1. Introduction

In 1866, the German scientist Kundt first reported the experimental phenomenon of acoustic energy suspended dust particles in the resonance tube and a upsurge of acoustic levitation research has emerged. In the 21st century, people focus on the application of acoustic suspension technology. In 2013, Daniele Foresti manipulated the droplets through an acoustic suspension device and achieved cell and DNA Fusion.[1] In 2016, Kai Melde calculated the surface phase distribution of the generator using the Fourier transform to realize the acoustical holography with a single-axis oscillator.[2] In 2017, Asier Marzo1, Adrian Barnes and Bruce W. Drinkwater used tinylev to manipulated object. [3]They provided a simple method to make acoustic levitation device and studied various sound field.[4][5]

At present, acoustic suspension is making rapid progress in chemical industry and medicine field. However, there are still some problems such as low levitation force and poor suspension stability in acoustic suspension technology. In this paper, the acoustic levitation principle is used to optimize the design of acoustic levitation device, and a series of operating platforms are designed to solve the difficulties of traditional platforms, enhance the levitation force and stability, and expand its application scope.
2. Theoretical considerations

2.1 Acoustics radiation force

The pressure gradient of sound waves can cause a pressure difference between the upper and lower ends of a small object to achieve suspension. When sound waves form a standing wave field, there are multiple stable suspension sites. By changing the phase difference of the two columns of acoustic waves in the opposite direction, the stationary node can be moved and the particles can be manipulated. We derive the acoustic pressure of the standing wave field to explain why the particles can be suspended.

According to the fluid motion equation:

$$\rho \left( \frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} \right) = -\frac{\partial p}{\partial x}$$  \hspace{1cm} (1)

Standing wave equation:

$$y = 2A \cos \omega t \cos kx$$  \hspace{1cm} (2)

After derivation calculus to amplitude, we could get the speed of sound waves at every point:

$$v = \frac{\partial y}{\partial t} = -2v_a \sin \omega t \cos kx$$  \hspace{1cm} (3)

Combing (1) and (3):

$$\rho (-2v_a \omega \cos \omega t \cos kx + 2v_a^2 k \sin^2 \omega t \sin 2kx) = -\frac{\partial p}{\partial x}$$  \hspace{1cm} (4)

Find the average integral of time, the first item on the left is zero,

$$\int_0^T \rho (-2v_a \omega \cos \omega t \cos kx + 2v_a^2 k \sin^2 \omega t \sin 2kx) dt = \int_0^T -\frac{\partial p}{\partial x} dt$$  \hspace{1cm} (5)

So,

$$\frac{\partial p}{\partial x} = -v_a^2 k \rho \sin 2kx$$  \hspace{1cm} (6)

The pressure gradient is the fundamental reason for the suspension of particles.

Assuming that the particle diameter is much smaller than the sound wave’s wavelength, The formula of acoustic radiation force can be approximated.

$$F = \frac{\partial p}{\partial x} V = v_a^2 k \rho V \sin 2kx$$  \hspace{1cm} (7)

In the equation, V is the volume of the particle. From this formula, it can be seen that the acoustic radiation force in the standing wave field is a rebound force. By (2) and (7), we can get a function of acoustic radiation force and standing wave amplitude about position coordinates as shown in the figure 1.

![Figure 1: Function of acoustic radiation force and standing wave amplitude on position coordinates](image)

It can be seen from Figure 1 that the particles will be suspended at the wave node, where the sound pressure is zero. Considering gravity, the particles will be suspended at the bottom of the wave node.

