Coupling effect of acoustic resonators for low-frequency sound suppression

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Abstract. Acoustic resonators like Helmholtz resonators, micro-perforated panels and quarter wavelength tubes are employed to suppress tonal noise for several industry application. The issue related to the design of these resonators is their bulkiness for low-frequency application and their narrow band behaviour. In this paper, microperforated panels and coiled quarter wavelength tubes are coupled in series and in parallel, tested inside impedance tube for sound absorption. The experimental samples are 3D printed with filament (PLA) additive manufacturing technique. The two acoustic devices are coupled and tested to reach broadband low-frequency noise suppression just by positioning one respect to the other in series or in parallel. The reported results demonstrate that the tonal behaviour of the acoustic devices can lead to enlarged absorption if they are tuned at similar frequencies. The disposition of the acoustic resonators and their frequency tuning hardly impact absorption: indeed, anti-resonance and filtering effect are experienced for series configuration, while parallel configuration is the sum of the two acoustic devices standalone absorption behaviour.

Introduction

Transport engineering has to develop vehicles, planes and ships with limited CO_2 and noise emissions. With regards to noise, sound absorbing structures are designed to suppress disturbance produced by acoustic sources and vibrating devices. Typical solutions include porous materials, Micro-Perforated Panels (MPPs), Helmholtz Resonators (HRs) and Quarter Wavelength Tubes (QWTs). Porous materials like fibers and foams are mostly used in transportation and building applications; MPPs are used for the design of acoustic liners that find several applications in the reduction of aircraft engine or automotive noise, but also in building acoustics. MPPs are composed by a thin plate with perforations followed by a backing cavity. Although a hole diameter of the order of 1 mm guarantees a large acoustic resistance and a reduced acoustic mass reactance, which results in a wide-band sound absorption [1], this cannot cover more than one or two octaves at low frequency [2]. Their micro-perforated structure can also be beneficial to suppress the sound disturbance without affecting the source performance: for instance, the small drag produced by a micro-perforated panel in the acoustic liners is the best compromise to reduce the engine noise without affecting the flow-path.

The main aim of this communication is to investigate the effect of the coupling of an MPP with a QWT in series and in parallel. Quarter wavelength tubes exhibit multiple resonance frequency when the length of the tube is an odd-multiple integer of the quarter of the wavelength (λ). Multiple resonance frequencies are exploited to extend the low-frequency region of influence of a hybrid model made by MPP and the tube. To cope with their excessive length requirement for low-frequency application, their channel is stretched into a spiral. In this paper, spiral-coiled quarter wavelength tubes (spiral resonator) are coupled with different MPPs to highlight interesting coupling properties like filtering, anti-resonance behavior and general low-frequency wide sound absorption. Generally, MPPs are made in titanium or steel; for this testing phase, they are herein 3D printed with PLA, and post-drilled to avoid manufacturing imperfection effects.

Definition of The Problem

An absorber based on the micro perforated panel has a perforated plate followed by a cavity (Figure 1a). An MPP, a perforated plate followed by a cavity (see Figure 1(a)) with holes diameter d and plate thickness t, has an impedance equal to $Z_{plate} = R_{plate} + j\omega M_{plate}$, with the resistance $R_{plate} = (32\eta t/\sigma d^2)\left([1 + (k^2/32)]^{1/2} + (\sqrt{2}/32)\,k(d/t)\right)$ and $M_{plate} = (\rho_0 \omega t/\sigma)\left(1 + [1 + (k^2/2)]^{-1/2} + 0.85(d/t)\right)$, with ρ_0 and c_0 density and speed of sound of air, η is the dynamic viscosity of air, σ is the perforation ratio and the generic coefficient $k = d\sqrt{\omega\rho_0/4\eta}$. The backing cavity is function of its dept D, with impedance: $Z_{cavity} = -jZ_0 \cot(\omega D/c_0)$ [1].

