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Airfoil-Shaped Acoustic Metamaterial for Sound Insulation and Air Ventilation

Seojoon Park

Daegu International School, Daegu, Republic of Korea

Email address:
2023anthony@gmail.com

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Abstract: In this paper, we introduce the new concept of acoustic silencers that disable noise to pass but permit the air ventilation. Conventional sound proofing structures prevent air ventilation between the interior and exterior where the sound is generated and propagated. Therefore, those sound proofing structures are hardly utilized in air flowing duct system or heat exchanging system with the needs of sound insulation. A design proposed in this paper has a shape of airfoil with narrow neck and empty cavity so that it acts like a Helmholtz resonator based acoustic metamaterial. This structure can be inserted in the air flowing duct and reduce the sound passing through the duct but does not resist the air flowing in the duct. Two different combinations of radii and cavities interact with each other so that the opposite phase of sound radiated from the neck makes the destructive interference, and the high transmission loss can be realized concludingly. The airfoil-shaped acoustic metamaterial can provide large open area and low flow resistance due to its geometrical concept, it is optimized in air ventilation as well. It is expected that the acoustic metastructure of the airfoil shape can be applied to various engineering problems that simultaneously deal with flow problems and noise problems, such as HVAC systems.

Keywords: Airfoil, Acoustic Metamaterial, Air Ventilation, Sound Insulation

1. Introduction

Sound proofing and control have long been highlighting topics in the field of acoustics. Conventional noise shielding structures utilize the reflection or absorption of noise to prevent the transmission of sound beyond certain boundaries. However, these structures have a disadvantage in that they are very difficult to apply in situations where air exchange or fluid flow is essential because they obstruct or block the flow of fluid. For example, in the case of an HVAC (Heating, Ventilation, and Air Conditioning) system where air circulation and noise issues are dealt with at the same time, a noise reduction technology with low airflow resistance is essential. Noise insulation strategies based on the law of mass or micro-perforated panels [1-2] are not suitable for solving these problems because they block the flow of air.

According to recent research trends, advances in acoustic metastructures, surfaces, and materials [3-6] have provided new possibilities to simultaneously solve air circulation and noise problems. It has demonstrated the potential to redefine noise problem solving for many industries and research areas, including noise control and isolation. Various acoustic metamaterials have been proposed for controlling low frequencies with thin and lightweight structures. Compared to conventional porous structures, due to their thin and space-efficient features, it has characteristics that can control noise even in harsh environments. By utilizing this structure, studies have been conducted to allow free-flow passage in devices and to maintain the function for noise reduction [7-18]. Many studies have shown a sufficient opening ratio for air ventilation and high-efficiency sound absorption of more than 90%, but design considering air resistance due to delamination or eddy currents generated in the process of air passing through the structure was not carried out.

Therefore, the meta-structure proposed in this study utilizes the shape of an airfoil with very low air resistance and does not allow the noise to pass based on the acoustic meta-characteristics based on the Helmholtz resonator. The hollow cavity and narrow-necked airfoil shape can reduce sound passing through ducts with airflow, but do not resist air flowing through the duct. Acoustic metamaterials in the form of airfoils can offer large open areas and low flow resistance.

2. Airfoil-Shaped Acoustic Metamaterial

Herein this work, we consider the noise reduction solution as a hybrid resonance that has remarkable sound proofing ability with deep sub-wavelength scale. The exterior shape of this acoustic metamaterial is constructed based on a symmetric airfoil such as NACA 0015 or 0024.

2.1. Acoustic Metamaterial with Coupled Resonance

The concept of hybrid resonance, known through recent studies, is that a new resonance mode is generated due to the interaction of structures having two or more different resonance modes, and the incident acoustic energy strongly radiates a reflected wave with a phase difference of 180 degrees (pi-phase). It is a method of controlling sound incidents by destructive interference due to phase difference, and has the advantage of being usable in various area. This resonance is expressed as coupled (or hybrid) resonance, and a typical way to implement it is to use different Helmholtz resonators. In 2016, Li et al. realize the perfect sound absorption at a specific frequency by finely adjusting only the neck radii of two resonators with the same cavity size and neck length, and verified the sound absorbing performance experimentally [19]. Due to the strong interaction between the resonators, coupled resonance occurs, the size of the wave is amplified by the characteristics of the opposite phase and strong resonance, and the dissipation by the thermo-viscous effect occurs strongly in the resonator neck, so that more than 99% of perfect sound absorption occurs. can be achieved. As shown in Figure 1, when different resonators are arranged in an intersection, the mutual hybrid resonance is very large and sound waves with opposite phases are generated. In the figure, blue and red indicate that the sound waves are out of phase.

