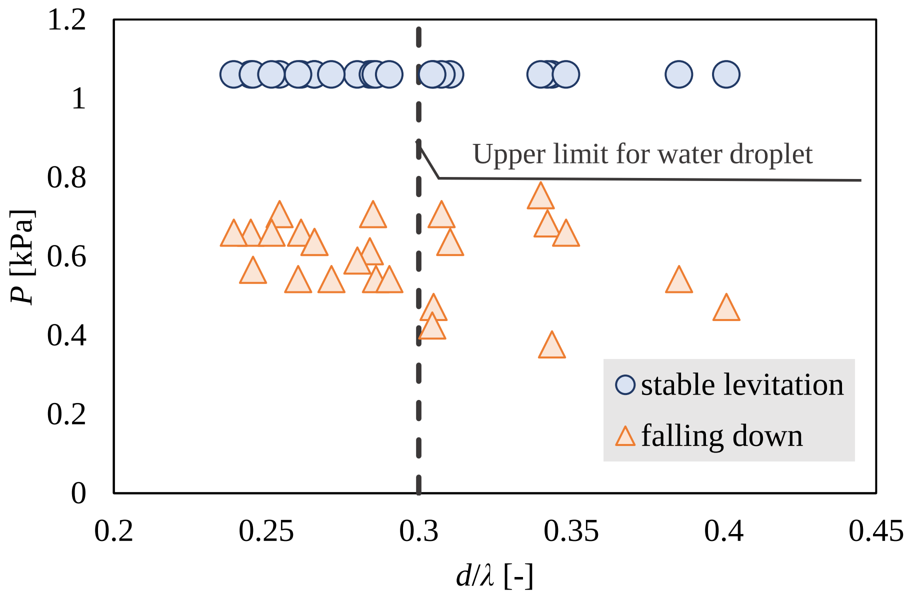
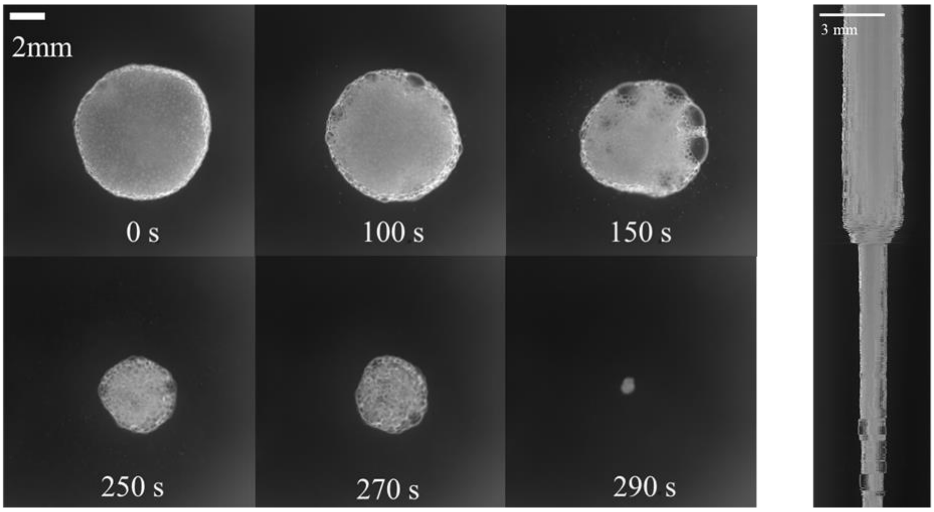


Figure 2. Levitation characteristics for foam in acoustic fields.

3.2 Foam collapse

Figure 3(a) shows the collapse process of foam levitated in an acoustic field. Snapshots was captured from above in **Fig. 3(a)**. The start time of levitation was set to 0 seconds. At 100 seconds, it was observed that the bubbles in the foam had expanded. By 150 seconds, the expanded bubbles began to concentrate radially within the foam. Following this, the foam rapidly decreased in volume due to bubble rupture, and this change became more gradual by 250 seconds. At 270 seconds, expanded bubbles similar to those seen at 100 seconds were observed again. By 290 seconds, a rapid decrease in volume was noted, followed by the foam eventually falling. Foam levitated in an acoustic field undergoes evaporation and drainage over time, causing the liquid film to thin.[7)] This leads to the coalescence of bubbles, resulting in an increase in bubble size. As evaporation and drainage continue, the enlarged bubbles eventually lose their pressure equilibrium in the acoustic field and burst. It is believed that the secondary droplets generated during the burst impact other bubbles, causing a chain reaction of consecutive collapse. **Fig. 3(b)** shows the spatiotemporal diagram of the foam collapse process. The spatiotemporal diagram was reconstructed by extracting the slice image from a specified row in each captured frame and aligning them over time to form a single image. This diagram allows us to observe the interfacial deformation before collapse. Additionally, as time progresses, enlarged bubbles become visible as dark regions at the edges of the bubble radius, where the background light is transmitted through the bubbles.