The particles in the acoustic field are balanced by the acoustic radiation force and gravity. So,
2.2 Superposition of sound fields

If there are ultrasonic oscillators that generate multiple sound fields, the sound pressure at any point in space can be described as:

\[ p = \sum_{n=1}^{N} \left( A_n / R_n \right) \exp(ik_n R_n) \exp(\pm i\phi_{on}) \]  

(12)

with \( p \) is the output power of the ultrasonic oscillator, \( R_n \) is the distance the sound waves travel, \( \phi_{on} + k_n R_n \) is the phase of the sound wave at R point, \( \phi_{on} \) is the phase difference in the signal itself, \( R_n \) is the distance from R point to the ultrasonic oscillator,which can be described as \( R_n = \sqrt{x_n^2 + y_n^2 + z_n^2} \). Change \( \phi_{on} \) and \( R_n \) can control the phase of sound waves at R points.

Stable suspension can generally be achieved at a point where the sound pressure is zero.

2.3 Vortex field

The properties of the vortex field compared to the standing wave field, which focuses and transmits orbital angular momentum.When the acoustic vortex is in contact with the object, the orbital angular momentum carried by it will be transmitted to the object, resulting in a certain amount of torque. The experiment proves that the ratio of torque to energy flow is equal to the ratio of the vortex field topology and the angular frequency[5] \((\text{The topological number is defined as the number of torsion times on a long wave range.})\)

We use phase coding to generate a vortex field: There are N sound sources on a circle with a radius evenly, The space angle between them is \( \Delta \phi = 2\pi / N \), phase difference is \( \Delta \phi = m\Delta \phi \) \((m \text{ is topological charge number})\), They all send out sinusoidal signals. So at the test point \((r, \varphi, z)\) the sound pressure of the N source was detected as:

\[ p_n(r, \varphi, z, t) = \left( A_0 / R_n \right) \exp(-jwt) \exp(ik_n R_n) \exp(\pm i\phi_{on}) \]  

(13)

With \( A_0 \) is the intensity of the sound source, \( k = w / c \) represents the number of waves, the sound source transmission distance \( R_n = \sqrt{(r \cos \varphi - a \cos \varphi_n)^2 + (r \sin \varphi - a \sin \varphi_n)^2} \), and transfer time \( t = R_n / c \).

3. Simulation and discussion

3.1 Ultrasonic container

Using eight symmetrical ultrasonic transmitters, line up in Figure 2. Different sound fields can be generated by adjusting the phase of each oscillator. The distribution of the sound field can be observed by injecting water into the container and then we can compare it with the simulation results. The left in figure 2 shows the simulated sound pressure distribution, and water wave in the right in figure 2 can reflect the actual sound field distribution.
We can observe a good match. The device can visually reflect the changes in the sound field and can be used as an acoustic chemical reaction vessel.

3.2 Double acoustic vortex device

3.2.1 Simulation of hemispherical standing wave field and vortex field

Figure 3 shows the hemispherical standing wave field (left) and the hemispherical vortex field (right). Different colors represent that oscillators own different phases.

According to formula 15, we use Matlab to simulate the sound field. The specific data is determined by the actual engineering parameters. The acoustic pressure distribution map and phase distribution map of the vortex field and the standing wave field can be obtained. Figure 4 shows the acoustic pressure distribution of hemispherical standing wave field. The sound pressure distribution in the cross section is on the left side and the sound pressure distribution in the longitudinal on the right side. It can be seen that the sound pressure at the middle node is close to zero, which is a stable suspension point.

Experiments show that the diameter of the suspended ball in the vortex field is smaller than that of the stationary wave field. Figure 5 show acoustic pressure distribution of hemispherical vortex field. The sound pressure distribution in the cross section is on the left side and the sound pressure distribution in the longitudinal on the right side. It can also be seen that the sound pressure is stable at zero. Figure 6 show the vortex field phase diagram. On the left is the phase diagram of the vortex field with a phase difference of $\pi / 4$, and on the right is the phase diagram of the vortex field with a phase difference of $\pi / 12$. And due to the tangential distribution of the acoustic velocity around the center in the vortex field, the small ball will rotate in the vortex field, and the ball with a large diameter will gradually deviate from the center rotation and finally escape.
3.2.2 Influence of Correlation Parameters on Vortex Sound Field

According to the theory of vortex field above, the volume of a suspended object is related to the wavelength, the distance from the sound source, and the number of topological charges. We change these parameters to simulate, and simulation results are shown as Figure 7 to Figure 11. From Figure 7, it can be seen that the relatively small part of the sound pressure increases after the wavelength becomes longer. Therefore, the volume of objects that can be suspended becomes larger. However, the change in distance has no effect on the volume, only on the quality. Figure 8-12 show that as the number of topological charges increases, the central sound pressure increases by zero, and the volume of a suspended object increases.

