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Original Article

A Study on Metamaterials with Bandstop Filter Characteristics by Structural Deformations in Metaspace

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Abstract - *This study aims to create metamaterials with single structures. It is important to understand the characteristics of single structures and to apply these single materials in various ways. In particular, if the same structures in virtual and real environments cannot express different acoustic pressure characteristics, it will be difficult for users to adapt, and the understanding of the space will be more vulnerable. Therefore, efforts are needed to apply structures that reflect these characteristics well. Therefore, this study aims to design a metaverse space that reflects structures that apply these characteristics well by studying metamaterials that can be applied equally in real and virtual environments. The proposed single structure can be applied in various ways, and satisfactory results were obtained from the measurements.*

Keywords - *Metaverse, Metamaterials, Single structures considering acoustic pressure characteristics, Center frequencies, Band stop structures.*

1. Introduction

General metamaterial research mainly refers to the arbitrary change of the special acoustic characteristics generated in nature, expressed in sizes, ranges, and frequency components. Such arbitrary changes are not created in nature but are created and studied through various changes. First, research is being conducted by dividing them into images and sounds. Metamaterials applied to image technology change the visual energy by changing the microstructure to adjust the reflection of vision or the transmittance of light, thereby changing the visual energy. The acoustic part affects the energy by emphasizing or decreasing the size or frequency components using sound characteristics. In images, research is continuously being conducted to affect the visual energy seen by the eyes by affecting the amplification or decrease of energy by affecting the transmittance of light. The acoustic characteristics change the size of the sound by repeatedly passing through a single structure and continuously passing through these changes through amplification or decrease.

Through these changes, more diverse structures can be derived. Recently, it has been possible to further enhance or reduce the emphasis or reduction through continuous contact or connection of physical structures, so it is possible to study these meta-characteristics by creating and evaluating a single structure. This research or metamaterials are used in image or sound applications that require arbitrary changes and are widely used in the fields of video and sound for changing physical structures. For this reason, it provides various energies through artificial changes. Recently, this research has been actively conducted mainly in physical structures and virtual spaces, and it is a field being studied in various spaces, including physical and virtual spaces. This application field is a technology that changes the frequency components of materials by changing the wavelength of a specific light. These technologies can be implemented through various controls that reduce or emphasize the frequency components. These metamaterials are also being studied and applied to technologies that measure and detect the characteristics of changing frequencies rather than focusing on the size of the wavelength. This technology can be implemented by arbitrarily changing the intensity of changing frequencies. This technology is receiving more attention in the field of signal processing and is actively applied in the fields of artificial intelligence and space utilization. Research is also being conducted to apply this technology to devices that emphasize specific frequencies and focus or disperse energy using metamaterials to increase efficiency. The main focus of this research is to make the change in acoustic energy identical in physical and virtual space. The core of acoustic metamaterials is the concept of a unit cell. A unit cell is a repetitive structural element of a material that enables overall acoustic control. These unit cells can have various shapes, such as holes, surfaces, and structures. These cells play a very important role in design and interact with sound pressure in a way that increases or decreases specific frequencies. The properties of acoustic metamaterials are very important for arbitrary control of sound waves. They can effectively act as acoustic filters that reflect or absorb specific frequencies and pass other frequencies. This filtering function is mainly used to selectively modify acoustic signals, such as emphasizing specific signals and minimizing background noise. Acoustic metamaterials are being studied for noise reduction. Metamaterials with this structure can reduce unwanted noise and are applied to building designs and precision systems. By reflecting and dispersing sound, noise levels in the surrounding or noisy industrial environments can be significantly reduced. Acoustic metamaterials can also act as acoustic lenses to focus or disperse sound waves [1-4, 8].