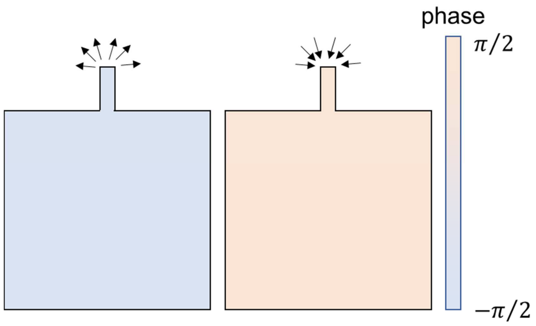

Figure 1. *Inverted acoustic phase of two different Helmholtz Resonators.*

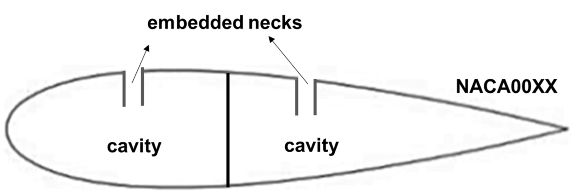

Figure 2. *Geometry of airfoil-shaped acoustic metamaetrial.*

2.2. Geometry of Airfoil-Shaped Acoustic Metamaterial

Figure 2 shows the application of the above-mentioned coupled resonance-based acoustic metamaterial concept to the shape of an airfoil. The acoustic metamaterial in the shape of an airfoil with a hollow interior has a neck shape inserted into its surface, causing dissipation by the thermo-viscous effect. A pair of two different resonators plays a role in controlling one single frequency noise, and by arranging several of them in parallel, high dissipation of acoustic energy can be realized. It is possible to control the target operating frequency by simply adjusting the radius of the neck, and it is expected that geometrical factor sweeps, machine learning, and optimization can be used as a process for designing it. For custom design, it would be good to control all various geometrical factors at the same time. There are a lot of adjustable factors such as neck radius, neck length, and cavity volume. Accordingly, the operating frequency to be obtained and energy dissipation at that frequency are very numerous. Therefore, the design approach using machine learning is expected to be proper to simultaneously grasp the purpose, such as the frequency bandwidth for sound absorption and energy insulation of more than 90%. Details on this strategy are described in the next chapter.

3. Design Strategy and Application

3.1. Design Strategy

First, there are three geometric factors that can be adjusted in design. Neck radius, neck length, size of the cavity. In the case of the cavity size, it is a variable dependent on the camber line of the air wing or the NACA number, but first of all, the operating frequency of each Helmholtz resonator is determined by three variables as shown in the following equation, so the adjustment factor is chosen as such.

$$f = \frac{c}{2\pi}\sqrt{\frac{S}{VL}}$$

Here, c is the speed of sound, S the area of neck, V the cavity size, and L the length of the neck. Since the frequency at which the mixing resonance appears basically appears between two different operating frequencies of the resonator, knowing the frequency of the resonator in advance like this will be of great help to figuring out where the actual operating frequency due to the mixing resonance will appear.

Second, the design goals can be set in three main ways. Peak target frequency, transmission loss at the peak frequency, and frequency band where more than 90% of energy dissipation is possible. Above all, the target frequency and sound absorption and insulation performance at that frequency are the most important, so if it is hard to find a design that satisfies the desired bandwidth, it may be better to give it up boldly.

Finally, target performance according to changes in geometrical factors are obtained through computer simulation, and numerous data are obtained by repeatedly executing them. In designing through machine learning, the number of data determines the accuracy of the design, so it will be important to secure as much data as possible while allowing computational resources and time. If a lot of data is accumulated, the algorithm that explains the relationship between geometrical factors and performance can be structured, and inversely derive a design with desired performance from the results. A schematic for this is illustrated in Figure 3.

