# Sound Energy Harvester with Frequency Tunable Acoustic Metamaterial Cavity

Kyungjun Song[1], Jae Eun Kim[2], Jedo Kim[3] and Kyung Ho Sun[4, a)]

[1]*Department of Nano-convergence System, Korea Institute of Machinery & Materials, 156 Gajeongbuk-Ro, Yuseong-Gu, Daejeon 34103, Korea*

[2]*School of Mechanical and Automotive Engineering, Catholic University of Daegu, 13-13 Hayang-Ro, Hayang-Eup, Gyeongsan-Si, Gyeongsangbuk-Do 38430, Korea*

[3]*Mechanical and System Design Engineering, Hongik University, 94 Wausan-Ro, Mapo-Gu, Seoul 04066, Korea*

[4]*Department of System Dynamics, Korea Institute of Machinery & Materials, 156 Gajeongbuk-Ro, Yuseong-Gu, Daejeon 34103, Korea*

[a)]sunkh@kimm.re.kr

## ABSTRACT

We demonstrate a new type of acoustic harvester by utilizing an acoustic metamaterial cavity designed by double coiled-up space like structures. In the case of double coiled-up metamaterials, high refractive index (n) miniaturizes the device at the subwavelength scale and high impedance (z) leads to efficient sound amplification rate inside the cavity, respectively. These miniaturized cavities enable to enhance the energy-convergence rate of acoustic harvester. When the resonant frequency of acoustic cavity coincides with the 1st natural frequency of the piezoelectric harvester, the amplification of sound pressure with 16dB sound pressure level gain leads to efficient acoustic mechanical-electrical conversion rate. Compared to acoustic harvesting method with only piezoelectric devices, experimental results illustrate that the proposed techniques exhibit six-time higher voltage output.

## 1. INTRODUCTION

For a low power electronic device, energy harvesting is promising way to obtain the ambient energies available in the daily life(Cook-Chennault, Thambi, & Sastry, 2008). The transformation of mechanical vibration and heat energy into electricity can be realized by utilizing the energy convergence mechanism such as piezo-electric materials(Tan & Panda, 2011). Recently, acoustic energy, which is abundant, clean, renewable source but is mostly wasted, is an alternative for a new type of energy harvesting sources energies (Beeby, Tudor, & White, 2005; Xie, Wang, & Wu, 2014; Abdelkefi, 2016). Even though acoustically induced vibration provides a low electrical-mechanical coupling compared to mechanical or thermal vibration, acoustic harvesting may be become feasible using the artificially designed resonant structures.

In order to obtain efficient acoustic harvesters, numerous works are realized by designing the several types of acoustic resonators. For example, simple Helmholtz resonator or quarter-wave resonator are popular ways to enhance the conversion efficiency by amplifying the sound pressure level (SPL) or introducing a sudden SPL gradient. Sonic crystals also provide another way for acoustic harvesting by breaking the symmetry of periodicity and then creating defect modes surrounded by periodic elements acting as a resonant cavity. In addition, acoustic grating consisting of a periodic slits array also yields sound energy amplification at one or multiple FP resonant frequencies, thus yielding an efficient sound harvester.

In this work, we introduce a new type of acoustic harvesters by utilizing acoustic materials (Sun et al., 2017). Acoustic metamaterials provide the promising way to manipulate the acoustic wave at will. For example, acoustic metamaterials lead to extraordinary acoustic material parameters such as negative density, negative bulk modulus and negative refractive index by utilizing monopoles, dipoles and combined (monopole+dipole) resonances, respectively. Recently, strong sound localization can be achieved by subwavelength domain with a low refractive index n and a low impedance z surrounded by coiled-ups space with a high n and a high Z (Song et al., 2014a; 2014b). Physically, a high refractive index $n$ leads to miniaturization of device scale with a low resonant frequency and high impedance Z allows to strong sound localization inside the subwavelength region with a low Z. When the piezo-electric device is located at the subwavelength metamaterial-cavity, a high acoustic-electrical energy convergence is realized by simultaneously matching the resonant frequencies of the metamaterial cavity and 1st natural frequency of the piezoelectric harvester.

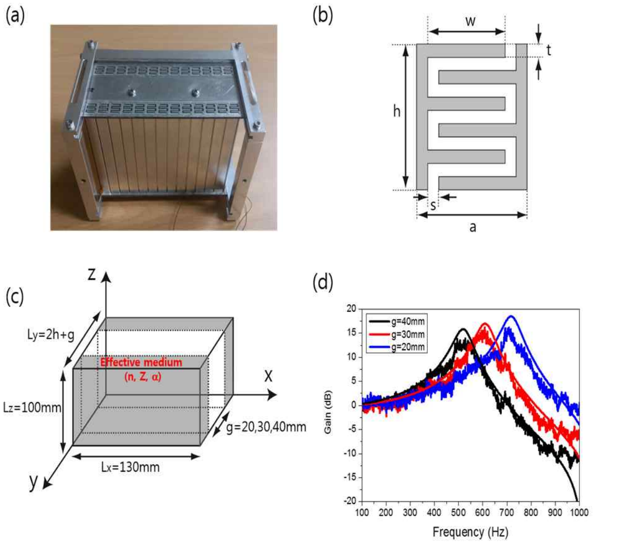


Figure 1. (a) Acoustic metamaterial cavity consists of double fishnet zigzag structures. (b) Unit cell geometry with h=11mm, s=1mm, t=1mm, w=7mm, and a=10mm. (c) Schematic of FEM simulation of 3D acoustic metamaterial cavity formed via two identical zigzag slabs with effective parameters (refractive index $n_{eff}$ and impedance $Z_{eff}$ ) and damping coefficient α (d) Experimental (lines with dots) and simulated (lines) SPL gain for metamaterial cavities depending on the gap size.

