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Study on Sound Propagation Control Based on Metasurfaces

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Abstract: As urbanization accelerates, noise pollution from public activities like square dancing has become a growing concern. This study focuses on the sound system used in square dancing and introduces directional acoustic propagation technology based on acoustic metasurfaces. The goal is to mitigate the noise impact on surrounding communities without compromising the experience of the dancers. Through a combination of theoretical design, acoustic simulation, 3D modeling and printing, and acoustic testing, we have successfully developed and verified both transmission and reflection acoustic metasurface structures. These innovations effectively reduce community noise pollution while maintaining the enjoyment of square dancing participants. The results demonstrate that this technology is cost-effective and compact, making it highly valuable for practical applications.

Keywords: Square dancing noise, Acoustic metasurface, Directional sound technology

1. Introduction

Square dancing is a popular and beneficial community activity, but it generates noise pollution, causing social concerns.[1] Current noise control relies heavily on regulations, which, though effective, demand substantial resources. Sound typically spreads in all directions. But with directional sound technology, it can be focused in a specific direction.[2] Applying this technology to square dancing sound systems can direct the sound to targeted areas, effectively reducing noise disturbance.

Common directional sound technologies include: ①Reflection Covers: an arc-shaped cover is installed on high-frequency speakers to focus sound waves in the direction of the cover; ② Loudspeaker Arrays: multiple speakers are arranged in an array, and directional sound is achieved by adjusting the time delay of sound waves from each speaker; ③Ultrasonic Directional Technology: sound is modulated by ultrasound and emitted in a directional way through ultrasonic transducers driven by an amplifier. [3]Each of these technologies has its own pros and cons, such as large volume or high cost.

In recent years, acoustic metasurfaces have seen significant development. These ultra-thin 2D composite materials can manipulate sound wave phases, enabling control of sound propagation with small-sized structures. This technology meets special application needs such as enhancing low-frequency sound absorption, sound focusing and even achieving acoustic invisibility.[4] By leveraging acoustic metasurfaces, sound waves can be vertically reflected or refracted to achieve directional sound transmission that meets specific needs.[5] Moreover, acoustic metasurfaces are

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small in size and low in cost, making them suitable for controlling the sound propagation of square dancing.

There are three common types of acoustic metasurface structures: Labyrinthine, Helmholtz-resonator and Membrane-type. Labyrinthine structure achieve phase modulation by artificially adjusting the length of sound wave propagation. Li.Y et al. designed an acoustic metasurface based on labyrinthine units using the concept of "space folding", see figure1(a).[6]The Helmholtz resonator structure is an important acoustic structure that maximizes the absorption of noise at specific frequencies through Helmholtz resonance. Jiang Xue et al. designed a Helmholtz-type acoustic metasurface composed of four Helmholtz cavities and a rectangular duct, see figure1(b). This metasurface can not only regulate the phase within the full phase range but also has a transmittance close to 1.[7]Membrane-type structure typically consist of membrane attached to mass blocks, which can produce large displacements to achieve energy absorption. Ma et al. designed a Membrane-type absorber based on hybrid resonance, see figure1(c).[8]