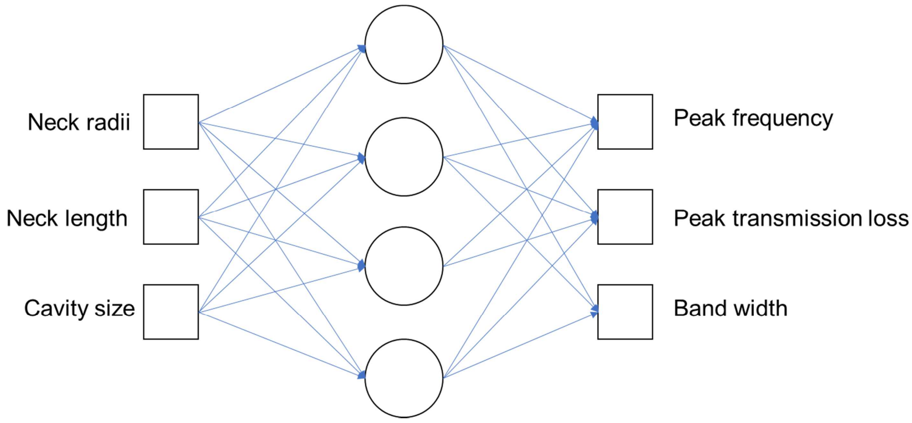

Figure 3. *Design strategy using machine learning concept.*

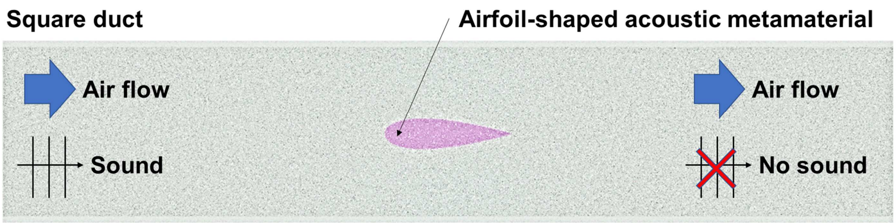

Figure 4. *Application of airfoil-shaped acoustic metamaterial in duct system.*

3.2. Possible Application

Ventilated acoustic metamaterial can be inserted into the duct system as shown in Figure 4 and can be used as a solution to minimize flow resistance and prevent noise from passing. As a representative example, the HVAC system used in buildings or automobiles has a structure that circulates air with a fan, it is very important to reduce the noise of the fan without disturbing the flow of air generated from the fan. In this case, such a structure can be a very suitable solution. Existing solutions such as acoustic louvers exist, but it is expected that the advantages of this structure in terms of air resistance will be very prominent.

3.3. Future Direction

In the case of this structure, it has the same shape as a real wing by simply expanding the shape of the airfoil in the span direction, but by utilizing the NACA shape in a different way, various airfoil-shaped acoustic metamaterial designs will be possible. For example, if the NACA shape is rotated in the axial direction, a fish-shaped structure will be created. By inserting a cavity and a neck inside this, a new shape of a streamlined acoustic metastructure can be developed. Alternatively, if a streamlined structure is designed along the inner wall of the duct, it will be possible to design a donut-shaped acoustic metastructure. This suggests a new direction for designing the most suitable structure according to the flow velocity distribution inside the duct, such as whether the flow velocity in the center of the duct is the highest or whether the flow velocity in the wall is the highest.

4. Conclusion

In this study, a new concept of the acoustic metamaterial to reduce noise in a situation where flow is considered was proposed. In order to minimize the flow resistance, the airfoil shape was used, and an attempt was made to introduce the latest research technology called acoustic metamaterial in terms of reducing noise. In order to design a structure with noise reduction performance at a target frequency, a design strategy using a lot of data and machine learning are presented. It is expected that the acoustic metastructure of the airfoil shape can be applied to various engineering problems that simultaneously deal with flow problems and noise problems, such as HVAC systems. As an extension of this study, effect of air flow on sound proofing performance of the airfoil-shaped acoustic metamaterials should be considered. Since the usual acoustic metamaterial or the phononic crystal are strongly affected by the convection of air, it is important to design the structure for different air flow speed (or Mach number). In addition, aerodynamic noise due to the air flow and the narrow neck could be another research interest.

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