FREQUENCY SELECTIVE MEMS MICROPHONE BASED ON A BIOINSPIRED SPIRAL-SHAPED ACOUSTIC RESONATOR

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ABSTRACT
Acoustic sensors that can detect specific sounds in everyday environments are of growing interest. Our approach to enable a low-power signal recognition system is to create a frequency-selective microphone that is tuned to match a frequency of interest. We present a frequency-selective MEMS microphone achieved by utilizing spiral-shaped acoustic resonators inspired by the spiral-shaped structures found in the human ear. The resonators were fabricated by 3D-printing and easily integrated with our test circuit board. Here, we demonstrate simulation results investigating the effect of output aperture locations, and experimental results achieving a 2.7x increase in sensitivity at the 430 Hz resonance frequency.

KEYWORDS
Acoustics, microphones, frequency-selective sensors, 3D printing

INTRODUCTION
There is a growing interest in always-on acoustic sensors to detect keywords or specific sounds in daily environments. These sensors, for example, would trigger in response to a specific signal, such as a car or truck engine, while not triggering due to noise, such as human speech or passing aircraft. The idea of this work is to create a smart microphone to enable such basic signal recognition with near-zero power consumption, where current devices are using the cloud [1]. As the first step to achieve a low-power signal recognition system, we demonstrate a frequency-selective microphone that is tuned to match a frequency of interest. It will enable filtering to select a targeted frequency range by amplifying the desired frequencies and, at the same time, suppressing other frequencies where interfering noise may be present.

One approach could be tuning the transducer’s mechanical resonance modes to specific audio bands. This has been demonstrated using an array of tethered circular membranes having various geometries to target multiple frequency bands [2]. However, it is difficult to achieve low frequency bandpass filters using this approach, especially for frequencies below 10 kHz. Such designs are also sensitive to manufacturing variations, making it challenging to achieve identical frequency bands from die-to-die.

An alternative approach is to tune the transducer’s acoustic resonance modes to match the frequencies of interest. This approach also has the benefit that these acoustic modes naturally appear at integer harmonics (e.g. \( f, 2f, 3f, \ldots \)), making them well-suited to selectively amplify the acoustic signatures of engines and other rotating machinery, which produce sound at harmonics of the engine’s RPM. Acoustic resonances are already present in MEMS microphones: commercial MEMS microphones typically have a resonance peak around 30 kHz which is an acoustic mode defined by the microphone’s package [3]. However, using acoustic resonance modes for audible frequencies (particularly below 1 kHz) requires relatively large-scale structures. Acoustic tube resonators require their tube length to be at least one-quarter of the wavelength, so a 430 Hz resonator will be 20 cm long. Other than the tube resonator, the Helmholtz resonator is one of the best-known acoustic resonators, having a resonant frequency determined by the physical dimensions of the neck area, neck length and the cavity volume [4]. The Helmholtz structure requires large volume (> 100 cm³) to achieve a low-frequency resonance. Similar to a Helmholtz resonator, encapsulating MEMS microphone in a resonating pipe will require very large volume approximately 1000 cm³ for 430 Hz resonator [5]. These conventional acoustic resonators for low frequencies will result in big structures.

In order to create a low-frequency resonator within a limited space, several space-saving techniques have been reported recently, such as zigzag [6], labyrinthine [7], and spiral [8] designs. Our solution is based on a spiral structure found in human ears. The cochlea located in our inner ear is a spiral-shaped cavity that transforms the vibration of the sound into nerve signals. Here, we designed a resonator for audio-frequencies with a spiral-shape inspired by this cochlea allowing the size of the resonator to be an order of magnitude smaller than prior designs, 5×5×1 cm³ for a 430 Hz resonator.

Figure 1: Geometry design and physical model of the spiral resonator. (a) Photograph of the 3D-printed structure from the resonator side, (b) from the MEMS microphone side, and (c) schematic illustration.
DEVICE DESIGN

The proposed spiral-shape resonator was 3D-printed using acrylic-based material and mounted on a test circuit board containing a MEMS microphone. Fig. 1(a) shows the geometry design of the resonator from the resonator side and Fig. 1(b) is viewed from the microphone side. Fig. 1(c) shows the schematic illustration of the resonator, where sound from an external source enters the resonator from an aperture on one side, and exits from the other aperture on the backside connected to the microphone.