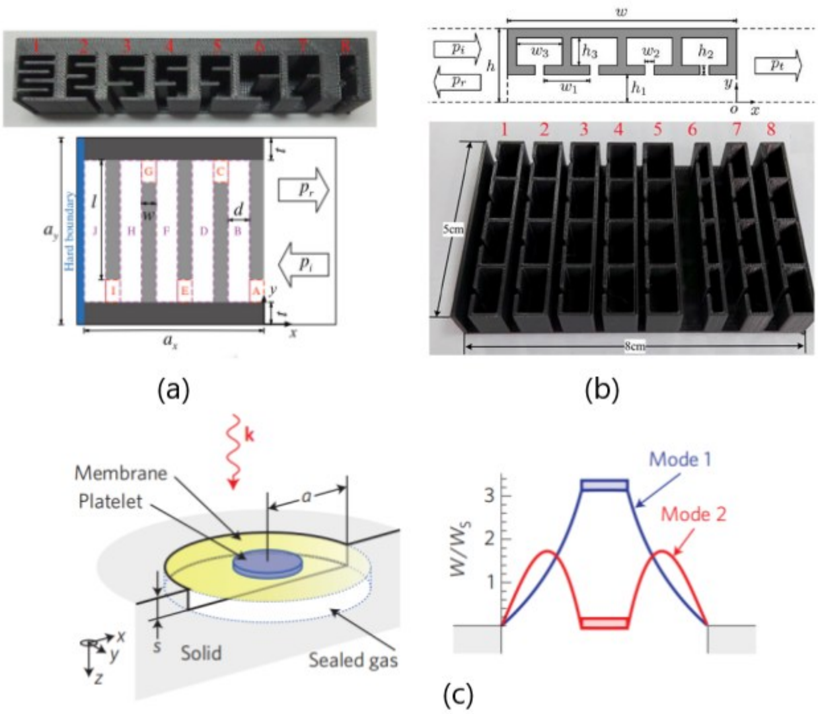

Figure 1: Different acoustic metasurface structures, (a) Labyrinthine structure (b) Helmholtz resonator structure (c) Membrane-type structure

2. Design of Acoustic Metasurface

2.1. Generalized Snell's Law

Snell's law, also known as the law of refraction, was first proposed by the Dutch physicist W. Snell in 1621. It describes the phenomenon of refraction of light when it propagates through two different media and is one of the most fundamental laws in the field of optics. Snell's law is also applicable to acoustics.

If both the incident and refracted media are homogeneous media and the interface is an ideal interface, with the Refraction Index of the two media being n_i and n_t, the incident angle beingθ_i, the reflection angle being θ_r, and the refraction angle being θ_t, see figure2.

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For the reflected wave: $\theta_i = \theta_r$
For the refracted wave: $n_i \sin\theta_i = n_t \sin\theta_t$

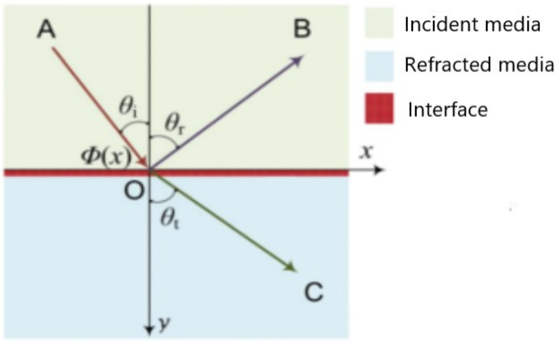

Figure 2: Schematic diagram of Snell's law

In 2011, Capasso et al. from Harvard University introduced the generalized Snell's law.[9] By creating a phase discontinuity at the material interface, they enabled arbitrary control over the propagation of electromagnetic waves. Both refracted and reflected waves follow this law. A concise proof for the refracted wave is provided below, see figure3.

Consider point A as the incidence point and point B as the refraction point. The wave velocities in the two media are u_i and u_t, and the corresponding wavelengths are λ_i and λ_t. Points C and D are the intersection points on the interface, with $|CD| = dx$. The phases at points C and D are ϕ and $\phi + d\varphi$. For small $d\varphi$, perpendiculars from C to AD@E and from D to BC@F can be drawn, and it is assumed that $|AC| \approx |AE|,|BD| \approx |BF|$.

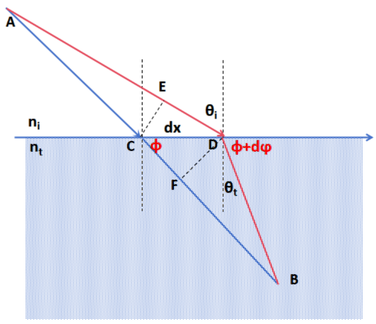

Figure 3: Schematic diagram for proving the generalized Snell's law of refracted waves

According to Huygens' principle, the phase change from A to B through different paths (the red path ADB and the blue path ACB) is the same. Therefore, the phase change from E to D is the same as the phase change from C to F.

$$\frac{|CF|}{u_t} \times \frac{2\pi}{T} = \frac{|ED|}{u_i} \times \frac{2\pi}{T} + d\varphi$$

Where $|ED| = dx\sin\theta_i$, $|CF| = dx\sin\theta_t$, $u_i = \frac{\lambda_i}{T}$, $u_t = \frac{\lambda_t}{T}$, substituting these into the equation and simplifying yields:

$$\frac{\sin\theta_t}{\lambda_t} - \frac{\sin\theta_i}{\lambda_i} = \frac{1}{2\pi}\frac{d\varphi}{dx}$$

