Deformation of water droplet levitated in the acoustic field

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Abstract

A small water droplet can be levitated around the node of the acoustic standing field. The sound pressure acting on the surface of the droplet will deform the water drop, but the surface tension of water will try to keep the water droplet a sphere. As the size of the droplet grows, the deformation will become greater. However, the error of experimental results of deformation as a function of the size compared to theoretical prediction becomes larger. Therefore, we try to improve the equation that also will have a good prediction at the large size of water. Furthermore, when the sound pressure changes periodically, the water droplets will resonate and become star shape. We discuss the resonance frequencies corresponding to different water droplet sizes.

Introduction

We are curious about the levitation phenomenon. We found the common levitations, including magnetic, optical, and acoustic levitation. The magnetic levitation force is relatively large, followed by acoustic levitation. However, acoustic levitation is not limited by the conductivity of the material. Therefore, it can be used to study the containerless solidification of non-metallic materials.

In our first experiment, we try to redo the levitation that causes by acoustic field in standing wave and analyze what happens the deformation will be due to the resistance between surface tension and pressure. We also try to improve the theory to the one with consideration about gravity. In the second experiment, we try to find out the deformation if we change the form of an input signal and analyze its characteristics.

Theory

1. When the water droplets are stationary:

In the acoustic standing wave, if we put a small droplet at the node, the droplet will be exerted by the sound pressure. Since the total pressure changes over time, the total force acting on the droplet will change from downward to upward and from upward to downward. Because of the high frequency of the sound wave, the droplet looks like being fixed in the air. As the two forces clamping the droplets, the droplet will be squeezed into an ellipsoid. Here, gravity doesn't affect the deformation but only the position of the droplet.

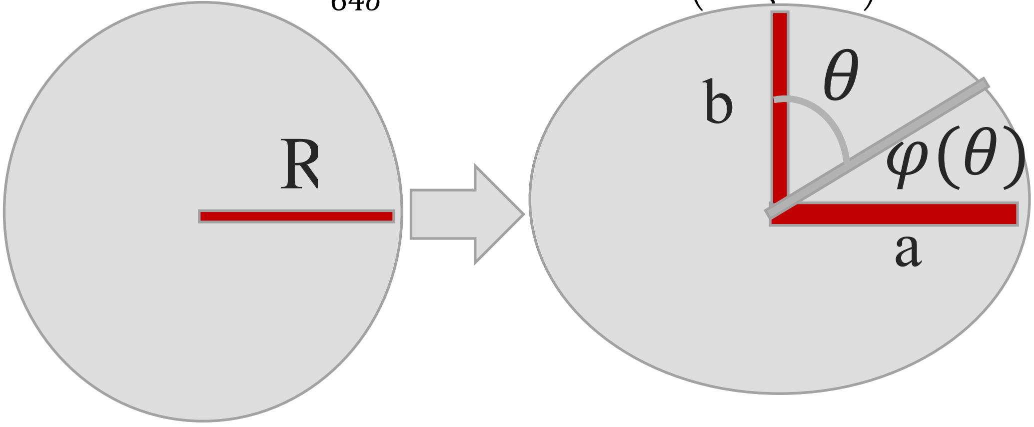
- Deformation of water droplet:

Here, the gravity doesn't affect the deformation but only the position of the droplet. So, the equation ignores the influence of gravity. Consider the droplet is a sphere with radius R initially, and the distance from the center to the edge of the sphere is$\varphi(\theta)$, we have that $\varphi(\theta)$ is equal to radius R plus $x(\theta)$.

$$\varphi(\theta) = R + x(\theta)\,, \qquad \frac{a}{b} = \frac{\varphi\left(\frac{\pi}{2}\right)}{\varphi(0)} = \frac{\mathrm{R} + \mathrm{x}\left(\frac{\pi}{2}\right)}{\mathrm{R} + \mathrm{x}(0)}$$

$$x(\theta) = -\frac{3}{64\sigma}(3\cos^2\theta - 1)R^2 P_s^2 \beta_0\left(1 + \frac{7}{5}(kR)^2\right)$$

[1]



R	**radius of a sphere with the same volume**
σ	**surface tension of water**
P_s	**pressure at the node**
β_0	**compressibility of air**
k	**wave number**

2. When water droplets are subjected to periodic sound pressure:

If the pressure of the sound pressure field changes periodically, the pressure drop may be unstable. This will result in the formation of waves extending radially around the droplet, perpendicular to the direction of the applied field. In the video, the result is shown as an asterisk.