These applications are particularly useful in medical imaging to transmit sound waves accurately and improve image quality and diagnostic capabilities. Metamaterial structures can be utilized to design acoustic barriers or shields that effectively block sound transmission in specific environments, such as concert halls or recording studios, to achieve optimal sound quality [5-7, 9, 10]. Therefore, this study aims to develop materials with acoustic filters that can be applied to signal processing. In this study, Chapter 2 introduces the existing structure of metamaterials and characteristics, and Chapter 3 introduces the proposed method and its characteristics. Finally, our research results and future research plans are introduced in the conclusion.

2. Existing Method

Most of the existing studies on metamaterials can be made into fixed structures that utilize reflection and refraction. It is about changing this change in energy into the size and frequency components of sound. Most of these metamaterials are utilized to change the acoustic pressure characteristics through structural changes. Most structural changes are made by combining horizontal and vertical energies. Existing studies have focused on simple structural changes, and this study developed a variable metamaterial that can change the reflection and refractive index by focusing on the acoustic aspect. Most of the existing studies have studied materials that change the properties of a single structure or change the area of space to change the energy generated. This basic structure is called a unit cell, and various structures have been created and utilized by repeatedly configuring this unit cell. However, this structural problem is that it is impossible to change, and it is difficult to apply structures once they are configured in various ways.

As a result, it has been difficult to use metamaterials in places where the purpose of the structure changes or where metamaterials can be used in various environments. Studying how to redesign and apply structures that can change this unit cell can be a very important topic. In particular, by changing the size of the unit cell, the frequencies required for sound pressure can be effectively controlled. Suppose the flexibility of this unit cell can be controlled as a customized unit cell according to the noise characteristics. In that case, various noises and sound pressures can be controlled, and these characteristics can be changed in the design so that they can be applied in environments where real-time control using filters is essential. Another important research topic is the scalability of the unit cell using the multilayer metamaterial design. The performance of the acoustic filter can be improved by repeating layers made of various materials or thicknesses. This multilayer method can expand the sound pressure control range by controlling specific frequency bands more effectively [2-4]. In addition, this study focuses on arbitrary frequency bandstop filters using metamaterials. Applying these characteristics well can also help increase adaptability by using them in virtual and physical spaces. By designing the area of the metamaterial to be variable, it is possible to effectively increase or decrease specific frequency bands by changing the band.

These features are useful in applications such as environmental noise reduction and audio signal processing, where minimizing unwanted frequency components is important. The unit cells applied this way can be scaled down, redesigned to the nanoscale, and applied as nanostructured acoustic metamaterials. These materials designed at the nanoscale can control sound pressure very precisely due to their sophisticated design and small surface area.

This development is particularly suitable for fields and applications where control of frequency components is essential. In addition, recent research is developing technologies that can change the structure through desired sound pressure or control by applying them to the design process of acoustic metamaterials. In artificial intelligence, by selecting optimal metamaterials for the environment, it is possible to develop algorithms that redesign acoustic filters with specific types of acoustic filters by learning and applying the characteristics of vast structures as data.

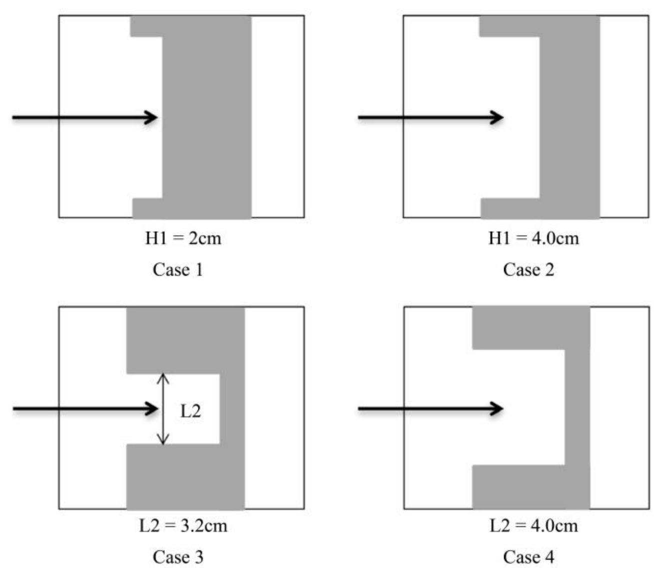


Fig. 1 Examples of meta-space structure through acoustic considerations using a single model

