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Technical Note

Experimental investigation of the sound absorption performance of compartmented Helmholtz resonators

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ABSTRACT

An experiment was derived in the present study to investigate the effects of coupling up two Helmholtz resonators on their overall sound absorption performance. The effect of compartmenting the cavity of a resonator on its sound absorption property was also discussed. Such cavity compartmentation in fact creates a coupled resonator with a front and a rear resonator. The results show that the coupling in many cases can improve the sound absorption capacity and widen the working bandwidth of the resonators provided that the uncoupled resonance frequency of the front resonator is larger than or equal to that of the rear resonator. Results also suggest that the best compartmentation is that with these uncoupled resonance frequencies very close to each other. It is also found that the undamped plane wave approach is sufficient to predict the resonance frequencies of the coupled resonators within engineering tolerance.
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1. Introduction

It is well known that acoustic resonators can produce high sound transmission loss and strong sound absorption at their resonance frequencies [1]. Owing to the simplicity in the resonator construction, various forms of resonators are very often used in duct-like structures for the attenuation of sound propagation. Examples include, for instance, the designs given in Refs. [2–6]. A resonator, when appropriately tuned, is very useful for attenuating low frequency noise. However, its very narrowband performance makes it not so suitable for dealing with noises which do not have substantial tonal characteristics.

Apart from attenuating noise in duct-like structures, the resonators are also used as low frequency sound absorbers in relatively reverberant large halls [7]. Tang [8] showed that the tapering of the resonator neck can enhance the performance of a resonator in terms of bandwidth and absorption coefficients. There are also efforts studying the use of microperforated membranes and panels in enhancing sound absorption (for instance, Kang and Fuch [9] and Kang [10]).

In the present study, the sound absorption performance of coupled Helmholtz resonators is investigated experimentally. These resonators can be formed by attaching a cavity to the rear end of a Helmholtz resonator where a hole is opened to produce the additional resonator effect, or by compartmenting the air cavity of a Helmholtz resonator. Under these conditions, the resulted device consists of two resonators and could have two resonance frequencies. It is hoped that under some suitable combinations of the cavity volumes and neck sizes, a broadband low frequency sound absorber for architectural acoustics application can be developed.

2. Resonance frequencies

For simplicity, undamped resonators are considered in this section. Fig. 1 illustrates the cross section of the proposed coupled resonator and the nomenclature adopted in the present study. The resonator is cylindrical and the holes are circular. In practice, the two vertical plates are thin. Under the long wavelength assumption, only plane waves will be setup inside the resonator.

The resonance frequency of the undamped coupled resonator can be estimated from considering the reactance, X. It can be shown after some tedious arithmetic that

$$X = 4\frac{\rho c}{\pi d_1^2} \times \frac{j[(d_1/d_2)^2\tan(kl_2)+\tan(kl_1)]+Z'[(d_1/d_2)^2-\tan(kl_1)\tan(kl_2)]}{1-(d_1/d_2)^2\tan(kl_1)\tan(kl_2)+jZ'[\tan(kl_2)+(d_1/d_2)^2\tan(kl_1)]}, \quad (1)$$

where $j=\sqrt{-1}$, ρ is the air density, c the ambient speed of sound, k the wavenumber and Z' is the acoustic impedance of the rear resonator normalized by that of the cross section of the front resonator cavity. It can be shown that:

$$Z' = -j\left(\frac{d_2^2}{d_3^2}\right)\frac{(d_3/d_4)^2-\tan(kl_3)\tan(kl_4)}{(d_3/d_4)^2\tan(kl_3)+\tan(kl_4)}, \quad (2)$$

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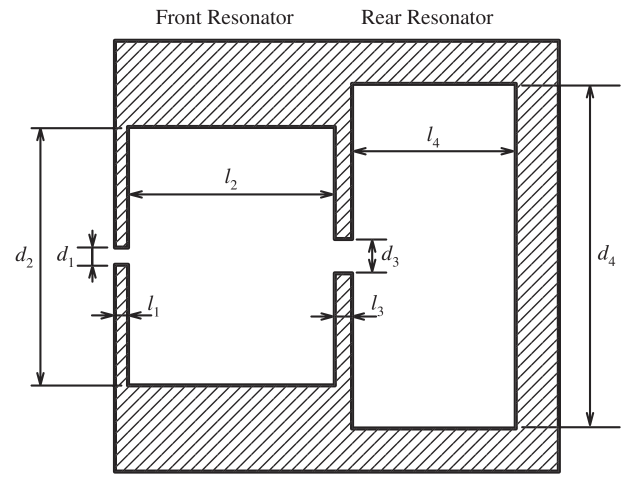

Fig. 1. Schematics of the coupled resonator and nomenclatures.

after ignoring the acoustic resistance of the rear resonator. Practically, the wavelength of the sound within the working frequency range of the resonator is very long compared to the length scale of the resonator, such that $kl_i \to 0$, where $i = 1, 2, 3$ and 4. One obtains

$$X \to \frac{4j\rho c}{\pi k d_1^2} \times \frac{\frac{d_2^2}{d_3^2} l_1 l_2 l_3 l_4 k^4 - \left[\left(\frac{d_1^2}{d_2^2} l_2 + l_1\right)\left(\frac{d_3^2}{d_4^2} l_3 + l_4\right) + \frac{d_1^2}{d_3^2} l_3 l_4 + \frac{d_2^2}{d_4^2} l_1 l_2\right] k^2 + \frac{d_1^2}{d_4^2}}{\left[\frac{d_1^2}{d_2^2} l_1 l_2 \left(\frac{d_3^2}{d_4^2} l_3 + l_4\right) + \frac{d_2^2}{d_3^2} l_3 l_4 \left(\frac{d_1^2}{d_2^2} l_1 + l_2\right)\right] k^2 - \left[\frac{d_1^2}{d_4^2} l_1 + \frac{d_2^2}{d_4^2} l_2 + \frac{d_3^2}{d_4^2} l_3 + l_4\right]}. \quad (3)$$

Eq. (3) suggests that $|X| \to \infty$ as $k \to 0$, or close to the value where the denominator vanishes such that the sound absorption property of the resonator vanishes. The latter frequency value, denoted by f_d hereinafter, is very much related to the total volume of the coupled resonator and those of the individual sections within the resonator.