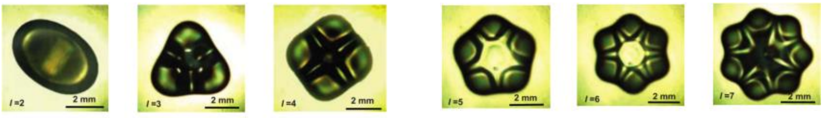
- Dynamic of drop by modulation:

After changing the input voltage into modulation, it will become a star shape deformation, the reference of modulation frequency will be:

$$f_m = \frac{1}{2\pi}\sqrt{\frac{\sigma}{\rho R^3}n(n-1)(n+2)}$$

[3]

R	**radius of a sphere with the same volume**
ρ	**Water density**
σ	**Surface tension of water**
n	**Number of peaks**

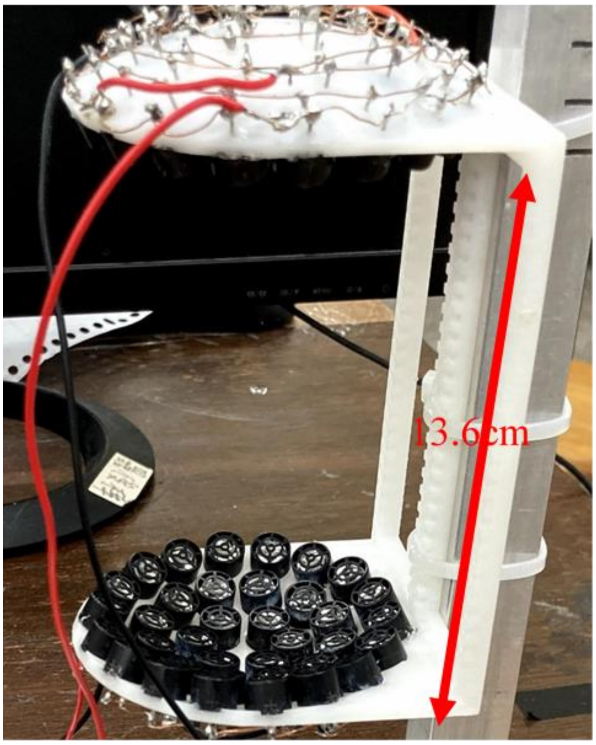


(a) (b) (c) (d) (e) (f)

[3]

Experiment Method

Exp1:



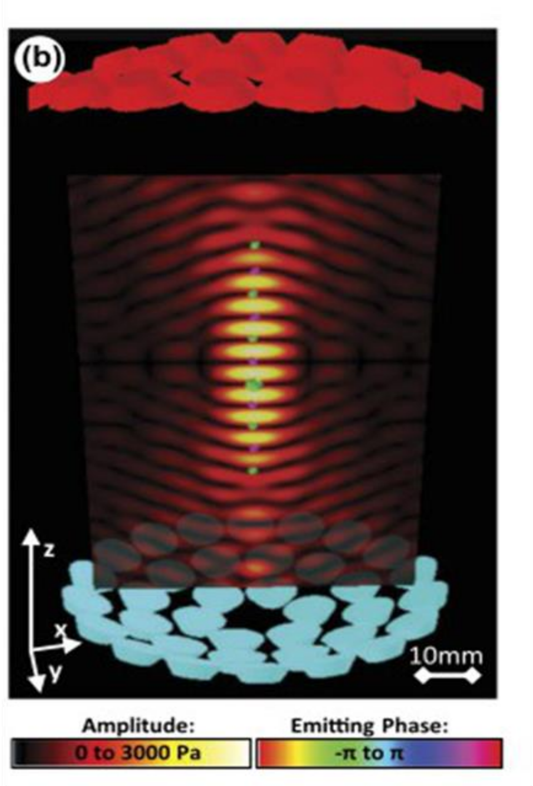


Fig1. There are 36 transmitters above and below each. (b)The distribution of the sound pressure field is simulated and displayed by the program. [2]

The main information of the experimental device comes from [2]. Among them, there are four important points. One is that there are 36 ultrasonic transmitters on the upper and lower sides. The second is that the frequency is 40khz. The third is that the L298N is used as the driver. Say, how much voltage is given to the L298N, it will give the sensor how much voltage, fourth, use the microphone to read the sound pressure.