Figure 1 shows four cases as examples. CASE 1 has a height of 2 dong, and CASE 2 shows the interview that strongly affects the sound as 4. The comparison in Figure 2 is a case where the pressure of the incoming sound affects the width. CASE 3 and 4 show the difference in understanding the depth. In the figure, the pressure of the incoming sound affects the width of the sound pressure, so the pressure increases. This area effect changes the pressure of the sound, which causes the characteristics to appear. A cutoff filter for specific frequency bands, also known as a notch filter, is a type of filter designed to block or attenuate signals within a range of specific frequencies while allowing other frequencies to pass. Because of this characteristic, it is widely used in various electronic, communication, and audio systems applications. Band-stop filters are particularly effective in removing interference from unwanted frequencies or certain types of noise. The basic principle of band-stop filters is to enable frequency selection and control. These filters are designed to target specific frequency bands (stop bands) where signals are greatly attenuated.

The power of the center frequencies of this stopband corresponds to the resonant frequency of the filter, where signals are attenuated to the maximum. Typically, such filters can be modeled using L-C circuits of inductors and capacitors. The L-C circuit's resonant frequency can selectively block or emphasize a desired frequency range by modifying the components. In the field of acoustics, band-stop filters have many applications. For example, they can be used in audio systems to remove or enhance components in a specific frequency band. In music and audio production, band-stop filters play an important role in improving sound quality by removing unwanted frequencies and helping improve the timbre of instruments. In addition, these filters can significantly improve the acoustic environment of a space where certain repetitive noises occur.

3. Proposed Methods

The proposed method consists of two approaches. It emphasizes or reduces the characteristics of pressure by utilizing the directional directivity of sound. This is because the wider the structure, the lower the resistance; the narrower the structure, the higher the resistance. By utilizing this characteristic, the magnitudes of sound pressure can be controlled. The second is a method utilizing vertical characteristics. This utilizes the characteristic that the sound pressure maintains a straight line and then weakens rapidly as it enters the vertical direction. The weakened sound intensity can maintain the characteristics of the pressure being emphasized and specific frequency bands being widened or narrowed depending on the size of the h and W spaces. So far, important characteristics create unique characteristics, such as the composition of sizes with various direct sound pressures and vertically divided characteristics. Here, changes in acoustic characteristics can artificially create the characteristics of metamaterials.

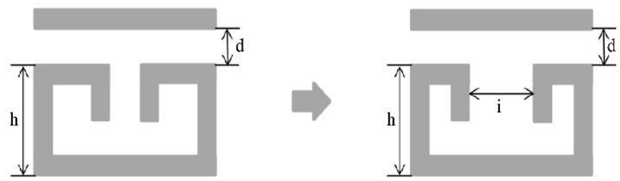


Fig. 2 Metamaterial structures with single-module acoustic pressure characteristics of the proposed methods

Since this metamaterial cannot be produced as a single unit and is continuously synthesized to change the sound pressure and produce the effect, this study emphasizes the characteristics of manufacturing and connecting multiple single unit objects. Metamaterials made of a single structure respond to characteristic frequencies. Different attenuations and emphasizes can be made in the spatial changes by passing through the vertical and horizontal sound energies. As shown in Figure 2, the structural material is modified in this study by adjusting the internal geometry of the metamaterial structure, which allows the acoustic characteristics to be changed.

This structure is described by several key variables. The overall height of the structure is denoted by h, which determines the vertical size of the entire structure. The gap between the top plate and the internal space is denoted by d.