An Archimedean-spiral quarter wavelength tube (Figure 1b) is modeled as a perforated plate modelled with Johnson-Champoux-Allard (JCA) approach [3], followed by a QWT, defined following the Low Reduced Frequency (LRF) model [4]. LRF theory studies the sound propagation inside the QWT with a lossy Helmholtz equation, where the density ρ_{eff} and speed of sound c_{eff} are modelled taking into account visco-thermal dissipation inside the narrow tube, and so the effective impedance $Z_{eff} = \rho_{eff} c_{eff}$ and the effective wavenumber $k_{eff} = \omega/c_{eff}$. The impedance of the QWT of length L writes $Z_{QWT} = -jZ_{eff}\cot(k_{eff}L)$. The impedance of the spiral resonator writes $Z_{SR} = 1/\phi_{inlet}\left[Z_{d_{in},JCA}\frac{-jZ_{QWT}\cot\left(k_{d_{in},JCA}t_{in}\right)+Z_{d_{in},JCA}}{Z_{QWT}-jZ_{d_{in},JCA}\cot\left(k_{d_{in},JCA}t_{in}\right)}\right]$, with $Z_{d_{in},JCA} = \rho_{JCA}c_{JCA}$ and $k_{d_{in},JCA} = \omega/c_{JCA}$ impedance and complex wavenumber of a perforated plated of thickness t_{in} and a circular inlet hole of diameter d_{in}, with $c_{JCA} = \sqrt{K_{JCA}/\rho_{JCA}}$, ρ_{JCA} and K_{JCA} effective speed of sound, density and bulk modulus. $\phi_{inlet} = A_{hole}/A_{plate}$ is the perforation ratio between the hole and the plate areas. The MPP is coupled with the spiral resonator in series (Figure 1c) and in parallel (Figure 1d), with the impedance of both systems evaluated through electro-acoustical analogy:

$$Z_{series} = Z_{plate} + \left[\frac{1}{Z_{cavity}} + \frac{1}{Z_{SR}}\right]^{-1}, \qquad Z_{parallel} = \frac{\left(Z_{plate} + Z_{cavity}\right)\cdot Z_{SR}}{\left(Z_{plate} + Z_{cavity}\right) + Z_{SR}}. \tag{1}$$

MPP and QWT coupling is evaluated through analytical, numerical and experimental viewpoints. Experimental tests are made to measure sound absorption coefficient α_{exp} inside a 100 mm diameter impedance tube: a speaker placed at one end of the tube excites the tube with a normal plane wave radiation; the sample is placed at the opposite end, backed by a rigid cavity. The dimension of the tube D_{tube} is a design parameter for any samples, that must have circular cross section with a 100 mm diameter. Therefore, the perforation ratio of the MPPs can be written as $\sigma = N_{holes}d/D_{tube}$, with N_{holes} number of the MPP holes. The sound absorption coefficient is estimated following the ISO 10534-2 1998 standard. Acoustic simulations mimic this experimental measurement with the impedance tube and the wall of both the MPP and the spiral resonator are considered rigid. The analyses are made with COMSOL Multiphysics, *Pressure Acoustics Module*. The geometrical properties of the four tested configurations are listed in Table 1.

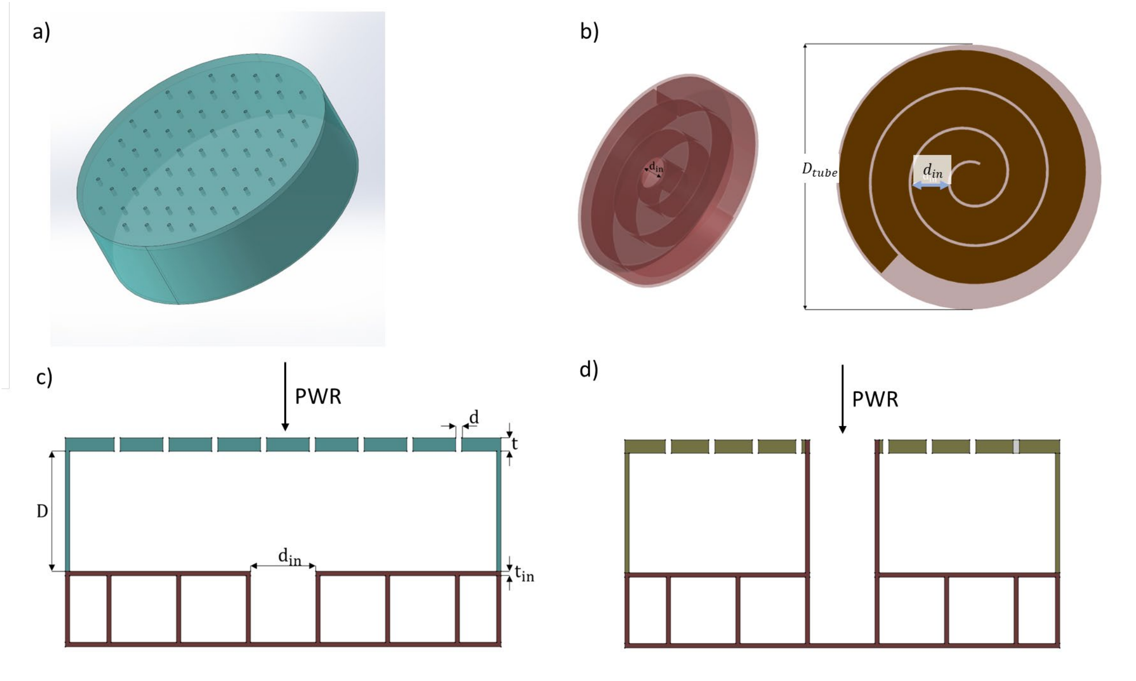

Figure 1: coupling scheme of the MPP and coiled QWT in a) series and in b) parallel.