1. There are 36 ultrasonic transmitters on the upper and lower sides.
2. Frequency of the ultrasonic transmitters: 40kHz
3. Input voltage represents an output sound pressure $\mathrm{P_s}$
   Ex: Input 16V(DC), $\mathrm{P_s}$: about 51000 $dyne/cm$^2
4. Get sound pressure $\mathrm{P_s}$: Using a receiver.

Exp2.

We will change the input signal, 16V(DC)→14~18V, which means a sound pressure (P_s) will change periodically. Because of resonance, a droplet will have a star-shaped deformation phenomenon at certain specific frequencies.

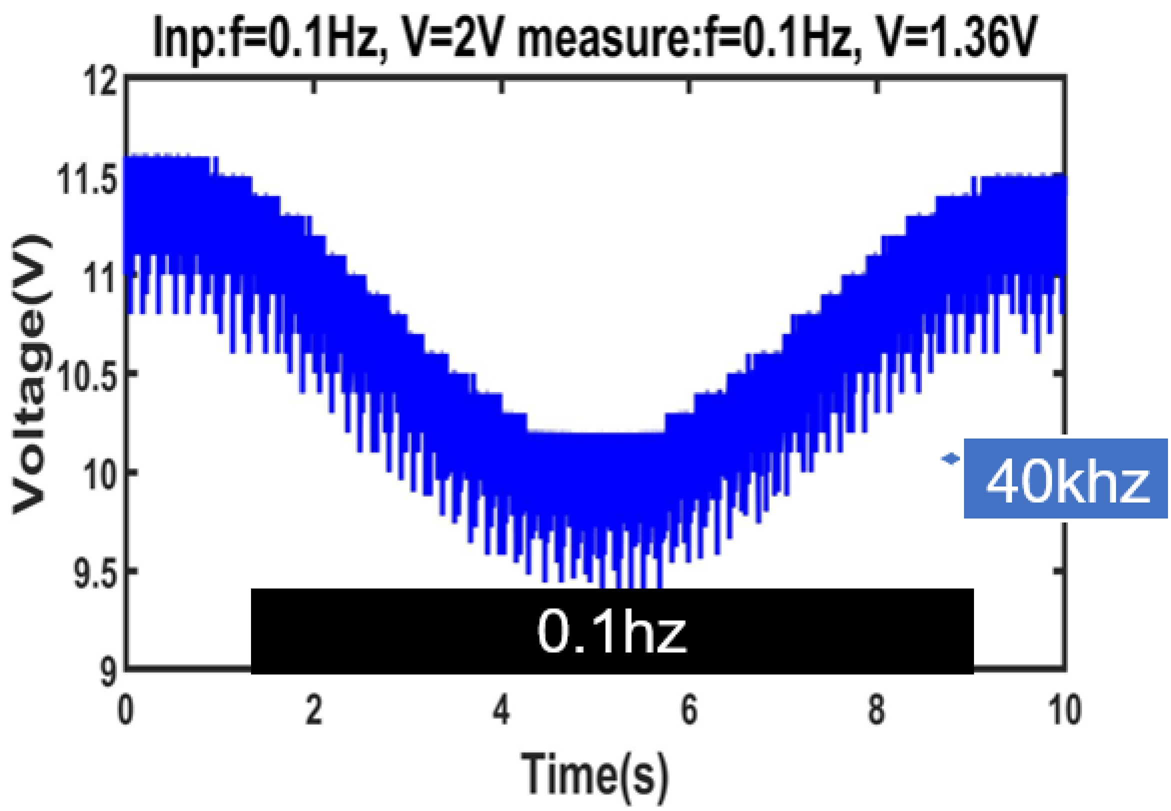


Fig2. Input the sine wave voltage that changes with the period to L298N, so that the sound pressure of the ultrasonic transmitter changes with the period.

Result

Exp1.