This gap affects how sound enters the interior and the sound pressure interacts. The internal gap between the vertical slots is denoted by i, which is a variable that is adjusted to modify the acoustic characteristics. Changing i can control the acoustic resistance R, because the narrower the gap, the greater the resistance to sound propagation. This affects the sound pressure P, which can be amplified or attenuated depending on the change in the structure. The internal spacing i between elements directly affects the acoustic resistance R. Specifically, as the internal gap narrows, the resistance increases. This relationship can be expressed as:

$$R \propto \frac{1}{i} \quad (1)$$

The sound pressure P is attenuated as the acoustic resistance increases. This behavior can be described by an exponential decay model:

$$P(i) = P0e^{-kR(i)} \quad (2)$$

P_0 is an initial sound pressure, and k is an attenuation constant, dependent on the material properties and structural characteristics. In addition, the structure also affects the frequency response f. In particular, changing the internal gap can change the resonant frequency, which allows the metamaterial to be modified to target a specific sound range. Controlling these frequency characteristics allows the design of structures that can emphasize, suppress, or filter specific frequencies based on their geometric configuration.

The internal spacing i also affects the resonant frequency f_0, based on an extended Helmholtz resonance model:

$$f0\,(i) \approx \frac{c}{2\pi}\sqrt{\frac{A}{V\cdot i}} \tag{3}$$

c is the speed of sound, A is an opening area, and V is the volume of the cavity. This relationship shows that adjusting the value of iii can modify specific frequency bands.

When multiple metamaterial units are connected, their combined acoustic response can be modeled as a sum or product of individual transfer functions $H_n(f;i_n)$, depending on the nature of their interaction:

$$H(f) = \sum_{n=1}^{N} H_n\,(f;in) \tag{4}$$

This well represents the sound pressure characteristics expressed by h, w, and d. h emphasizes or attenuates the sound pressure level, and w has the characteristic of broadening or narrowing the bandwidth of frequencies. h can represent the center frequency characteristics of the band well. The single structure metamaterials made in this way are calculated to make the appropriate size in Equation (1). This equation can be controlled in various ways to emphasize or attenuate the appropriate sound pressure level to make the metamaterial. It is possible to make a metamaterial plate with various characteristics that emphasize or attenuate specific sounds by connecting multiple single structures made in this way. Figure 3 shows this configuration well. In this study, we evaluated the change in characteristics using 10 units to emphasize these characteristics.

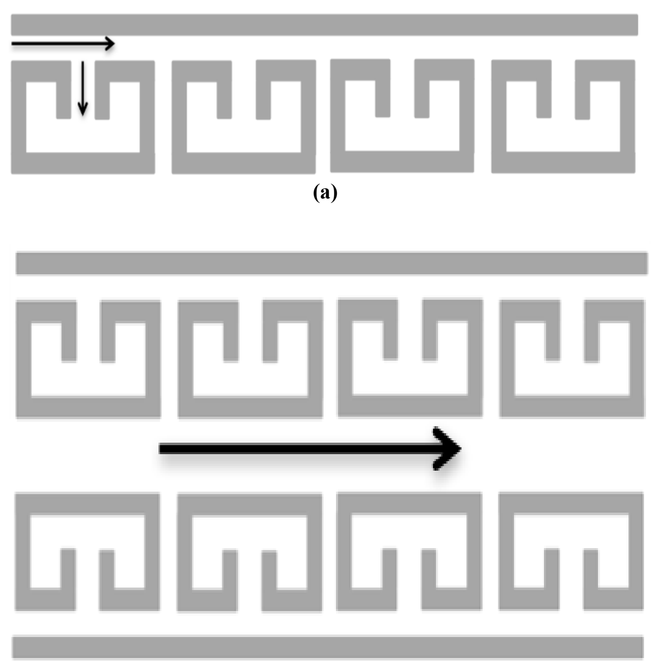
$$A = \frac{d}{(h\ x\ i)}\,N \tag{5}$$

Where N = numbers of a simple model,

The sound pressure P is influenced by the size and shape of the structure, which can be expressed in terms of h, w, and d. The sound pressure is mainly controlled by h (height) and w (width), so the following equation can describe this relationship:

$$P(\hbar, w, d) = \alpha\,\frac{h}{w}\,f(d) \tag{6}$$

P represents the sound pressure level. h(height) affects how much the sound pressure is either amplified or attenuated. w(width) has an impact on the bandwidth of the frequencies that the structure can handle. The ratio of h to w plays a crucial role in determining how the sound pressure behaves. d (length) influences how the sound pressure varies as the sound propagates through the structure. f(d) is a function that describes how the sound pressure changes with respect to the length d. α is a constant that accounts for material properties and other physical factors affecting sound propagation. The characteristics shown in Figure 2 are those of a single cell. This is a linear sound pressure, but losses occur, and the lost pressure's characteristics cause resonance in a closed space again. It can be confirmed that the sound pressure of this resonance affects the linear increase or decrease, increasing specific frequencies. In addition, the holes of the inlet where the sound pressure is combined can be designed considering the characteristics of low and high frequencies. A single cell is made in this way, as shown in Figure 3. A single cell can be made into a series structure that combines multiple cells to amplify the pressure amplitude. And cells of a parallel structure can have the effect of increasing the frequencies that occur in the pressure resonance. This structure is an example of using series and parallel structures. Various structures can be transformed into linear structure metamaterials, parallel structure metamaterials, or series-parallel mixed materials. In this study, these characteristics were emphasized and utilized in various experiments. This study helps reduce the difference in sound pressure between physical space and virtual space by applying various filters using metamaterials that are upgraded from previous studies.



(a)

(b)

Fig. 3 A plate of metamaterials that connects multiple single structures

The center frequency of the sound pressure, which is crucial for defining the main frequency that the metamaterial is designed to emphasize, is affected by both h (height) and d (length). The center frequency is the frequency at which the material resonates most strongly, and its value can be controlled by adjusting these two parameters. The following equation represents this relationship:

$$fcenter(\hbar, d) = \gamma\,\frac{h}{d} \tag{7}$$

f_{center} is the center frequency of the metamaterial. h (height) affects how the center frequency is shifted. Increasing the height tends to increase the center frequency. d(length) also affects the center frequency. As the length increases, the center frequency decreases. γ is a constant that depends on the material and design. This equation shows that the center frequency increases as the height h increases and decreases as the length d increases. By adjusting both h and d, the designer can fine-tune the center frequency to match the intended acoustic characteristics.

In Table 1, this study tested the characteristics of the series and parallel types. In the case of the series, it can be seen that the amount of change is mostly directly related to the sound pressure. However, in the case of the parallel, it can be seen that the change is concentrated on the frequency amount. If these characteristics are appropriately combined into series and parallel, they can be applied in various ways.

Table 1. Evaluation of the characteristics of serial and parallel metamaterials

Parameter	Serial Type	Parallel Type	Serial-Parallel Type
SP Changes	1.3	1.03	1.6
F Changes	-	100~200HZ	100~200HZ

When designing a metamaterial, the overall characteristics of the structure are determined by the combination of multiple individual units. Each unit can have different values for h, w, and d, and their collective effects can be used to design a metamaterial that emphasizes or attenuates specific frequencies or sound pressures. The total sound pressure of a metamaterial made up of multiple units can be calculated by summing the sound pressures of the individual units:

$$P\ total\ = \sum_{i=1}^{n} P(\hbar i, wi, di) \qquad (8)$$

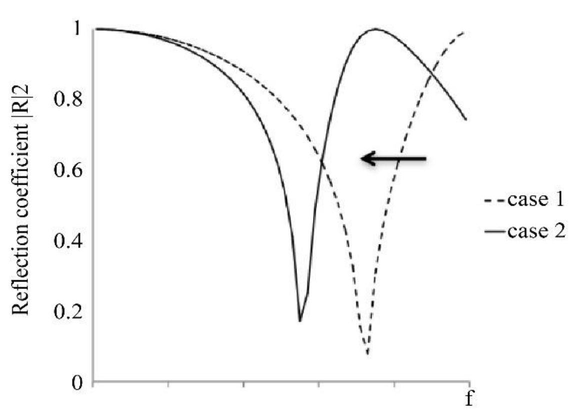
P total is the total sound pressure of the entire metamaterial. $P(h_i,w_i,d_i)$ is the sound pressure of each individual unit. n is the number of units in the metamaterial (in your case, 10 units). This equation shows that the overall sound pressure of the metamaterial is the sum of the sound pressures from each individual unit. By carefully designing each unit (adjusting h, w, and d), the designer can create a metamaterial with tailored sound pressure and frequency characteristics. For example, certain units might be designed to amplify specific frequencies, while others might attenuate them. In this structure, the characteristics of the input sound pressure were investigated by making it strong or weak. These characteristics are expressed as follows. When a metamaterial structure is composed of multiple unit cells, the overall acoustic behavior of the system is determined by the combination of the individual frequency responses of each unit. This behavior is captured by the transfer function H(f), which represents how an incoming sound wave at frequency f is transformed as it passes through the structure. Suppose the interaction between unit cells is weak, meaning each unit acts independently without significantly affecting the others. In that case, the total transfer function can be modeled as the sum of the individual transfer functions:

$$H(f)\ =\ \sum_{n=1}^{N} Hn(f;\ in) \qquad (9)$$

This additive form is suitable for systems where each unit contributes to different frequency bands, allowing the overall response to cover a wider spectrum by accumulating the individual effects. On the other hand, if the interaction between units is strong. For instance, when the units are closely packed or acoustically coupled. the behavior becomes more complex. In such cases, the transfer function is better represented as the product of the individual unit responses:

$$H(f)\ =\ \prod_{n=1}^{N} Hn(f;\ in) \qquad (10)$$

This multiplicative form reflects nonlinear interactions, where the influence of each unit is dependent on the response of the others. It can lead to more pronounced filtering or resonant effects, such as creating a sharp bandgap or strong attenuation at specific frequencies. The difference between the thick solid line and the dotted line in Figure 4 shows that the center frequency components change as the structure area changes, and the depth of the center frequency in the same line changes when the signal is strong or weak in Equations (9) and 10. In Figure 4, the bold line emphasizes the frequency characteristics lost using a single structure plate of connected metamaterials. Here, the center frequencies change according to the number of i in the structure. This is because the change in the center frequencies changes the magnitude of the pressure due to the rapid changes in the sound pressure and affects the surrounding structures. These characteristics are well expressed when applied. Figure 4(c) shows the measurement evaluation performed on a single structure.



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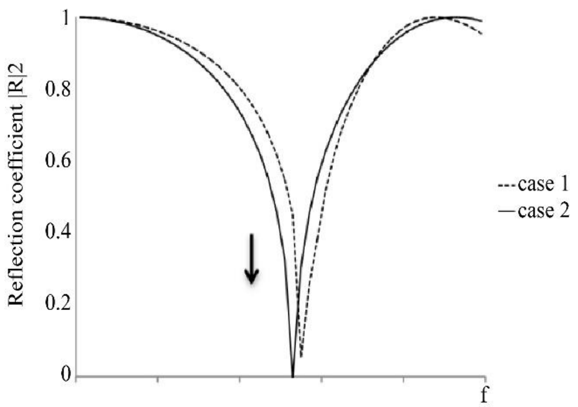

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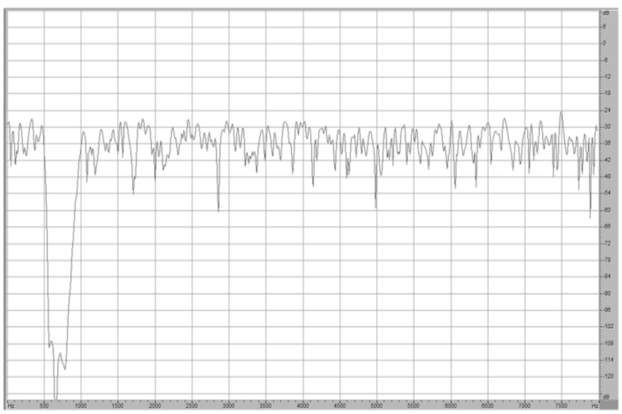