We also discover that we don’t need to increase the number of topological charges. Just let the phase of oscillators alternate positively and negatively (Figure 9) can increase zero sound pressure zone.
Figure 8: The top side is the sound intensity distribution when the topological charge number is 0, 1, 2, 3 and the down side is the phase distribution when the topological charge number is 0, 1, 2, 3 (The area investigated is 10mm*10mm).

Figure 9: 24 oscillators are set in a circle. (a)(d) are the sound intensity distribution and the phase distribution when oscillator array is +++-+-++-++++++. (b)(e) are the sound intensity distribution and the phase distribution when oscillator array is ++-+++--+---++++. (c)(f) are the sound intensity distribution and the phase distribution when oscillator array is +-+-+-+-+++-+-++. (The area investigated is 100mm*100mm).
By observing the simulation above, we discover the parameter determining the radius of zero sound pressure zone, which can be approximately described by equation 13. ‘+’ ‘-’ means the initial phase between two oscillator is pi. $r$ is the radius of zero sound pressure zone. $\lambda$ is sound wavelengths. Using this equation we can calculate the size of zero sound pressure zone and manipulate large objects.

3.3 Two-dimensional sound display screen

According to the principle of acoustic suspension, we can design a two-dimensional standing wave field with multiple suspension points (Figure 11). By changing the phase of the oscillator, we can control the change of the sound field to move or arrange the tiny objects to form a two-dimensional sound display.

Figure 11: Sound display and design simulations of some phase patterns (The area investigated is 75mm*75mm)

3.4 Analysis of the size of the suspended particles in a hemispherical standing wave field

We put the phase of the two-acoustic vortex device into the above situation for experiment and put different diameter foam ball into the hemispherical standing wave sound field, gradually adjust the DC power supply voltage until the ball falls, record the minimum voltage required to suspend different small and large balls, the voltage adjustable range is 0-20V. The results show in Table 1.

Table 1: The relationship between ball diameter and the minimum pressure required for suspension

<table>
<thead>
<tr>
<th>Ball diameter/mm</th>
<th>Ball diameter /wavelength</th>
<th>Minimum Voltage/V</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.12</td>
<td>Unable to levitate</td>
</tr>
<tr>
<td>1.5</td>
<td>0.17</td>
<td>16.6</td>
</tr>
<tr>
<td>2.5</td>
<td>0.29</td>
<td>14.4</td>
</tr>
<tr>
<td>3</td>
<td>0.35</td>
<td>11.6</td>
</tr>
<tr>
<td>4</td>
<td>0.46</td>
<td>14.3</td>
</tr>
<tr>
<td>5</td>
<td>0.58</td>
<td>Unable to levitate</td>
</tr>
</tbody>
</table>
From the software simulation, the distance between the peaks of sound pressure is 7mm. The actual measured ball with a diameter of 5mm will pop up from the sound field. Figure 12 show the distribution of acoustic pressure in middle line of device. As the diameter of the ball decreases, it can be seen from Figure 12 that the sound pressure used to support the ball decreases. It is also true that more voltage suspension is required in the experiment.

![Figure 12: Distribution of acoustic pressure in middle line of device](image)

4. Conclusion

In this paper, the essential principle of acoustic suspension is first deduced, and a series of acoustic suspension operation platforms are created based on the principle. The manipulation of particles in the single acoustic wave field and vortex field is simulated and tested, and a large number of vortex fields are performed. The effect of the minimum pressure and sound field on the size of the suspended object is analyzed.

REFERENCES