The above equation is the expression for the generalized Snell's law for the refracted wave. Similarly, the expression for the generalized Snell's law for the reflected wave can be obtained:

$$\sin\theta_r - \sin\theta_i = \frac{\lambda_i}{2\pi}\frac{d\varphi}{dx}$$

Therefore, whether for the reflected wave or the refracted wave, the reflection angle and the refraction angle can be manipulated to achieve the desired acoustic effects by controlling the phase gradient at the interface.

2.2. Design Process of Acoustic Metasurfaces

Incorporating the generalized Snell's law, the design process of acoustic metasurfaces can be summarized as follows:

Step1: Determine the Frequency of Interest based on the specific acoustic problem under investigation.

Step2: Select an appropriate topological structure, define the design objectives, derive the expression for the phase gradient, and then integrate it to obtain the relationship curve between phase and position.

Step3: Determine the geometric dimensions and variable of the acoustic unit cell, establish the relationship between the geometric variable and the propagation distance, as well as the relationship between the propagation distance and the phase. Then derive the relationship between the geometric variable and the phase. Combine this with the phase-position relationship obtained in Step2 get the relationship between the geometric variables and the position.

Step4: Determine the geometric dimensions of the acoustic unit cell at each position to obtain the structural diagram of the acoustic metasurfaces that can achieve a 0-2π phase shift.

Step5: Utilize the symmetry of sound waves to mirror the 2π phase-modulated acoustic structure obtained in Step4, thereby constructing a multi-period structure that can achieve 4π phase modulation.

2.3. Design of transmission Acoustic Metasurfaces

The frequency analysis result of a typical square dance song measured using Audacity software is shown in the figure4 below. From the spectrum, it can be seen that sounds below 300 Hz are relatively prominent, while the high-frequency parts mainly appear at 746Hz, 1488Hz, and 3000Hz. Since the human ear is relatively sensitive to sounds in the range of 1000~4000Hz, 3000Hz is chosen as the frequency of interest for this research project.

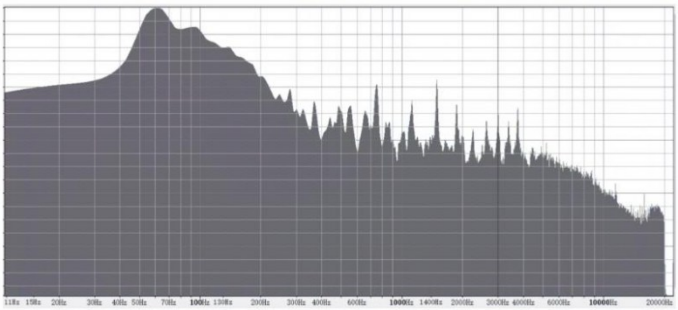

Figure 4: Spectrum diagram of square-dance song clips

The labyrinthine acoustic metasurface structure is adopted. For the transmission acoustic metasurface, it is expected to achieve the effect shown in the figure5(a). After passing through the metasurface, the sound wave can propagate perpendicularly to the metasurface.

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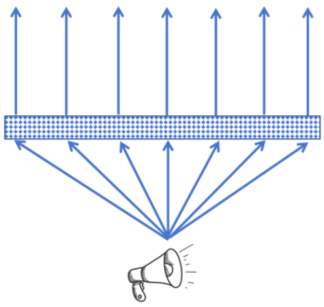

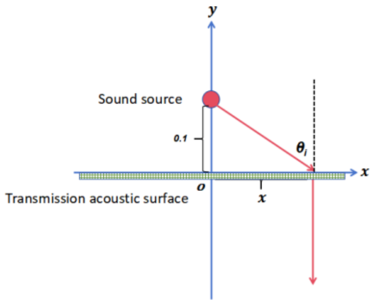

Figure 5: (a) Design requirements and (b) Analysis Schematic Diagram for transmission acoustic metasurfaces

Combining the formula of the generalized Snell's law for refracted waves, the following variables are determine: ①Both media are air, so $\lambda_i = \lambda_t = \lambda$; ②The horizontal distance from the sound source to the center of the sound surface is assumed to be 0.1m; ③ For the incident angle θ_i, $\sin\theta_i = \frac{x}{\sqrt{x^2+0.01}}$; ④The refraction angle $\theta_t = 0°$, see figure5(b). As shown in the figure below.