One can also observe that there exist two wavenumbers for any combinations of ls and ds at which resonance occurs ($X = 0$). It should be noted that the neck lengths l_1 and l_3 are replaced by the corresponding effective lengths in the estimation of resonance frequencies because of the non-vanishing acoustic resistances [11]. In the foregoing discussions, the undamped lower and higher resonance frequencies of the coupled resonator are denoted by f_l and f_h respectively. It can be inferred directly from Eq. (3) that f_l is lower than the resonance frequencies of the individual resonators which make up the coupled resonator, while the opposite is observed for f_h. The resonance frequencies of the front and rear resonators in the present study are, respectively [11],

$$f_f = \frac{c}{2}\sqrt{\frac{d_1^2}{d_2^2 l_2 (l_1 + 0.85 d_1)}} \text{ and } f_r = \frac{c}{2}\sqrt{\frac{d_3^2}{d_4^2 l_4 (l_3 + 0.85 d_3)}}. \quad (4)$$

The existence of the acoustic resistances reduces the sharpness of the resonance such that there can be significant sound absorption between the two resonance frequencies of the coupled resonator. In the foregoing analysis, the lower and higher damped resonance frequencies are denoted by $f_{l,d}$ and $f_{h,d}$ respectively.

One can infer from Eqs. (1) and (3) that resonance can take place at the resonance frequency of the front resonator if this frequency is very much different from that of the rear resonator such that the very high magnitude of the acoustic impedance of the latter produces a nearly rigid surface reflection at its entrance. The acoustical performance of the coupled resonator will then be close to that of the front resonator. It is also expected that the coupled resonator will not resonate at the resonance frequency of the rear resonator in general (Eq. (1)).

3. Experimental setup

The instrumentation used in the present investigation was the same as that in Tang [8]. The sound absorption coefficients of the resonator at normal incidence were measured using the Brüel & Kjær Type 4206 impedance tube assembly with the analyzer Brüel & Kjær 2144 and the software BZ5050. The resonators tested were made of Perspex and the internal diameters of the cavities were fixed at 94 mm ($d_2 = d_4$) for simplicity. The cavity compartmentation was achieved by fixing a thin Perspex plate inside the coupled resonator. The neck lengths l_1 and l_3 were fixed at 3 mm. The overall length of the coupled resonator was varied by moving the resonator rod, whose one end was fixed to the end-plate inside the resonator. Single resonators were also used as base cases for comparison purposes.

4. Results and discussion

The sound absorption performance of coupled resonators formed by attaching an additional cavity is discussed in the first place. Under this circumstance, l_2 is fixed. The sound absorption coefficients for $d_1 = 2$ mm, $l_2 = 20$ mm with l_4 ranges from 20 mm to 100 mm are shown in Fig. 2. Fig. 2a and b illustrate the corresponding results for $d_3 = 5$ mm and 3 mm respectively, while Fig. 2c presents the results of a single resonator with $d_1 = 2$ mm under various cavity lengths. It can be observed that the presence of the additional resonator in this case does not produce significant change to the general characteristics of the sound absorption compared to the single resonator case of the same overall cavity length. For a fixed overall cavity length, the sound absorption peaks at nearly the same frequency, though there seems to be a very small drop in this frequency for the case of $d_3 = 3$ mm. However, a reduction in the sound absorption coefficient upon cavity attachment is in general observed except when the overall resonator length is relatively large. The results shown in Fig. 2 reveal that the sound absorption capacities of the coupled resonators and the single resonators increase with their overall lengths.

It can also be observed from Fig. 2a and b that there are small peaks at frequencies above 180 Hz, which is the effect of the resonator coupling shown in the previous section. The resonance frequency of the front resonator lies between those of the coupled resonators and this agrees with the deduction of Eq. (3). In addition, it is noticed that the major sound absorption peaks of the coupled resonator are a bit more broadband than those of the corresponding single resonators.

The effects of increasing d_1 to 4 mm on the sound absorption of the coupled resonator are illustrated in Fig. 3. For $d_3 = 2$ mm, $f_{h,d}$ does not seem to change with l_4 (Fig. 3a) The sound absorption at $f_{l,d}$, which is in principle due to the presence of the rear resonator, is slightly higher than that of the single resonator of the same inlet mouth diameter and the cavity length (c.f. Fig. 2c). At this value of d_3, the sound absorption at $f_{l,d}$ is lower than that at $f_{h,d}$. The increase of d_3 strengthens the sound absorption at $f_{l,d}$, but weakens that at $f_{h,d}$ as illustrated in Fig. 3b and c. The separation between the damped resonance frequencies also increases with increasing d_3. Further increase in d_3 further increases the importance of the front resonator (Fig. 3c) and will eventually mask out the effect of the rear resonator as has already illustrated in Fig. 2a.

Fig. 4a–c illustrate the sound absorption coefficients of single resonators with $d_1 = 5$ mm, 4 mm and 3 mm respectively.

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