SIMULATION RESULTS

Fig. 2 shows the simulated frequency response of the spiral resonator with various sound attenuation levels. Increasing the attenuation level resulted in significantly reducing the quality factor of the resonance. An attenuation value of 0.3 Np/m was chosen for the rest of the simulation to replicate the experimentally-observed frequency response.

For this simulation, the resonator has the sound inlet and the microphone located at the same position of the spiral (0-degree). The ratio of the input pressure and output pressure of the resonator was calculated to evaluate its performance. The equivalent circuit model is shown on the bottom left of Fig. 2, resistance $R$ determines the amplitude at resonance, inductance $L$ and capacitance $C_s$ determine the resonance frequency $f_s$, while parallel capacitance $C_p$ determines the anti-resonance frequency $f_p$. $C_s$ depends on the location of the sound inlet, while $C_p$ depends on the location of the microphone. Equations for $f_s$ and $f_p$ are [9]:

\[
    f_s = \frac{1}{2\pi \sqrt{LC_s}} \quad (1)
\]

\[
    f_p = f_s \sqrt{1 + \frac{C_s}{C_p}} \quad (2)
\]

In this resonator model, the volume of the cavities are described by the capacitances $C_s$, $C_p$ [10]. The two cavities for the spiral resonators are (1) the cavity toward the center end and (2) the cavity towards the outer end, both starting from the microphone location. Therefore, the ratio of the two cavity volumes equal to the ratio of the arc lengths because the cross-section areas are the same.

Next, we investigated the effect of shifting the aperture location of the sound outlet at which the microphone is placed. Fig. 3(a) shows 6 different designs where labels are indicating the angle between the two apertures along the spiral path. Starting from 0-degree where the sound inlet and microphone are placed at the same position, and all the way around to 720-degree where the microphone is located at the other end of the spiral. Fig. 3(b) shows the simulated frequency response of the 6 resonators. The resonance frequencies for all 6 designs were identical at 445 Hz since

\[
    f_p = f_s \sqrt{1 + \frac{C_s}{C_p}} \quad (2)
\]

Figure 2: Simulated frequency response of the spiral resonator with varying sound attenuation levels.

Figure 3: Simulated frequency response of the spiral resonator with varying sound input/output aperture locations; (a) illustration of the 6 designs, and (b) FEM simulation results.

Figure 4: Linear relationship between anti-resonance frequency $f_p$ and the ratio of the spiral length from the microphone location ($l_1$: length to the center, $l_2$: length to the outer end).
the sound inlets were located at the same position. On the contrary, anti-resonance frequencies for the 6 designs varied due to the different microphone locations. Correspondingly, the bandwidth of the resonators varies with the shift of anti-resonance frequency. Moving the microphone location not only resulted shifting the anti-resonance frequency, it also changes the amplitude of the resonance mode. As changing the microphone location is equivalent to changing the node of the detection point, the response amplitude of the 1st resonance mode at 445 Hz increased as the detection point is shifted from 0-degrees to 720-degrees. These results indicate the ability to control the resonator specifications by optimizing the geometry of the spiral structure. Considering the tradeoff between the maximum amplitude of the pressure ratio and the bandwidth we fabricated 180-degree and 360-degree designs by 3D-printing.

Fig. 4 shows that the anti-resonance frequency $f_p$, with resonance frequency $f_s$ fixed at 445 Hz, is proportional to the ratio of the spiral length from the microphone location to the center $l_1$, and to the outer end $l_2$. Each $f_p$ value, computed from the FEM simulation shown in Fig. 3, was used to derive the capacitance ratio $C_s/C_p$ (inner figure). The ratio of frequencies $f_p/f_s$ were calculated from equation (2) using these $C_s/C_p$ values (outer figure y-axis). The outer figure x-axis is the length ratio $l_1/l_2$, which were numerically calculated from the geometry of the 4 designs (0, 180, 360, 540-degree). $f_p/f_s$ and $l_1/l_2$ are linearly related in accordance with the following equation (3) with $R^2=0.9996$.

$$f_p = f_s \left(1 + \frac{l_1}{l_2}\right)$$

All the FEM simulations shown in this paper were done using the material ‘acrylic’ for the resonator walls in COMSOL Multiphysics. Furthermore, the results were the same when ‘epoxy resin’ was used as the resonator material.