Through integral calculation, the relationship between phase and position can be obtained:

$$\varphi = -\frac{2\pi}{\lambda}\sqrt{x^2 + 0.01}$$

The relationship between phase and position can be represented in the form of a curve as shown in the figure6 below.

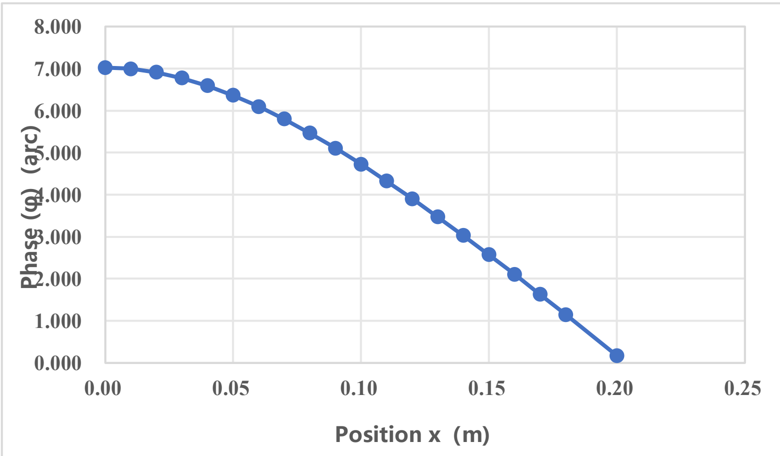

Figure 6: phase vs position graph

The figure7 below shows a typical acoustic unit. It is composed of partitions (blue) and a frame (black). The sound wave propagates along the red path. As the length and number of partitions change, the propagation path changes, which causes a change in phase. In the figure, there is one horizontal plate on the left and zero horizontal plates on the right. This acoustic unit is referred to as the "1+0" type transmission acoustic surface structure. To achieve different propagation paths, different types of acoustic surface structures can be used.

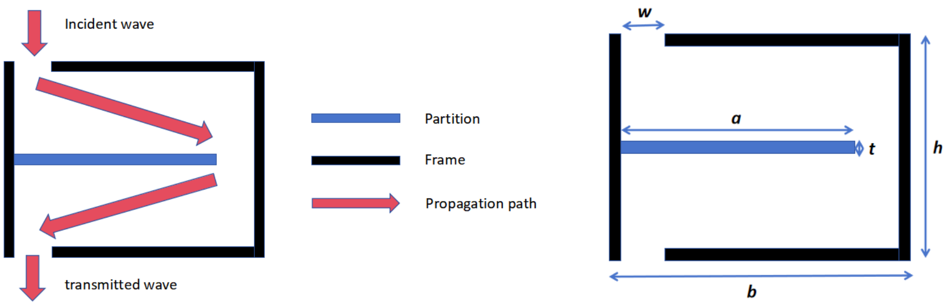

Figure 7: Typical acoustic unit

From ϕ vs. x graph, it can be seen that to achieve a phase change of 2π, the width of the acoustic unit is b=0.0376m. The set height is h=0.0025m, the material thickness is t=0.001m, the width of the opening and exit is w=0.008m, and the length of the baffle is a. A parameter δ=a−0.0356 is introduced to represent the length by which a single baffle extends beyond the center line of the unit.

The figure8 shows the variation of the propagation distance with δ and the variation of the phase with δ of different types of acoustic units. Combining the above graph, the final design values can be obtained.

