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Passive Sound Amplification Through the Combination of Acoustic Metamaterials and Materials

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Abstract:
Growing case of hearing loss has been reported due to global population ageing and over-uasge of hearing technology. However, only 14% of American adults with hearing loss use hearing aids. The high out-of-pocket costs for hearing aids constitute a major barrier to the wide spread usage of hearing aids. In this research, a macro-metamaterial-based hearing aid has been developed. Ring shaped meta-material-based sound amplifier has found to amplify input sound wave by 41.86 folds at 600 Hz. The current design can be easily translated to manufacture cost effective, 3D printable and battery-less hearing aids which would increase the prevalence of hearing aids among impoverished population with hearing loss.

***Key Word**:Intrathecal; Sound Amplification; Metamaterials; Engineering; Acoustic*

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I. Introduction

Over 430 million people in the world suffer from hearing loss that disables their hearing to a major extent. This is on a constant rise due to hearing exacerbation caused by the over-usage of hearing technology and global population aging. However, hearing aids can be very costly. The average cost of hearing aids is 2000 USD per device. People also need one device per ear, resulting in the average cost of a pair of hearing aids reaching 4000 USD. Recent study suggest that this cost would be a catastrophic expense for 77% of American with functional hearing loss. Moreover About 1 in 5 of the world's population suffers from hearing loss, and 80% of those people live in middle to low-income countries where the majority do not have access to hearing aids.[1] Untreated hearing loss, resulting from the lack of funds to purchase these hearing aids, can cause several problems from something as minor as less efficient communication to an increased risk of depression and dementia [2]. The goal of this project is to provide a more cost-friendly yet effective alternative to conventional hearing aids by using macro-metamaterial and combining it with various materials to amplify vibrations. The project plans to use the structure found in Park et.al. and use various materials to increase the band gap width to widen the amplification range based on frequency.

A metamaterial is a material in which, rather than using the qualitative properties of a material, physical and structural manipulations are used to improve not only its efficiency but also its quality and usage. Metamaterials are used in various applications, such as structural integrity (including origami), vibration and acoustic wave control, and others. Its application to amplify sound and vibration is an intriguing aspect of metamaterial research. Previous research has used metamaterial to nullify and amplify vibration and sound. Nowadays, cavity mode is actively researched in an acoustic metamaterial, in which a model's cavity is used to amplify the vibration. Even though it is active, there are significant areas to investigate, and this study is targeted at investigating the vibration control of cavity modes. The primary area tested is the hearable resonance, or 20–20,000 Hz, because the goal is to develop a bone-conduction device that can amplify sound to a hearable range. The research was selected because of its advantages over existing bone-conduction devices. Nowadays, bone-conduction devices use electricity, which emits an electric magnetic field (EMF). Some people are hypersensitive to EMF and may be unable to use conventional bone-conducting headphones. People with electro-hypersensitivity benefit greatly from bone-conducting headphones that do not require electricity. This study will investigate and test a model based on previous research for practical applications in amplifying vibrations and resonance without using electricity.

II. Material And Methods

A metamaterial is an artificially manufactured structure that is used to obtain qualities usually not found in nature. [4]. Metamaterials are used in various applications, such as structural integrity, vibration and acoustic wave control, filtration, and electromagnets [5][6][7]. Its application to amplify sound and vibration is an intriguing aspect of metamaterial research. Previous research has used metamaterial to modulate signal output and waveguide sound waves. However, devices that attempt amplification are limited to a narrow band of frequencies, with devices having one optimal frequency that amplifies sound well and rapidly damped as farther from the resonance frequency. This is a major drawback towards the hearing aid amplification as audiblefrequency ranges from 20 Hz to 20 kHz. [8] Hearin, I plan to build upon the device in Park et.al and improve it by combining macro metamaterial with various materials [9].

In Park et.al, a structure in Fig1 is introduced.

The equation of the motion of the nth cell can be

$$m\frac{\partial^2 w_n}{\partial t^2} = \alpha(w_{n+1} - w_n - 0.5a\theta_{n+1} - 0.5a\theta_n) \tag{1a}$$

$$\begin{aligned} I\frac{\partial^2 \theta_n}{\partial t^2} &= \beta(\theta_{n+1} + \theta_{n-1} - 2\theta_n) + 0.5a\alpha(w_{n+1} \\ &\quad - 0.5a\theta_{n+1} - w_n - 0.5a\theta_n) \\ &\quad - 0.5a\alpha(w_{n-1} + 0.5a\theta_{n-1} - w_n + 0.5a\theta_n). \end{aligned} \tag{1b}$$

Figure 1. Scheme of metamaterial sound amplifier.