**EXPERIMENTAL RESULTS**

The resonators (180, 360-degree) were 3D-printed from acrylic-based material then attached to the PCB with a MEMS microphone. Here, we used a COTS-MEMS microphone (ICS-40300, Invensense) capable of a linear response up to 130 dB-SPL, sensitivity of -45±2 dBV, and flat frequency response from 6 Hz to 20 kHz. A speaker (NS-6490, YAMAHA) with frequency response from 45 Hz to 23 kHz was located 1 m from the device. Fig. 5 shows the experimental setup. A data acquisition system was used to generate the sound from the speaker and to collect the data from the microphone.

The reference measurement was done without the use of the spiral resonator, equivalent to the response of an unfiltered MEMS microphone. Then, we measured the response of the filtered MEMS microphone using the 3D-printed resonators. The gain of the filtered result compared to the unfiltered result is shown in Fig. 6. The points show the experimental result and the lines show the simulated results of both designs. The experimental results showed the same trends with simulation results. While the resonance frequency stayed the same, the anti-resonance frequency was higher for the 360-degree design. Moreover, the amplitude at resonance and anti-resonance were almost doubled for the 360-degree design compared to the 180-degree.
degree design. In the experiment, the sound pressure was amplified by a maximum of 9 dB at the 1st resonance mode, 430 Hz. At the anti-resonance frequency, 500 Hz and 620 Hz for the 2 designs, the sound pressure was suppressed by -12 dB and -24 dB respectively. The mismatch of the resonance/anti-resonance frequencies between simulations and experiments are likely to be caused by the difference in the boundary conditions at the ports. Since the total wall length is much longer than the surface roughness scale, the difference in the material properties, for simulations (acrylic and/or epoxy resin) and the actual 3D-printings (acrylic-based), is expected to have less effect. The mismatch of the resonance/anti-resonance frequencies between simulations and experiments are considered to be caused by the difference of material properties in the simulated material (acrylic and/or epoxy resin) and the actual 3D-printing material (acrylic-based). Since the resonance/anti-resonance frequencies are proportional to the speed of sound in air affected by the surrounding walls of the resonator, the mechanical properties of the material are important factors. Although the sound pressure was amplified at the resonance frequency and suppressed at the anti-resonance and higher frequencies, its value was maintained at frequencies lower than the 1st resonance mode. This behavior is similar to a low-pass filter with different damping factor $\zeta$ which is, for this work, related to the attenuation level of the sound pressure inside the resonator.

The linear sensitivity of the MEMS microphone was measured at 430 Hz, the frequency where the highest amplification was observed, with results shown in Fig. 7. First, to provide a reference sensitivity, the microphone sensitivity was measured to be 7 mV/Pa without a resonator. The result agrees with the microphone datasheet ($\approx 7.1$ mV/Pa). The sensitivity increased by nearly a factor of 3 with the use of the 3D-printed spiral resonators; the measured sensitivity was 18 mV/Pa with 180-degree resonator and 19 mV/Pa with 360-degree resonator, which were 2.6x and 2.7x greater, respectively. The sensitivity decreased by a factor of 4 at 500 Hz by using 180-degree resonator, where the gain is smallest at the anti-resonance. Thus, the sensitivity of the microphone was controlled to a desired value by tuning the resonator design.

**CONCLUSION**

As a first step to enable a smart microphone that can detect specific frequencies, we aimed to create a frequency-selective microphone that is tuned to the users’ desired frequency. We demonstrated a frequency-selective MEMS microphone achieved by utilizing the spiral shape which was considerably more compact than prior acoustic resonator designs. Proof-of-concept resonators were 3D-printed and easily integrated with our test circuit board. The FEM simulation results predicted the effect of the inlet and outlet port locations on the resonator frequency response. The experimental results agree with the FEM predictions and demonstrate the fact that the resonance amplitude, bandwidth, and the anti-resonance frequency are controllable by the design of the spiral geometry.

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**REFERENCES**


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