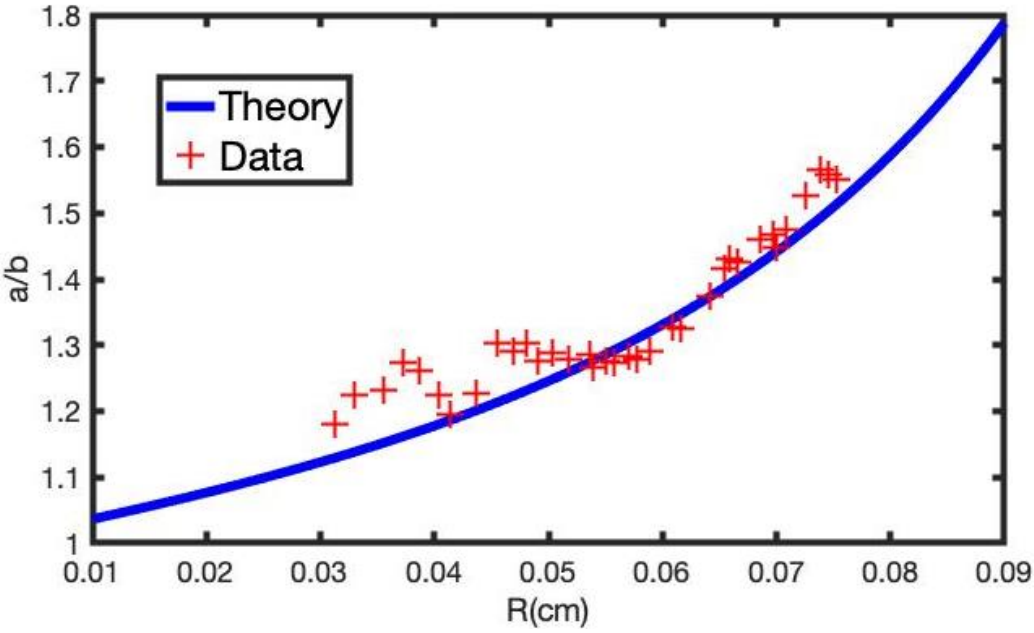


Fig3. The deformation of the smaller water droplets can fit the curve we expect. ($p_s = 51000\ dyne/cm^2$)

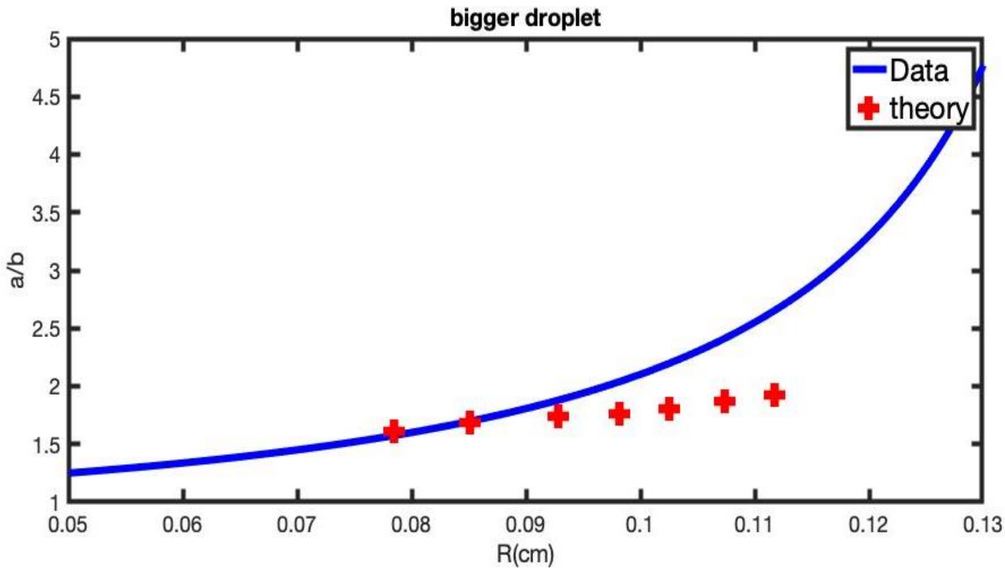


Fig4. The bigger droplet seems to have smaller deformation compared with our expectation. ($p_s = 51000\ dyne/cm^2$)

The deformation of the smaller water droplets can fit the curve we expect. (Fig3.) But for the bigger droplets, the data start not to fit the theoretical curve. (Fig4.) The bigger droplet seems to have smaller deformation compared with our expectation.

