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Microarticle

Deep subwavelength split ring neck acoustic resonator

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ABSTRACT

Here, a novel acoustic resonator is proposed, realizing deep sub-wavelength form. An embedded split ring neck configuration is adopted, which makes the acoustic resonator being flat while lowering the acoustic resonance frequency. This resonant frequency can also be varied through changing the length of split ring neck. The effectiveness of analytical prediction is demonstrated through a case study, and perfect sound absorption is realized in low frequency range. The thickness of the proposed acoustic resonator is 1/79 of the resonant frequency's wavelength, making such apparatus deep subwavelength.

Introduction

Acoustic Helmholtz resonator has been widely used in noise reduction, energy harvesting and combustion instabilities control applications [1–4]. At specific incident frequency, with the help of Helmholtz resonator, the sound field can be manipulated artificially. However, the traditional Helmholtz resonator's size is bulk in the low frequency range, which increases its fabrication cost and hinders its deployment in narrow spaces.

To decrease its size, several approaches have been adopted to design subwavelength acoustic device [5–10]. For instance, a metasurface structure was proposed in Ref. [8], which realizes perfect sound absorption in a manner different from another work [10]. Here, inspired from the split ring design from electromagnetic metamaterials [11], a novel deep subwavelength acoustic resonator with split ring neck is proposed in this work.

Description of the proposed resonator

The schematic diagram of the proposed acoustic resonator is shown in Fig. 1. The split ring neck is composed of an inner neck and an outer neck. At one side, the inner neck is connected to the acoustic inlet. At the other side, the inner neck and outer neck are connected via a gap. Then, another side of the outer neck is connected to a cylinder acoustic cavity via an outer gap. The edges of the cap are mounted to the cylinder cavity.

Here, the radius of acoustic inlet is r_1, and the inner split ring neck's thickness is $r_2 - r_1$. The outer split ring neck's thickness is $r_4 - r_3$.The thickness of the upper cap is h_1 and the height of the embedded neck' is h_2. The thickness of the embedded neck's bottom is h_3. The cavity's thickness is h_4. The corresponding angle of inner gap is θ_1 and the corresponding angle of outer gap is θ_2.

Resonant frequency prediction

In the low frequency range, acoustical-electrical analogy provides a convenient way to find the acoustic device's resonant frequency. Assuming acoustic fluid is lossless, the acoustic resonance occurs when the imaginary part of the synthesized impedance equals to zero.

For the proposed acoustic device, its impedance can be divided into five parts, which is shown in Fig. 2. The items $Z_1 \cdots Z_4$ represent acoustic impedances of different domains concerning the embedded split ring neck. The impedance of sound cavity is represented by Z_5.

The acoustic impedance expression of different parts can be represented as follows:

$$Z_1 = j\omega\rho_0 L_1/S_1 \tag{1}$$

where $L_1 = h_1 + h_2$, $S_1 = \pi r_1^2$;

$$Z_2 = j\omega\rho_0 L_2/S_2 \tag{2}$$

where $L_2 = r_2 - r_1$, $S_2 = h_2 \frac{r_1 + r_2}{2}\theta_1$;

$$Z_3 = j\omega\rho_0 L_3/S_3 \tag{3}$$

where $L_3 = (2\pi\frac{r_3 + r_4}{2} - \frac{r_3 + r_4}{2}\theta_2)/2$, $S_3 = 2(r_3 - r_2)h_2$;

$$Z_4 = j\omega\rho_0 L_4/S_4 \tag{4}$$

where $L_4 = r_4 - r_3$, $S_4 = h_2 \frac{r_3 + r_4}{2}\theta_2$;

$$Z_5 = -j\rho_0 c_0^2/(\omega V) \tag{5}$$

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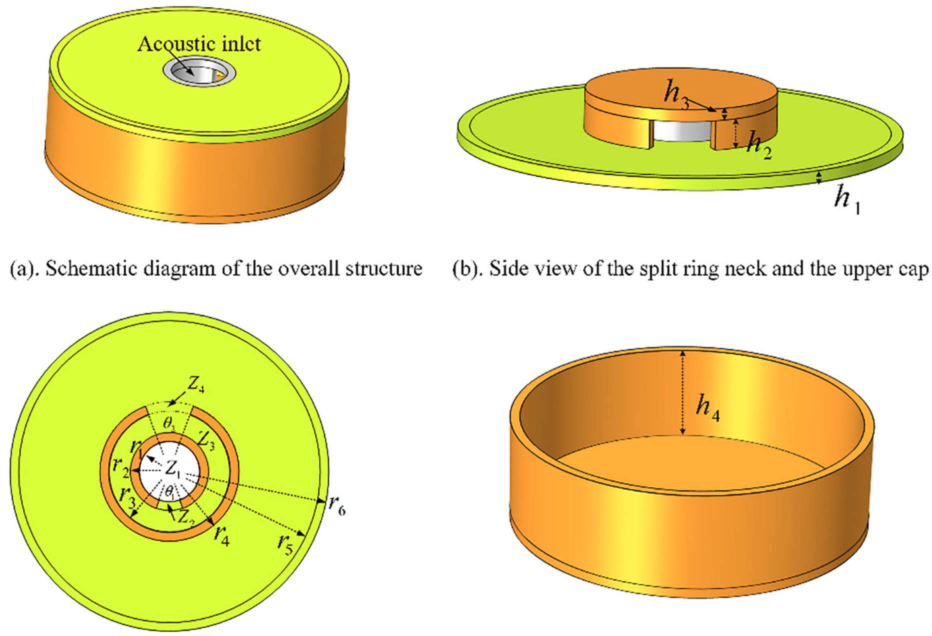

