Enhanced Sound Pressure Level by High Effective Index of Refraction and Impedance in an Acoustic Metamaterial Cavity

Kyungjun Song$^1$ and Jedo Kim$^2$

$^1$ Korea Institute of Machinery and Materials, Daejeon, Korea
$^2$ Department of Mechanical Engineering, Pukyong National University, Busan, Korea

*corresponding author: jedokim@pknu.ac.kr

Abstract- We design and experimentally demonstrate an acoustic metamaterial localization cavity which is used for sound pressure level (SPL) gain using double coiled up space like structures. This unique behavior occurs within a subwavelength cavity that is 1/10th of the wavelength of the incident acoustic wave, which provides up to a 13 dB SPL gain. We show that the amplification results from the Fabry-Perot resonance of the cavity exhibiting simultaneously high effective refractive index and effective impedance.

To confine the acoustic energy into a small volume, it is necessary to create a subwavelength region surrounded by a high impedance, $Z$, and a high index of refraction, $n$, that provide highly efficient sound entrapment and miniaturization of the device, respectively. However, materials that exhibit both high $Z$ and $n$ values are virtually nonexistent in nature because the speed of sound ($c$) in a material generally increases with the density ($\rho$). Acoustic metamaterials are promising candidates for circumventing this fundamental limitation because artificial periodic structures can be manipulated to achieve unprecedented control over sound wave propagation.

In this study, the acoustic metamaterial cavity that is designed and constructed for this study is shown in Fig. 1a. This sample has dimensions of $10 \times 4.2 \times 13$ cm with a unit cell size, $a$, of 1 cm. We design three different samples, as shown in Fig. 1b, with identical unit cell sizes but different structures. Thus, different path lengths, $l$, are obtained by changing the flange length, $w$. The localization cavity is created using two acoustic metamaterial slabs that are separated by a subwavelength air gap, $g$, to form a cavity. The stiff corrugated structures form an artificial “zigzag” path along the direction of wave propagation, effectively creating a “coiling-up” space [1-3].

![Figure 1](image_url)

**Figure 1** (a) acoustic metamaterial cavity composed of double coiled up space like structures. (b) three samples with progressively shorter path lengths, $l$, obtained by decreasing the flange length, $w$. 
Such a structure is ideal for the versatile control of $n_{\text{eff}}$ and $Z_{\text{eff}}$ because progressively longer paths can be easily realized by elongating the flange length, as can be seen for samples 1 to 3. The amplification rate of the metamaterial cavity is measured in an anechoic chamber using a B&K microphone that is placed inside the cavity to measure the sound pressure level (SPL). We use COMSOL, a finite element software package, to theoretically predict and compare the SPL using the structure as aluminum and air as the working fluid.

**Figure 2** (a) experimental (lines with dots) and simulated (lines) sound level gains for samples 1, 2, and 3 with $g = 1$ cm; experimental peak frequency for each sample was $f = 990, 1420, \text{ and } 2880 \text{ Hz}$, respectively; white noise with a frequency range of 71 Hz – 5.65 kHz was used for signal generation; (b) experimental (lines with dots) and simulated (lines) sound level gains for sample 1 with $g = 1, 2, \text{ and } 3$ cm; peak frequency for each case was 990, 741, and 621 Hz, respectively.

The results in Fig. 1c show that sample 1, which has the highest refractive index, produces the highest gain of up to 13 dB at a fundamental frequency of 990 Hz. This result is in almost agreement with the theoretical prediction. At this frequency, the wavelength is approximately 35 times the periodicity and 10 times the total length of the structure in the direction of wave propagation. The figure shows that progressively lower gains and higher fundamental frequencies are observed for samples 2 and 3 as the path length is reduced by decreasing $w$. In addition, we demonstrate novel independent control of $n_{\text{eff}}$ and $Z_{\text{eff}}$, which is unprecedented in conventional materials, thereby paving the way for limitless applications in a variety of areas.

The versatile scalability of our design enables its usage over wide frequency ranges, which can be applied to ultrasonic transducers and imaging when micro- or nano-fabrication techniques are used.

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**REFERENCES**