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Innovative origami-based solutions for enhanced quarter-wavelength resonators

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ABSTRACT

Sound absorption at low to moderate frequencies using quarter-wavelength resonators requires significant resonator's length (for instance 28 cm for 300 Hz), a condition very often uncompatible with a practical use of this kind of resonators for sound absorption applications. To deal with this drawback, we investigate in this study innovative ways to design more compact and confined quarter-wavelength resonators by shifting their resonance frequency while keeping constant their length.

This exploratory process led to a hybrid solution: a paper-folded (origami) spiral is inserted in the resonator and acts as an equivalent porous medium whose inner characteristics enhance the absorption properties of the resonator. Especially, by modifying the resonator's tortuosity, origami-spirals make possible to artificially extend the resonator's length, thus obtaining with shorter geometries the absorption properties of longer resonators.

1. Introduction

Passive noise control represents a key subject in several engineering applications. In acoustics, several solutions are usually employed to perform a passive noise attenuation. They mainly consist in using porous materials (foams or multi-layered systems [1]), viscoelastic materials and resonators. Porous materials are often very efficient for high frequencies, but usually have poor performances at low frequencies where the energy emitted by the sources is relatively high. In practice, many noise spectra encountered – such as road traffic, or even the solid noise induced by a vehicle – have a high energy in the low frequencies, and induce a significant discomfort for humans. Dealing with the problem of low frequency noise absorption is therefore a crucial problem whose solutions are nevertheless rare.

One of the best current solutions to suppress low frequency resonances is to link the treated site with another linear resonant system that serves as an absorber such as resonators (for example Helmholtz resonator [2,3]). Resonators are indeed a very fitting solution for targeting precise frequencies. It stands especially true for low frequencies were a very high absorption level can be easily obtained by the proper dimensioning of the resonator's length and diameter.

On this work, we focus on the **Q**uarter-**W**ave-length resonator (abbreviated with *QW resonator*). Previous works [4–6] already illustrated how this system can be used to target specific frequencies. The quarter-wavelength resonator consists of a cavity closed at one end and open at the other one. Due to the entrance and end boundary conditions, it enters into resonance whenever an odd multiple of a quarter of the wavelength of the wave is equal to its length. At these resonance frequencies, maximum sound absorption takes place. The length of the resonator therefore determines the main frequencies at which sound is best absorbed. To attenuate low frequencies, the length must therefore be long (for example around 28 cm for 300 Hz) which can

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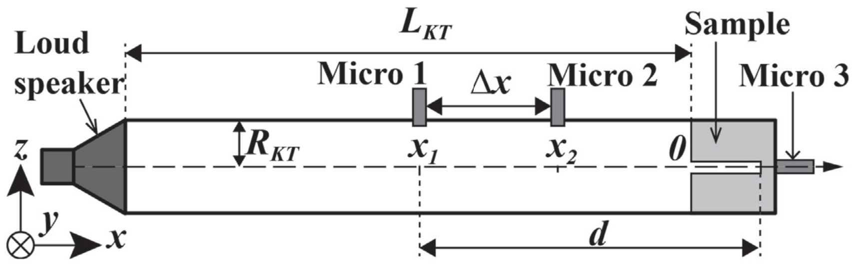

Fig. 1. General sketch of an impedance tube system (also known as Kundt tube).

be problematic for applications where only a limited space is available for the sound absorption system. To overcome this limitation and make easier the practical use of resonators when the available space is limited, we proposed in a former study [7] to bend the resonator, to obtain a smaller thickness of this system in the normal to the wall direction, while keeping good resonance properties at low frequency. However, bending the resonator only reduces the normal-to-the-wall thickness, without changing the absolute length of the system. Therefore, it does not modify the inner volume taken by the resonator, another crucial characteristic for confined applications.

Thus, alternative ways to target sound absorption at low frequencies by using more compact sound absorbers are required.

In this study, we expose unconventional attempts to enhance quarter-wavelength resonators by shifting the resonance frequency towards lower frequencies while keeping the same length of the QW resonator's cavity.

We tried using a hybrid approach by filling the resonator's cavity, in order to combine the QW resonator absorption properties with the performances of various acoustically efficient materials. Starting from classical absorbent porous materials, this article therefore relates the vast exploratory process (6 distinct studies, with nearly 600 different experiments) which led to the design of enhanced quarter-wavelength resonators using carefully designed origami-spirals inserted in the resonator's cavity.

Origami is the japanese word for the ancient art of paper folding, and more usually design a paper-folded structure. In addition to be aesthetically pleasant art forms, origamis also proved to be a very original way to design transformable metamaterials [8]. Some authors proposed origami-like metamaterials to tune adjustable material properties, especially in mechanics (see for example [9,10]). Recently, multiple studies [11–13] proposed reconfigurable acoustic waveguides based on three-dimensional origami-inspired metamaterials. Finally, a recent study [14] uses tunable origami-based helmoltz resonators for noise control.

The paper is organized as follows:

- In section 2, the experimental and simulation methods are presented.
- In section 3, the results of the basic preliminary studies are shown, which led to the definition of the fundamental properties looked for the improvement of the quarter-wave-length resonator.
- Finally in section 4, the proposed solution based on filling the quarter-wave-length resonator with origami spirals is considered and analyzed.

2. Experimental and simulation methods

Because most of the results of this article consist in experimental measurements, we first start this section by describing the experimental setup, before detailing the analytical and numerical aspects of this study.

2.1. Experimental methods

2.1.1. Impedance tube measurements

Different kind of acoustical measurements have been performed using 2 different impedance tubes (also known as Kundt tubes): a Bruel & Kjaer Type 4106 Kundt tube (labelled B&K from now on) used in a two microphones configuration for sound absorption, and a smaller home-made Kundt tube used in a 3 microphones configuration for transmission measurements to extract the intrinsic acoustical parameters through an inversion procedure exposed in section 2.2.3.

An impedance tube consists of a loud speaker at one extremity of a long cavity, here a circular tube. The investigated sample is placed at the other end. A general sketch of a Kundt tube system is shown in Fig. 1 in which the main geometrical parameters are defined. Fig. 2 shows photos of both Kundt tube systems we used, B&K (cf. Fig. 2a) and home-made (cf. Fig. 2b). The specific geometrical dimensions of each system are summarized in Table 1.

A B&K 4178 1/4 inch microphone, equipped with a B&K 2633 pre-amplifier is used, and can be placed at several positions of the upper part of the tube (before the sample). The loudspeaker of the Kundt tube is fed with a B&K 2706 amplifier. A B&K 2690 amplifier processes the signals received by the microphone. A National Instruments NI PXI-1031 chassis generates input signals. The noise absorption coefficient is measured using two microphone positions (this method, called the transfer function method, is defined in standard EN ISO 10534-2, 2003 [15]). Measuring the transfer function between the two microphone's