(c)

Fig. 4 Shows the frequency characteristics using 10-unit metamaterial plates and the frequency shifts according to the change in structure

The decrease in characteristic frequency is shown to have affected the sound pressure as the characteristics change through the vertical and horizontal directions. In addition, the phenomenon of the depth of the sound pressure becoming deeper strengthens the directivity of the sound, and it has the characteristic of generating various characteristics by continuously being affected by the changes in the structures as they pass through. In this study, applying these characteristics to various metamaterial environments is very suitable for creating spaces that match the characteristics of the structures when applied to virtual space structures. These characteristics are well expressed in various ways in real environments. However, if they are reflected and implemented in virtual spaces, it will be possible to study virtual space metamaterials that reduce the gap between virtual and real environments.

4. Conclusion

In this study, we created a single structure by changing the acoustic characteristics of metamaterials and their physical structures. We studied whether this structural change can change the acoustic characteristics. We confirmed that the characteristics according to the change in a specific structure were properly changed by focusing on them. By utilizing various metamaterials of this structure, acoustic characteristics can be effectively improved in physical space.

In particular, the structure was first verified by focusing and changing the frequency characteristics. By implementing the metamaterial used here, specific acoustic characteristics can be emphasized through repeated use. The characteristics of the metamaterial are changed based on research that focuses on or disperses specific frequencies for the structure by changing the length and depth of the single structure. These structural characteristics can attenuate or amplify specific frequency components, which can be usefully utilized in customized acoustic applications. In virtual environments such as the metaverse, structures generally have visual characteristics, so there are limitations in implementing various acoustic characteristics. However, if structures are designed close to physical space, acoustic characteristics can be emphasized more effectively, and users can adapt more. This approach allows us to optimize the changing acoustic performance as we modify the diverse structures of virtual space. In this study, we developed and verified a virtual space metamaterial that can induce changes in various frequency domains. The acoustic properties of these structures can be changed in various environments by utilizing the characteristics of the various virtual spaces. The experimental results were compared and analyzed to improve the intended characteristics.

This study shows the potential of virtual space metamaterials to modify and improve acoustic properties and aims to manage more effective acoustic qualities in both physical and virtual spaces. Rapid changes in environmental properties in the initial metaspace create a problem between real and virtual spaces. It is expected that these spatial changes will help to increase adaptability by sensitively changing acoustic properties. Adaptability occurs according to acoustic changes due to rapid changes in virtual space screens. In addition, rapid changes in various sounds and ambient noises due to environmental changes appear in both the acoustic effects experienced in virtual and real spaces. In accordance with these adaptive changes, sounds similar to the acoustic properties felt in real life should be provided.

If these acoustic effects are changed randomly, they should be adapted to the initial head-mounted set and applied according to environmental changes, such as dizziness or nausea. In this case, we provide environments that can change in various ways in the real environment by considering the characteristics of metamaterials. Since it is impossible to properly implement the acoustic characteristics that should appear in real and virtual environments, this study can solve this problem by using metamaterials that can change dynamically. If we utilize the optimal environment for compatibility of physical space in virtual space, we can improve sensitive environmental adaptability. This study provides the foundation for the development of complex models based on simple structures, and we can see that further research on the arrangements and compositions of these models can improve their application in virtual spaces such as the metaverse. In the future, we aim to develop more advanced models that can be applied to complex buildings and structures. We will continue to research and improve these models so that they can be effectively integrated into various virtual environments. These developments will greatly enhance the acoustic experience in these spaces and provide innovative sound management and design solutions.

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