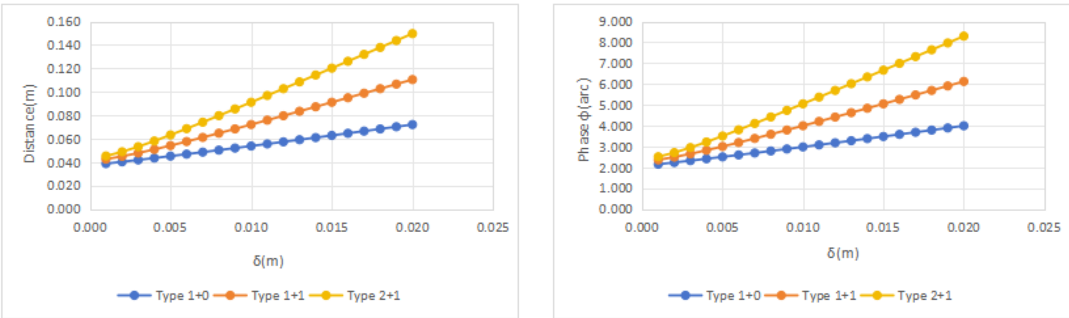

Figure 8: Graphs Distance vs. δ and Phase vs. δ

Using AUTOCAD, draw the structures of the six acoustic units and use the mirror tool to draw the symmetrical six acoustic units as shown in the figure9.

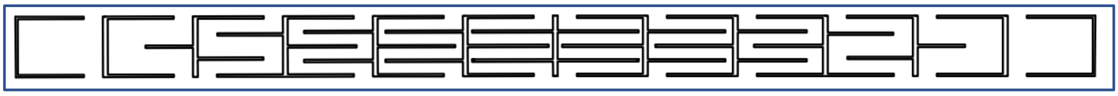

Figure 9: CAD drawing of transmission acoustic metasurface

To achieve the design goal of vertical refraction for reflection acoustic metasurfaces, complete the design of reflection acoustic metasurfaces by referring to the design process of transmission acoustic metasurface, see figure10.

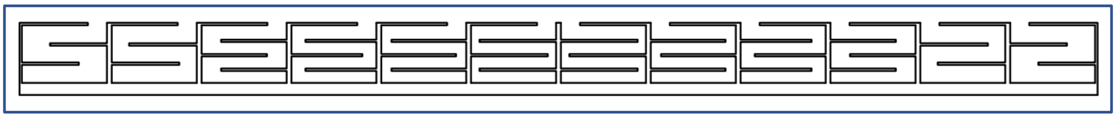

Figure 10: CAD drawing of reflection acoustic metasurface

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2.4. Simulation Analysis of transmission Acoustic Metasurface

Simulation is conducted using Comsol software for the analysis of transmission acoustic metasurfaces. Prior to the simulation analysis, the following preparatory work needs to be completed:

①Two regions are set above and below the acoustic metasurface, namely the incident region and the exit region, with a height of 0.4m and a width of 0.451m, see figure11.

②An absorption zone with a width of 0.05m is set around the acoustic field, which can completely absorb the sound that hits its surface, see figure11.

③The emitted sound is a plane wave with a frequency of 3000Hz.

④The material of the acoustic surface is ABS, while the incident region, exit region, and the gaps in the acoustic surface are all filled with air.

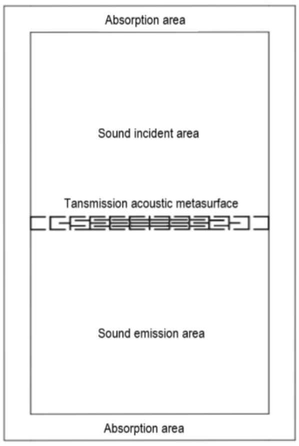

Figure 11: Comsol simulation settings

The figure12 shows the simulation results. From the simulation results, it can be seen that after passing through the transmission acoustic surface at different incident angles, the sound waves become vertically emitted, achieving the design objective.

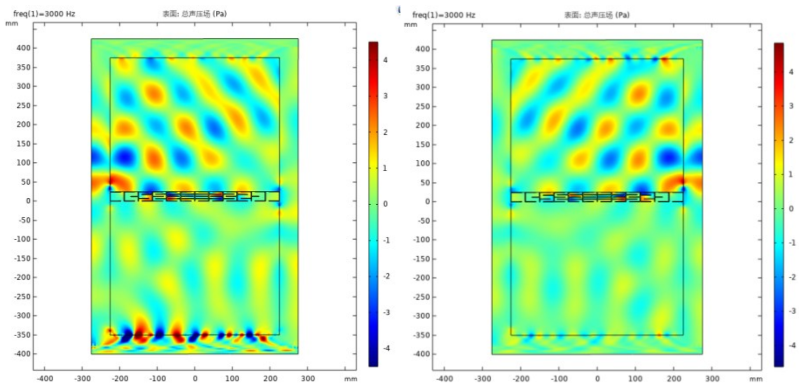

Figure 12: Comsol simulation result

3. Experimental Verification

3.1. Implementation of Acoustic Metasurfaces

Taking the transmission acoustic metasurface as an example, a 3D model is established in Inventor software. Considering the height of the loudspeaker and the capability of the 3D printer, the height is set to 15cm, see figure13. Three units are grouped together to generate four STL files for 3D printing.