[9]

Because of its periodicity, the system’s n-1th term and n+1th term can be replaced by the nth term with the Floquet Bloch condition.

$$\begin{aligned} &w_{n+1} = e^{-ika}w_n,\, w_{n-1} = e^{ika}w_n, \\ &\theta_{n+1} = e^{-ika}\theta_n,\, \theta_{n-1} = \theta^{ika}w_n. \end{aligned}$$

Substituting the previous equation into the first equation and simplifying gives

$$\begin{aligned} &-m\omega^2 w_n = \alpha(e^{-ika} + e^{ika} - 2)w_n + 0.5\alpha a(e^{ika} - e^{-ika})\theta_n, \\ &-I\omega^2\theta_n = \beta(e^{-ika} + e^{ika} - 2)\theta_n + 0.5a\alpha(e^{-ika} - e^{ika})w_n - (0.5a)^2\alpha(e^{ika} + e^{-ika} + 2)\theta_n. \end{aligned}$$

By using the Euler's equation, the exponential term from the previous equation can be shown as

$$e^{-ika} + e^{ika} = 2\cos(ka) \text{ and } e^{-ika} - e^{ika} = -i2\sin(ka).$$

Substituting this into the previous two equations results in

$$\begin{aligned} -m\omega^2 w_n &= 2\alpha[\cos(ka) - 1]w_n + i\alpha a\sin(ka)\theta_n, \\ -I\omega^2\theta_n &= -i\alpha a\sin(ka)w_n + \{2\beta[\cos(ka) - 1] \\ &\quad - 0.5a^2\alpha[\cos(ka) + 1]\}\theta_n. \end{aligned}$$

The equation shown in matrix form is

$$\begin{bmatrix} 2\alpha\{\cos(ka) - 1\} + m\omega^2 & i\alpha a\sin(ka) \\ -i\alpha a\sin(ka) & 2\beta\{\cos(ka) - 1\} - 0.5a^2\alpha\{\cos(ka) + 1\} + I\omega^2 \end{bmatrix} \begin{bmatrix} w_n \\ \theta_n \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

The equation when k = 0 is

$$\begin{bmatrix} m\omega^2 & 0 \\ 0 & I\omega^2 - a^2\alpha \end{bmatrix} \begin{bmatrix} \omega_n \\ \theta_n \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

Since the determinant must be 0,

$$m\omega^2(I\omega^2 - a^2\alpha) = 0,$$

The equation solved is

$$\omega_0 = 0 \text{ and } \omega_3 = a\sqrt{\alpha/I}.$$

The equation when k = π/2 is

$$\begin{bmatrix} m\omega^2 - 4\alpha & 0 \\ 0 & I\omega^2 - 4\beta \end{bmatrix} \begin{bmatrix} \omega_n \\ \theta_n \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

The equation solved is.

$$\omega_1 = 2\sqrt{\beta/I} \text{ and } \omega_2 = 2\sqrt{\alpha/m}.$$

The Metamaterial Sound Amplifier (MSA) was effective at increasing the vibration in a certain bandgap, which was calculated with shear stiffness (α), bending stiffness (β), mass (m), and rotational inertia (I) periodically arranged with the periodicity (a). The rotation angle of the nth unit cell (wn) and its z-directional displacement (θn). The W_1 is the opening of the bandgap while W_2 is the closing of the bandgap.

The rotational inertia of cylindrical structure can be described as:

$$I = \frac{1}{2} M(R_1^2 + R_2^2)$$

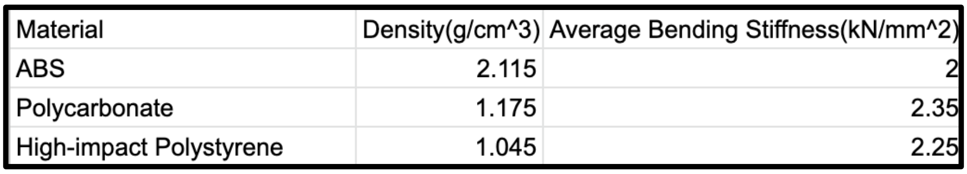
where M is mass, R_1 is the outer radius and R_2 is the inner radius of Fig 1. The bending stiffness of an object can be calculated by S = F/δ, where S is the bending stiffness, F is the total load, and δ is the bending deflection. The shear stiffness can be calculated by G = Fl/A

Δx. The G is the shear stiffness, F is the force acted on the object, A is the area where the force acts on, and Δx is the displacement of the object.

One of the challenges in optimization of MSA remains with the interdependence between M, I, α, and □ . Changing the R_1 and R_2 affects both the mass and the stiffnesses. Optimization through manipulating the given variables to decrease the W_{opening} and increase W_{closing} is inefficient. Instead of being limited to one material and manipulating the structure of the shape for trivial improvement, changing the material properties of the MSAwould allow the shear stiffness, bending stiffness and mass to be manipulated more effectively.

III. Result and Discussion

The first step would be to design the MSA with various materials. The materials chosen for the MSA were Aluminum, Steel, Acrylonitrile Butadiene Styrene, Polycarbonate, and High Impact Polystyrene. These metals were chosen because of their superior conductivity of sound waves, while the plastics were chosen for their low bending stiffness, as shown in figure 2. There would be 2 designs per material, where the inner radius of the cell is manipulated to change the rotational inertia. This is to maximize the bandgap of the MSA, thus increasing the range of amplification of each MSA. The design would use the designing software Fusion 360 to get an intricate and accurate design.