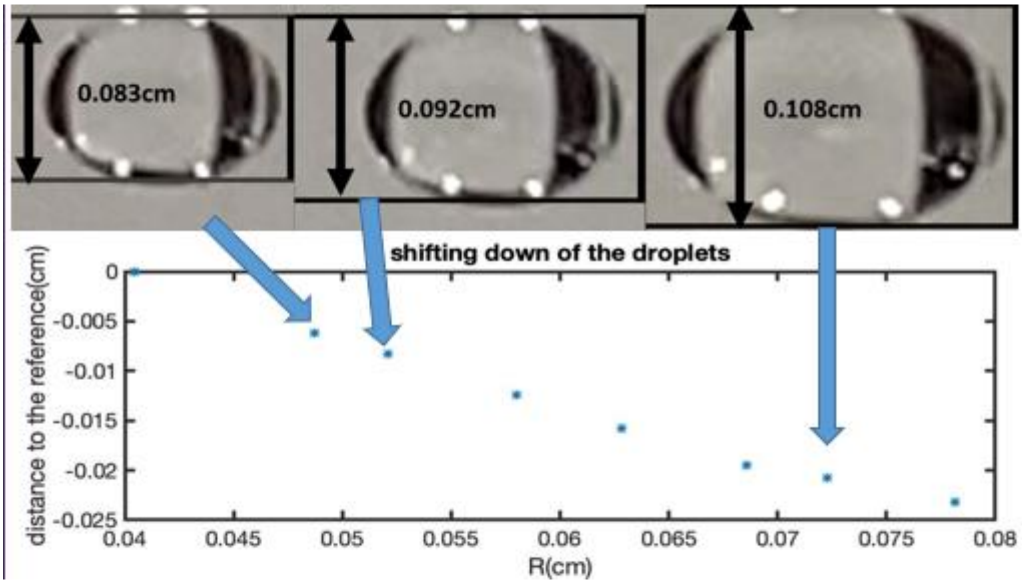


Fig5. We find out that there are shifting down for the bigger droplets.

Since we fix the camera, we find out that there are shifting down for the bigger droplets. (Fig5.) We think the displacement from the node makes the result doesn't fit the equation.

For the bigger droplets, the distance of shifting down can be 0.2 millimeters long. For the bigger droplet, the ratio of the position changing seems to be slower. Since the bigger droplet needs more supporting force to levitate, the force upward is greater than the force downward. Since the deformation of droplets needs two forces with different directions to squeeze, we think that the larger difference between these two forces makes the deformation smaller.

Exp2.

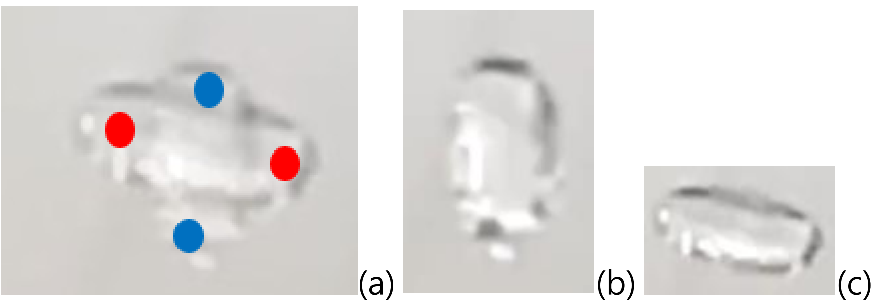


Fig6. Two-peak(n=2), (a) Overlap (b) and (c).