(a). Schematic diagram of the overall structure (b). Side view of the split ring neck and the upper cap

(c). Cross-section view of the split ring neck and the upper cap (d). Sound cavity (upper cap removed)

Fig. 1. Illustration of the proposed deep subwavelength acoustic resonator.

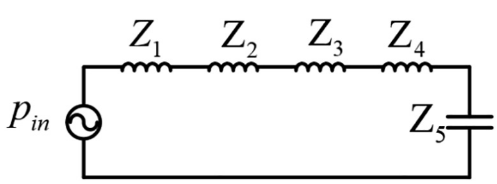

Fig. 2. Acoustical-electrical analogy of the proposed acoustic resonator.

where $V = \pi r_5^2 h_4 - \pi r_4^2 (h_2 + h_3)$.

The total acoustic impedance is the summation of these impedances of different parts:

$$Z_{total} = Z_1 + Z_2 + Z_3 + Z_4 + Z_5 \quad (6)$$

Case studies

Here, a set of parameters are provided to quantize the proposed acoustic resonator, which are given as: $r_1 = 7\ mm$, $r_2 = 9\ mm$, $r_3 = 14\ mm$, $r_4 = 16\ mm$, $r_5 = 35\ mm$, $r_6 = 37\ mm$, $h_1 = h_3 = 2\ mm$, $h_2 = 5\ mm$, $h_4 = 20\ mm$, $\theta_1 = \theta_2 = 2\pi/9$. According to the previous analyses, the calculated acoustic resonant frequency is occurred at 205 Hz.

To demonstrate its sound absorption property, pressure acoustic and thermoviscous acoustic modules are adopted in COMSOL™ finite element simulation environment, which includes background sound excitation field and the proposed device respectively. The excitation strength is set to 1 Pa.

A classical Helmholtz resonator is also investigated for comparison purpose. With respect to the Helmholtz resonator, the radius of opening neck and the radius of sound cavity are kept the same as the proposed acoustic device. However, to realize similar resonant frequency, the neck's length is set to 86 mm and the height of sound cavity is 30 mm.

The sound absorption coefficients of these acoustic devices are shown in Fig. 3.

Because the embedded split ring neck increases thermoviscous loss substantially, the proposed device can realize perfect sound absorption around 196 Hz, which is very close to the analytical prediction. Between 188 Hz and 205 Hz, the absorption coefficient is higher than 0.7. In contrast, with respect to the classical Helmholtz resonator, the peak of sound absorption coefficient is only 0.61, being much lower than the proposed acoustic resonator. The total height of the sample is only 0.022 m, and the acoustic wavelength of the resonant frequency is 1.75 m, which demonstrates that the proposed acoustic resonator is deep subwavelength.

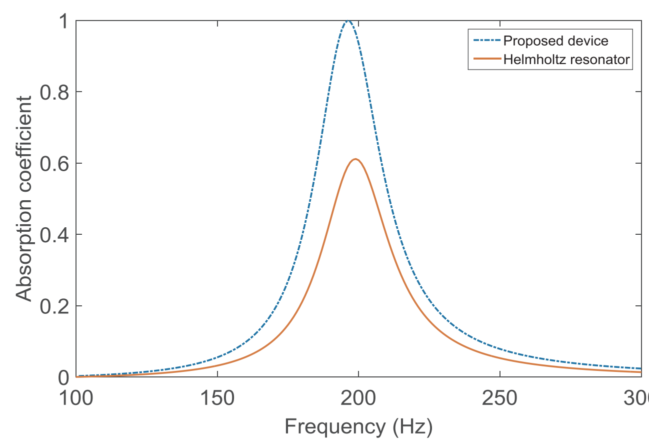

Fig. 3. Sound absorption coefficients of the two acoustic resonators.

Conclusions

In this work, a deep subwavelength acoustic resonator is proposed, which adopts the split ring neck configuration. This configuration makes the acoustic resonator planar and compact, which can realize perfect sound absorption in the low frequency. The geometry parameters of the split ring neck can be changed, which influence the sound absorption frequency. Besides, the proposed device can be used for acoustic energy harvesting, which will be demonstrated in future studies.

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