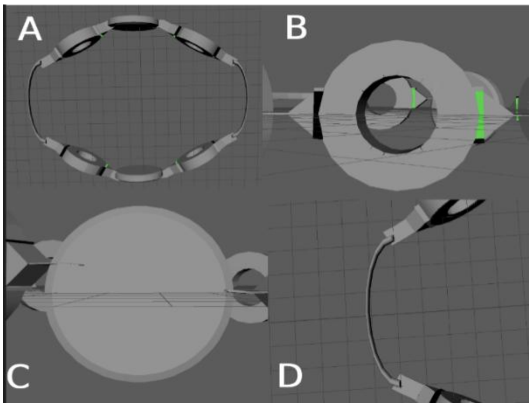
Material	Density(g/cm^3)	Average Bending Stiffness(kN/mm^2)
ABS	2.115	2
Polycarbonate	1.175	2.35
High-impact Polystyrene	1.045	2.25

Figure 2, density and bending stiffness of plastics chosen for experiment

The next step would be to measure the bending and shear stiffness of each MSA. The MSA would be printed by using the printing service provided by Protolabs. This would give us different values required to optimize the bandgap of the MSA since both the opening and closing depend on the stiffness of the MSA. The bending and shear stiffness of each MSA prototype will be measured using V-5 Stiffness Tester model 150-E.

Then, the vibration amplification would be measured by using a Portable Vibration Exciter attached to a fixture, then measuring the amplitude of the vibration with a LDV (Laser Doppler velocimetry). The LDV was chosen because it measures the vibration in a contactless manner which would not interfere or change the vibration output. This will let us see how wide the bandgap of the MSA is, and see if the optimization done was effective or not.

Finally, MSA would then be combined into a headgear form, in which vibrations would also be measured and tested for sound amplification.



[Fig. 3, 4]

A-prototype has been designed in a headset structure (Fig. 3, 4) being the final product. The headset design was made as an example to test the level of sound amplification.

The fig 5shows the amplification of the input sound wave iby the current prototype.

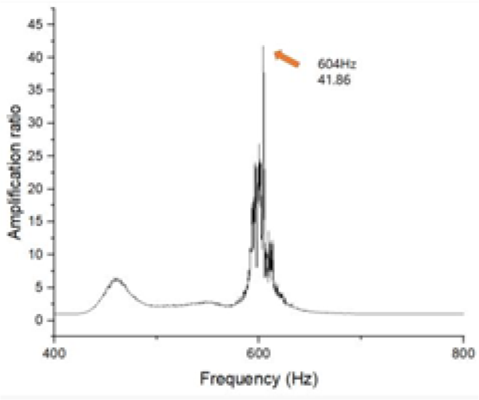


Figure 5, Amplification Ratio

At 604Hz, the input sound wave has been amplified by 41.86 times with a band-gap of 100 Hz. While this has been a significant amplification the band-gap of signal amplification remaned narrow comparing to the human's hearable frequency range which is 20-20000 hz. The amplification frequency primarily depends on the inherent design of MSA. In future work, a tandemly arranged MSA array with different specification would allow to broaden the amplification band-gap frequency.

IV.Conclusion

The goal is to design a hearing aid that can generate amplification in all audible frequency bands and to spread it to various classes at a lower price. We will create an optimized structure through collaboration with laboratories capable of 3-D printing and design. By designing an optimized structure, it will create a more complete structure through using different materials that will help.

An acoustic metamaterial was selected in this study to replace conventional bone-conduction devices. This is because it does not use electricity. Because there is no need for electricity, there is no risk of running out of batteries, allowing the user to roam freely without fear of a sudden halt in usage. Another advantage is safety. There is no risk of electrocution even in wet conditions because the headphones in this study do not use electricity. Furthermore, the device does not emit electromagnetic waves, ensuring the user's safety while wearing the headphones. Electromagnetic waves expose citizens to ELF-EMF in a heavily industrialized environment, causing major concerns throughout the field.

This study could be improved using lithography or a more precise 3-D printer. This would enable the surfaces to be smoother and more detailed, allowing vibration to travel more smoothly around the device. A smoother journey means that the vibration will be more evenly distributed, resulting in a finer and more adjustable vibration, increasing the efficiency of the device. If this aspect of sound amplification using cavity modes was further investigated, it could have massive implications around the globe. Cheaper hearing aids such as headphones made from less expensive materials would benefit millions of people suffering from hearing problems and enable the working class to afford better. If this aspect of sound amplification using the combination of metamaterial and material were further explored, it could bring massive impacts around the globe. Cheaper hearing aids/headphones from less expensive materials would help millions of people with hearing problems, and help the working class afford better hearing aids.

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