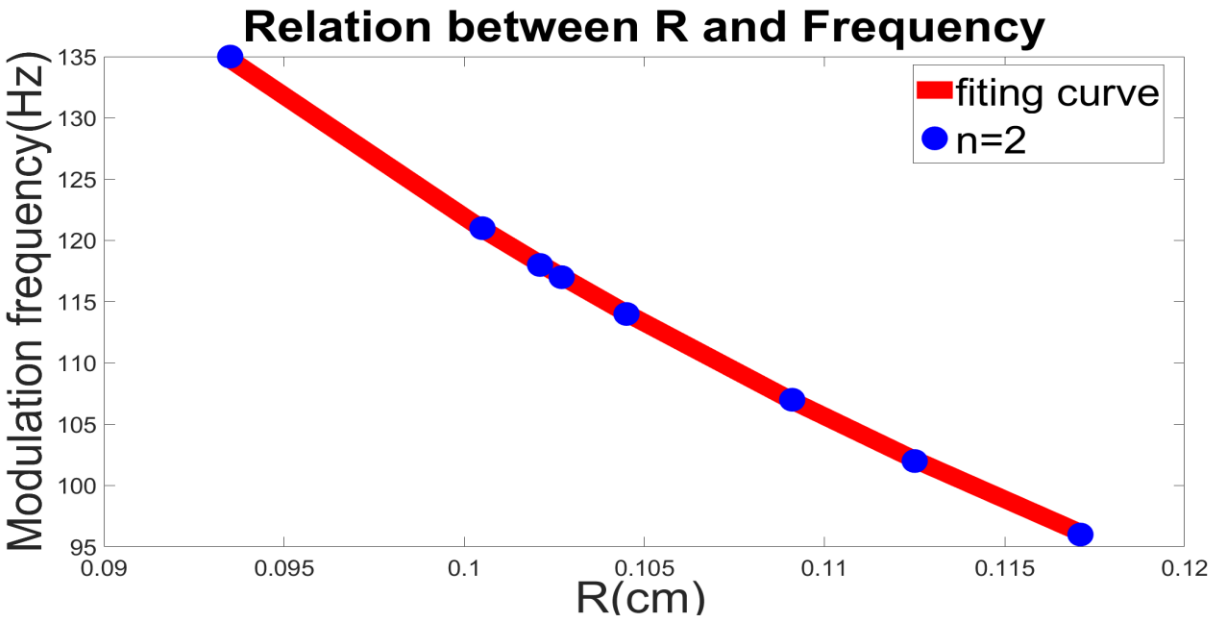


Fig7. The result we find has a good agreement that the radius will influence the frequency. $\sigma = 73.112 \, {}^{dyne}/_{cm} \left(72.75 \, {}^{dyne}/_{cm}\right), \rho = 0.996 \, {}^{g}/_{cm^3} \, (0.997 \, {}^{g}/_{cm^3})$

According to the experimental video (Fig6.), we can see the shape of the water drop when n=2. It shows that the water droplet does resonate at a certain frequency, and as the size of the water droplet becomes larger, the frequency required for resonance becomes smaller (Fig7.). And with a 240fps camera, the process of water droplet deformation can barely be recorded. However, in the experiment, we found that although the larger the water droplet (the larger the R), the lower the required frequency and the easier it is to observe, but when the water droplet becomes larger, it also means that it is easier to fall due to vibration. Therefore, If the voltage in the higher range is not used throughout the experiment, only a small range of water droplets can be observed.

Because according to the data, L298N is used to receive DC voltage. Therefore, during the experiment, it is impossible to know the highest frequency that L298N can withstand. We are afraid that the experimental device will be damaged during the experiment suddenly, so we only discuss the resonance phenomenon of water droplets when n=2.

Conclusion

In Exp.1, we use the equation without considering the impact of gravity. With the equation, we can see the $\frac{a}{b}$ become bigger as the radius R increase. The result shows it meets in the small radius condition but not in the bigger droplets. The error is from the displacement from the node caused by gravity.

In Exp.2, according to the formula and experimental data, it can be found that the larger the radius of the water droplet, the smaller the required resonance frequency. In addition, it has also been shown that more star-shaped angles (n>2) require higher frequencies.

Reference

[1]. Trinh, "Equilibrium shapes of acoustically levitated drops." J. Acoust. Soc. Am. 79.5 (1986)

[2]. Marzo, "TinyLev: A multi-emitter single-axis acoustic levitator." Rev. Sci. Instrum. (2017)

[3]. Shen, "Parametrically excited sectorial oscillation of liquid drops floating in ultrasound." Phys. Rev. E 81.4 (2010)