(a) Snapshots of the levitated foam (b) Time-space diagram

Figure 3. Collapse process of levitated foam in acoustic levitation

The drainage process during the foam collapse can be observed through the reduction in foam volume captured in the recorded images.

Figure 4 shows the results of the temporal change in foam area. The horizontal axis represents the time with the start of foam levitation set as 0 seconds, and the vertical axis represents the dimensionless area obtained by dividing the area S from the images by the initial area S_0. The comparison was made with samples having initial diameters of d=12.08, d =8.38 [mm]. A gradual decrease is observed from 0 to around 100 seconds. A rapid decrease in area begins around 130 seconds. After approximately 230 seconds, the change becomes gradual again, with another rapid decrease observed around 270 seconds. The cause of the rapid decrease in area is attributed to the continuous collapse of bubbles. The bubbles that make up the foam vary in volume, resulting in differences in internal pressure. This pressure difference causes the liquid films to merge. The merged bubbles eventually burst due to external pressure, and the secondary droplets ejected during this rupture can penetrate other bubbles, causing a chain reaction of continuous collapse.

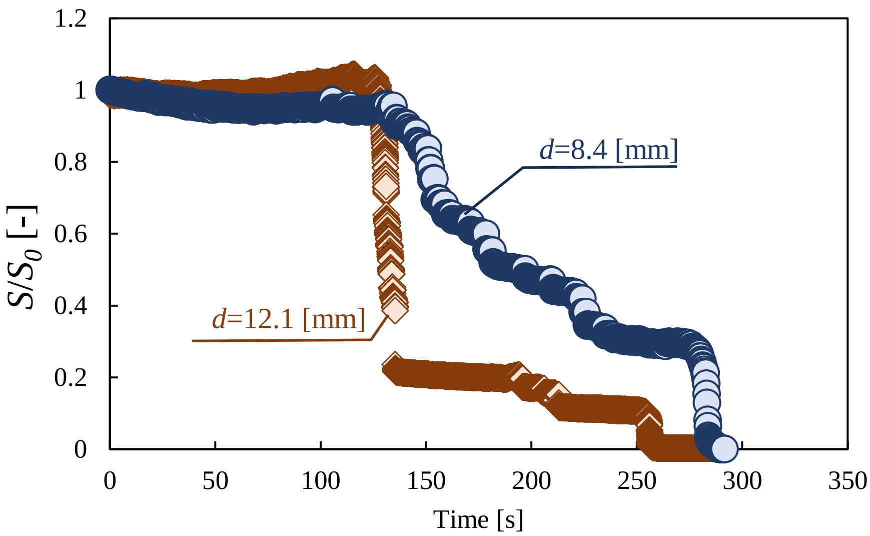


Figure 4. The evolution of foam area

4. Conclusion

In this study, we aimed to understand the interfacial instability phenomena of levitated foam and achieve high-precision stable control. We investigated the levitation conditions of the foam, visualized the collapse process, and measured the area changes during collapse.

The levitation conditions for the foam showed that it remained suspended within the dimensionless diameter range of 0.24< d/λ < 0.4. The visualization of the foam collapse process revealed that, over time, expanded bubbles appeared in parts of the foam. There was a rapid decrease in area at a certain point, and this process repeated several times. The temporal change in the area of the levitated foam indicated a gradual decrease up to around 100 seconds, followed by a rapid decrease starting at approximately 130 seconds. The change became gradual again after 230 seconds, with another rapid decrease observed around 270 seconds. The cause of the rapid area decrease is attributed to the continuous collapse of bubbles.

References

1) Yarin, A. L., Weiss, D. A., Brenn, G., and Rensinl, D.: Acoustically levitated drops: drop oscillation and break up driven by ultrasound modulation, International journal of multiphase flow, Vol. 28, No. 6 (2002), pp. 887 910.
2) Foresti, D., Nabavi, M., Ferrari, A., and Poulikakos, D.: Acoustophoretic contactless transport and handling of matter in air, Proceedings of the National Academy of Sciences, Vol. 11, No. 31 (2013), pp. 12549-12554.
3) Xie, W. J., and Wei, B.: Dependence of acoustic levitation capabilities on geometric parameters, Physical Review E, Vol. 66, (2002), 026605.
4) Aoki, K., and Hasegawa, K.: Acoustically induced breakup of levitated droplets, AIP Advances Vol.10, No. 5 (2020).
5) King, L. V.: On the acoustic radiation pressure on spheres, Proceedings of the Royal Society of London. Series *A-Mathematical and Physical Sciences* 147.861 (1934), pp. 212-240.
6) Danilov, S. D. and Mironov, M. A.: Breakup of a droplet in a high‐intensity sound field, *The Journal of the Acoustical Society of America, Vol.* 92, No. 5 (1992) pp. 2747-2755.
7) Ji, X. et al. "Extraordinary stability of surfactant-free bubbles suspended in ultrasound." *Droplet* 3.2 (2024): e119.