The STL files are imported into the software of the 3D printer and the printing can be carried out, see figure14.

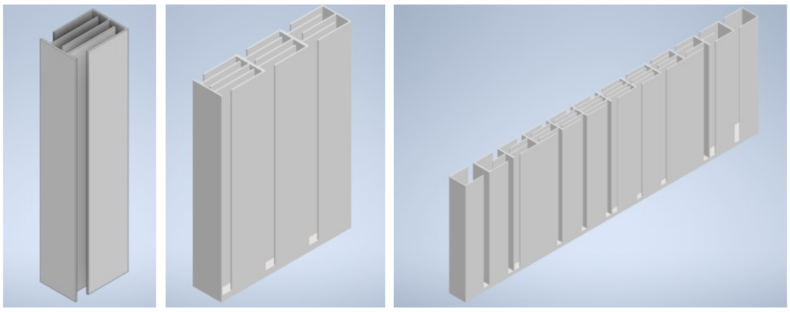

Figure 13: The modeling process of Inventor

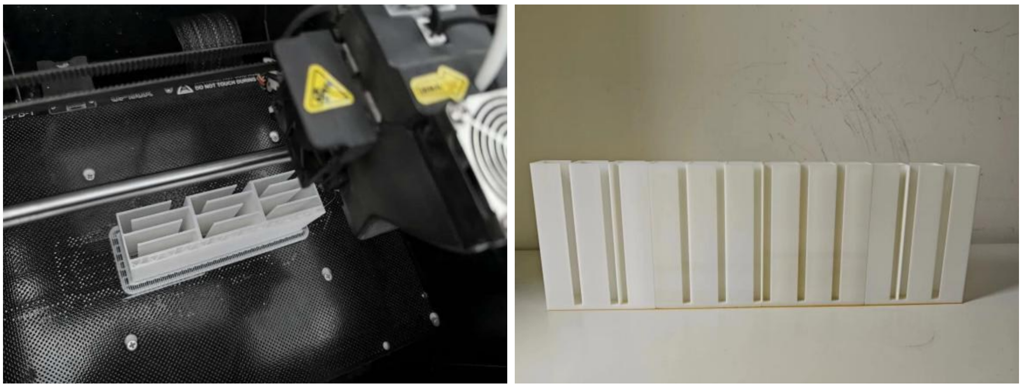

Figure 14: 3D printing process

3.2. Testing Environment

Acoustic measurements typically require a quiet environment. To ensure the accuracy and stability of the acoustic measurement results, the following measures were taken: ① A test area was fixed, with dimensions of 1.8m in length and 1.2m in width. The positions for placing the acoustic surface, loudspeaker, and microphone were marked. ② Since the test was conducted in a living room at home, where strong reflections from surrounding furniture and walls were present, 0.5m high sponge blocks were arranged around the acoustic field to form an acoustic barrier. ③ During the testing, windows were closed, curtains were drawn, air conditioning and other household appliances were turned off and no personnel movement was allowed.

The acoustic test platform consists of a sound-emitting unit, a wireless microphone kit, and an analysis unit. The sound emitting unit is composed of a Bluetooth speaker and a smartphone with an audio generation app installed. The wireless microphone kit includes a transmitter and a receiver. The transmitter is connected to the microphone and placed at the measurement position, while the receiver is installed on a computer. The analysis software used is the previously mentioned Audacity, which is installed on a laptop .

3.3. Testing Process

The design plan involves placing a transmission acoustic metasurface 10cm in front of the loudspeaker and a reflection acoustic metasurface 10cm behind the loudspeaker. To study the effects of various acoustic metasurfaces, the following four experimental conditions are set: ① ZT1: no acoustic metasurface; ② ZT2: with a transmission acoustic metasurface; ③ ZT3: with a reflection

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acoustic metasurface; ④ ZT4: with both a transmission acoustic metasurface and a reflection acoustic metasurface, see figure15.