## 2. DESIGN OF ACOUSTIC METAMATERIAL CAVITY

The 3D metamaterial cavity is designed for acoustic harvesting systems as illustrated in Fig. 1(a). This structure consists of high refractive medium designed by subwavelength unit cells with h=11mm, s=1mm, t=1mm, w=7mm and a=10mm, as shown in Fig. 1(b). These double fishnet structures have dimension of Lx (130mm) X Ly (2h+g) X $L_Z$ (100mm). In order to tune the resonant frequency and fundamental mode of harvester, Ly (Y-dimension) is tailored by manipulating the gap g between two identical metamaterial slabs. Here, we use the COMSOL, a finite element software, to theoretically predict sound pressure amplification of 3D cavity that is formed by metamaterial slabs with effective medium parameters such as refractive index $n_{eff}$ and $Z_{eff}$ as shown in Fig. 1(c). Furthermore, the damping mechanism of thermal-viscous losses are inevitable for accurate amplification prediction because of rigid slabs with narrow zigzag channels. Fig. 1(d) shows the sound amplification by changing the gap size g=20mm, 30mm and 40mm, respectively. Experimental results are closely agreement with FEM calculations with effective parameters and damping coefficient α=20dB/m. As the gap increases, the SPL gain and resonant frequency become smaller because of increased cavity volume. If we design 3D metamaterial cavity with g=30mm, this cavity yields up to a 16dB SPL gain at about 600Hz.

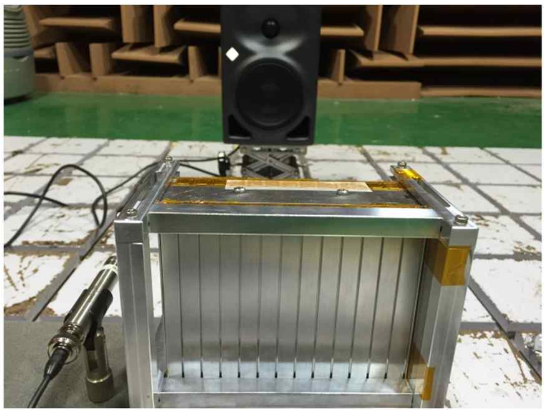

Figure 2. Experimental setup for acoustic energy harvesting based on metamaterials

Fig. 2 illustrates the basic schematic of the experiments of metamaterial-based acoustic harvesters. The speaker is connected to function generator (Agilent 33522A). The measured output voltage is recorded with oscilloscope. Figure 2 illustrates the experimental setup for the proposed sound energy harvesting system. A loudspeaker, 600 mm away from the metastructure, is operated by the function generator (Agilent 33521B) to generate a uniform sound pressure of 100dB. A personal computer equipped with dynamic signal analysis software (m+p International: SmartOffice) records the induced voltage of the piezoelectric bimorph plate and the SPL of a microphone (PCB 378B02) obtained by a data acquisition module (National Instruments: NI 9234).

Here, the performances of four comparative systems are examined; without the metamaterial cavity (in the air) and with the metamaterial cavity of $g = 28$, 30 and 32 mm. Figure 3 shows the SPL of the incident sound wave measured in front of the metastructure, where the measured SPL is between 99.8 dB and 100.2 dB in the frequency range of from

450 Hz to 750 Hz ( $\Delta f = 10$ Hz ). As expected, the proposed system consisting of the cavity with $g = 30$ mm yields a maximum output voltage of 258.5 mV at 600 Hz. This value is 6.32 times higher than that of the piezoelectric bimorph plate without the acoustic metamaterial cavity (40.9 mV at 600Hz).

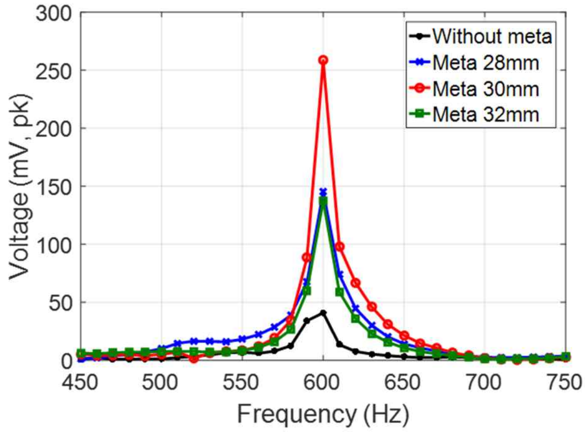


Figure 3. Experimental results: measured open-circuit output voltage (peak value) as a function of the frequency

## CONCLUSION

In summary, we demonstrated an acoustic energy harvester by utilizing the acoustic metamaterials and piezo-electric devices. Half-resonator type acoustic metamaterial can be proposed to achieve an efficient energy harvester. Furthermore, acoustic metamaterials provides the enhanced sound energy amplification inside the cavity, thus yielding the efficient electric energy generation from piezoelectric devices.


## ACKNOWLEDGEMENT

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