Table 1: geometrical properties of the objects of study.

	d [mm]	N_{holes}	D [mm]	t [mm]		d [mm]	N_{holes}	D [mm]	t [mm]
$MPP_{1,series}$	1.0	33	27	3.0	$MPP_{2,series}$	1.4	65	27	3.0
$MPP_{1,parallel}$	1.0	32	27	3.0	$MPP_{2,parallel}$	1.4	64	27	3.0
	d_{in} [mm]				t_{in} [mm]		L [mm]		
SR_{series}	15				1.0		451		
$SR_{parallel}$	15				1.0		481		

Samples are 3D printed with PLA, and post-drilled to maximize the accuracy of holes diameter. Spiral resonators are different for series and parallel configuration: while for the first one the length L represents the length of the spiral path, for the parallel configuration is the sum of the length of the spiral path and the elongation to have the inlet at the top of the perforated plate, as it is possible to see in Figure 1b. Respective lengths L for SR in series and in parallel are reported in Table 1. The SR_{series} has first two harmonics at 190 and 570 Hz; $SR_{parallel}$ has first two harmonics at 178 and 535 Hz. MPP_1 has resonance peak around 283 Hz, hence between the first and the second SR harmonics. MPP_2 has resonance peak around 560 Hz, and it is designed to see resonance interaction effects between the second SR harmonics and the MPP characteristic frequency.

Results

Experimental sound absorption of the aforementioned samples is plotted in Figure 2 and each test shows a good match with theoretical and numerical predictions, which are nearly superimposed. The series coupling shows interesting properties: when the spiral and the MPP has no superimposed resonances, any spiral harmonics after the MPP resonance is filtered, and poor absorption peaks are visible (Figure 2a); on the other hand, when the MPP resonance is tuned at a similar frequency of the SR second harmonics, their interaction implies an anti-resonance effect, with the peak split in two and with a drop down of the sound absorption in correspondence of the resonance (Figure 2a). Filtering and antiresonance effect completely disappear in the parallel configurations (Figure 2c-d), with each peak preserved by their coupling.

Conclusions

Coupling an MPP and a QWT can extend the bandwidth of the acoustic efficiency. The parallel configuration induces properties that are deemed more useful with respect to the series

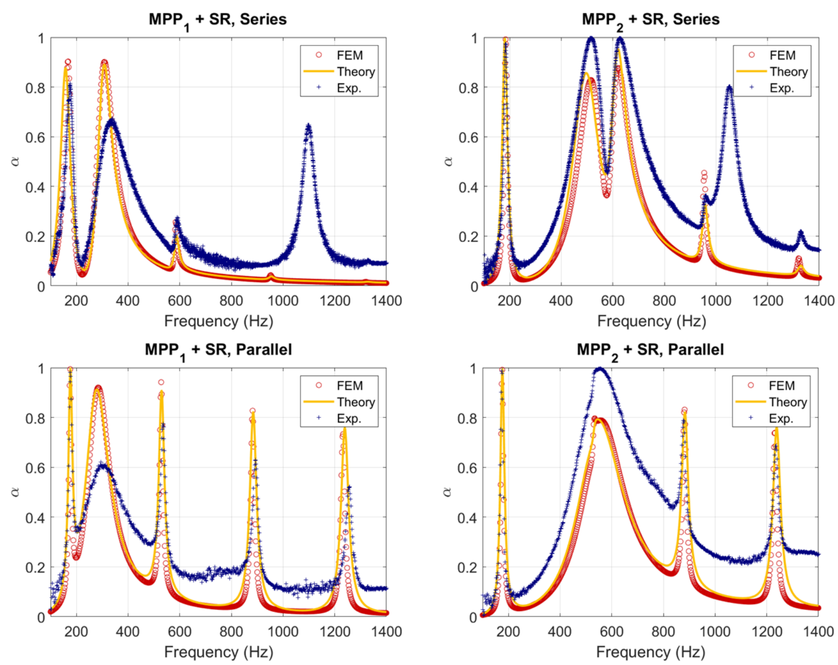

Figure 2: Sound absorption plot of the series and parallel coupling of two $\boldsymbol{MPP_S}$ coupled with 190Hz SR.

configuration. The larger inlet dimension that is required for the parallel configuration nevertheless limits its application. For instance, an engine acoustic liner cannot accept a 15 mm opening, because it would be unacceptable for aerodynamic and engine performance reasons. The series configuration could be easier implemented for an acoustic liner, but the relative position of each absorption peak brought by the MPP and the QWT is crucial. Future developments will involve different materials and manufacturing considerations.

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