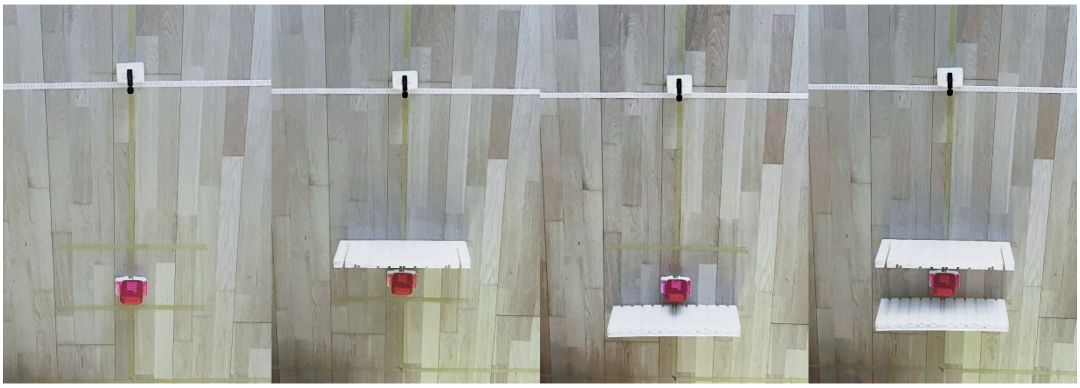

Figure 15: Four experimental conditions

With the center of the front surface of the speaker as the coordinate origin, arrange 4 measurement points on each side of the center line on the parallel lines at distances of 40cm, 50cm, and 60cm from the speaker. The spacing between adjacent measurement points is 10cm. Place the microphone at different measurement points each time to test the sound level at different points.

3.4. Measurement Results and Analysis

Draw a curve chart for different test distances, with four curves in the chart corresponding to four test conditions: ZT1, ZT2, ZT3 and ZT4, see figure16.

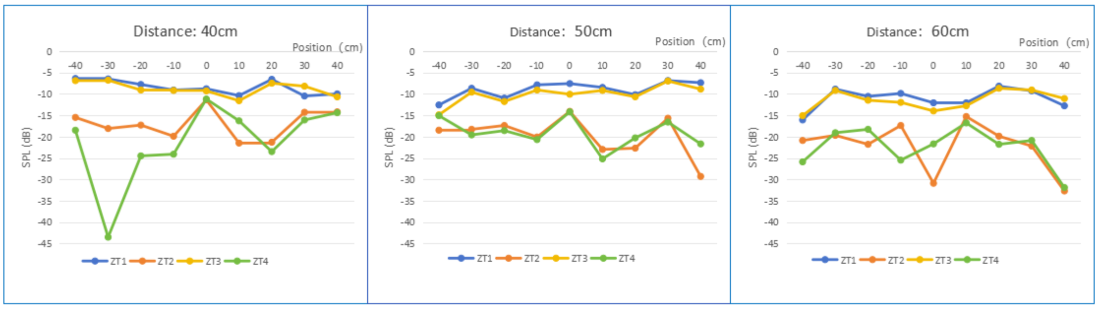

Figure 16: The sound pressure level distribution at different positions in front of the source

When the test distance is 40cm, after the sound wave from the speaker is modulated by the transmission acoustic metasurface, the sound wave exhibits the characteristic of unidirectional transmission. Specifically, in the vertical emission direction, the sound pressure level attenuates by approximately 2dB. At x=±20cm, the sound pressure level attenuates by 12dB. This change mainly stems from the refraction effect of the transmission acoustic metasurface on the incident sound wave.

When the test distance is 40cm, when the transmission and reflection metasurfaces are combined, the transmitted sound wave also shows strong unidirectional transmission. At x=±30cm, the attenuation of the sound pressure level is as high as 30dB. This phenomenon indicates that the addition of the reflection metasurface further enhances the directivity of the sound wave.

When the measurement distance increases to 50cm, the overall sound pressure level received by the microphone attenuates to approximately -10dB, but the sound wave still exhibits good directivity. This is because as the transmission distance of the sound wave increases, its energy density gradually decreases.

When the test distance increases to 60cm, the directivity of the sound wave deteriorates.

4. Optimization and improvement

4.1. Optimization solution

Simulation and experiments have proven that the "transmission + reflection acoustic metasurface" has a certain effect on the directional propagation of sound. However, as the test distance increases, the effect of directional propagation gradually deteriorates, necessitating further optimization and improvement.

Under the condition of a relatively long measurement distance, the weakening of the sound wave's directionality indicates that some sound waves are transmitted around the metasurface through diffraction. Therefore, the height of the acoustic surface can be increased to reduce the interference of diffracted waves see figure17(a). In addition, the sound wave is attenuated after multiple reflections within the metasurface. By rounding the corners, the surface can be made smoother to reduce the attenuation, see figure17(b).

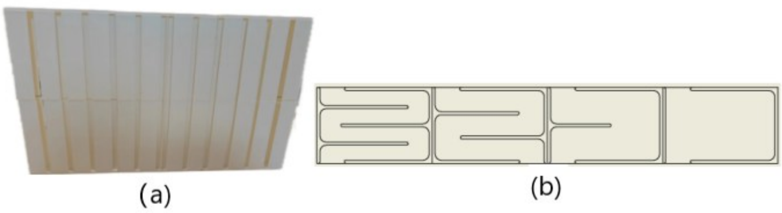

Figure 17: Optimization Solution, (a) Increase the height of the acoustic metasurface (b)Add rounded corners

4.2. Experimental Verification and Analysis

The verification experiment considered four test conditions: ① YZ01: no acoustic measures are adopted; ② YZ02: transmission + reflection acoustic metasurface without rounded corner treatment; ③ YZ03: transmission + reflection acoustic metasurface with rounded corner treatment; ④ YZ04: transmission + reflection acoustic metasurface with rounded corner treatment and a height twice as high. The test results are shown in the following figure18.

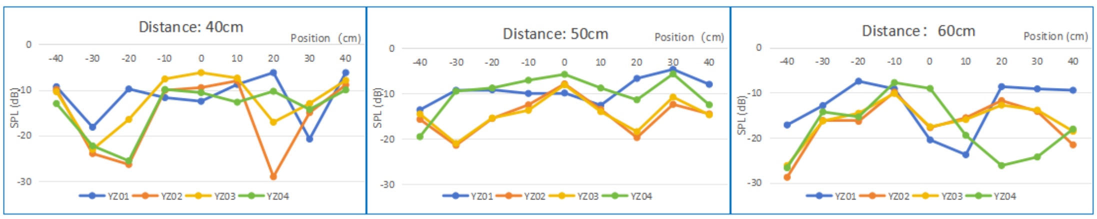

Figure 18: The sound pressure level distribution at different positions in front of the source

At a test distance of 40cm, when the metasurface is introduced, the sound pressure level of the vertically emitted sound is approximately 16dB higher than that in other directions, demonstrating a good sound directive effect. Among them, under the YZ03 condition, at the central position, the sound pressure level is about 3dB higher than that of the other three states, proving that the rounded corner treatment can reduce the loss of sound when passing through the metasurface.

At a test distance of 60cm, under the YZ04 condition, a high sound suppression effect (up to 19dB) is exhibited in both inclined emission directions, which is better than that of YZ02 and YZ03 (about

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8dB). This indicates that by increasing the area of the acoustic metasurface, the diffraction of sound waves is suppressed, further enhancing the sound directive effect.

Based on the above mentioned analysis, it can be found that the rounded corner treatment can reduce the sound pressure loss. At the same time, appropriately increasing the height of the acoustic metasurface can improve the directivity effect and the optimized design has achieved the expected goals.

5. Summary

This paper integrates various scientific research methods such as theoretical design, simulation calculation, 3D manufacturing, and experimental verification. It innovatively introduces the directional sound propagation technology based on acoustic metasurface technology as an effective method to control the noise of square dancing. For the first time, a combined method based on transmission and reflection acoustic metasurfaces is proposed, its working principle is analyzed and the effectiveness of this scheme is verified.

This paper provides a practical application scenario for the research frontier of acoustic metasurfaces. The research results can also expand the manipulation of meta-materials in mechanical waves such as water waves.

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