Vibroacoustic effects of resonant sonic crystals in sound absorption

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Abstract

A resonant sonic crystal made of solid elastic clamped beams is experimentally analysed in this work. The sonic crystal studied in this work has three characteristics: (i) a low filling fraction, (ii) a high frequency Band Gap and (iii) resonant scatterers. Due to the properties (i) and (ii), the sonic crystal behaves as an equivalent fluid with acoustic properties very close to ones of the air. This means that the crystal is almost impedance matched, being the crystal transparent to the incident waves. However, the resonant elements have a resonance frequency in the range analysed in this work, introducing an absorption peak due to the resonances produced by the vibroacoustic coupling. The two microphone transfer function method is used to measure the (complex) impedance and then to evaluate experimentally the absorption coefficient of the 2D SC made of a set of parallel solid beams in the low frequency regime.

Keywords: vibroacoustics, sonic crystal, sound absorption, impedance tube.

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1 Introduction

Phononic crystals (PC) are artificial materials formed by a periodic arrangement of inclusions embedded into a host isotropic and homogeneous material, featuring the propagation of longitudinal, transverse or mixed longitudinal waves. A particular case of PC is the so-called sonic crystal (SC), in which the host material is a fluid and, thus, only longitudinal waves are allowed to propagate [1]. The acoustic behavior of these structures is mainly conditioned by two important design parameters: the lattice constant, *a*, and the filling fraction, *ff*. The distance between two neighboring scatterers is referred to as the lattice constant [2]. It defines the relationship between the geometrical properties of the lattice and its band gaps (ranges of frequencies where sound propagation through the periodic system is not allowed). The filling fraction is defined as the ratio between the volume occupied by scatterers and the total volume occupied by the unit cell [3]. Due to the presence of band gaps, which endows them with a great potential for several applications such as wave guiding, filtering, sound isolation and vibration damping [2], the interest in SCs has increased in the last three decades.

The calculation of the homogenized parameters allows the control of their refractive properties [4], as in long wavelength regime (low frequencies), where $\lambda >> a$, these structures behave as homogeneous materials with effective parameters (i.e., effective sound speed and effective density).

The effect of the vibroacoustic behaviour is of great interest in noise reduction, as it enhances the sound absorption properties of many different materials and structures. For this reason, this phenomenon has been widely studied. Some examples are the extra absorption peaks experimentally detected considering Micro-Perforated Panel Absorbers (MPPA) versus rigid MPPAs [5] and the study of a sub-wavelength multi-resonant scatterer (SMRS) to report perfect and broadband absorption for audible sound [6].

In this work, we study the vibroacoustic effects of a SC by measuring the sound absorption and sound reflection coefficients with an impedance tube. Also, due to the design of a plunger that allows changing the thickness of the air layer placed behind the SC, the effect of the different thicknesses of the air chamber are also studied.

2 Determination of sound absorption coefficient

The sound absorption coefficient of the samples analysed in this work will be determined by using the transfer function method. This procedure, extensively detailed in the standard UNE-EN ISO 10534-2, is based on the use of an impedance tube, two microphone locations and a digital frequency analysis system for the determination of the sound absorption coefficient of sound absorbers for normal incidence [7]. This well-known method has been widely used by many authors in a big amount of publications [8-11], especially in acoustical material characterization for building engineering.

In order to measure the sound absorption coefficient of SCs, a methacrylate impedance tube of squared cross section has been designed and manufactured.

As specified in the standard, an impedance tube requires two perforations for the two microphone positions. This method presents a critical frequency, f_c, for which the wavelength matches the distance between the microphones, *s*, and the acoustic pressure is very similar in both microphones, generating problems in data processing. To avoid this problem, an additional hole has been included in the design in order to allow exchanging the microphones and also improving the resolution in the low frequency regime. However, as is shown in Table 1, the critical frequency is higher than the limit working frequency of the tube, so measures have been done using one microphone position.

Table 1 – Details of the system.

x_1 (cm)	x_2 (cm)	s (cm)	Frequency range (Hz)	f_c (Hz)
19	10	9	192-1732	1905

Continuous white noise is emitted by a loudspeaker using a signal generator and the pressure signal in each position is registered using two 4189-1/2-inch free-field Brüel&Kjær prepolarized microphones with a Type 2761 prepolarized preamplifier each. Both microphones have been calibrated considering as a reference a pressure level of 94.0dB at 1kHz. The loudspeaker is connected to a power amplifier.

The transfer function, H_{12}, between the two microphones can be defined as the complex ratio between the pressures registered in these positions [7]. As long as the analysed frequencies are smaller than the cutoff frequency of the tube, plane waves propagate and so the transfer function method can be obtained as follows

$$p_1 = e^{-jk_0x_1} + re^{jk_0x_1} , \quad (1)$$

$$p_2 = e^{-jk_0x_2} + re^{jk_0x_2} , \quad (2)$$

$$H_{12} = \frac{p_2}{p_1} = \frac{e^{-jkx_2} + re^{jkx_2}}{e^{-jkx_1} + re^{jkx_1}} , \quad (3)$$

Where p_1 and p_2 are the acoustic pressures registered by each microphone, k is the wavenumber, x_1 and x_2 are the distances between the sample and both microphones and r is the reflection coefficient.

However, since H_{12} is directly obtained when performing acoustic measurements, it is possible to calculate the reflection coefficient, r, and the absorption coefficient, α, as follows

$$r = \frac{H_{12}e^{-jkx_1} - e^{-jkx_2}}{e^{jkx_2} - H_{12}e^{jkx_1}} , \quad (4)$$

$$\alpha = 1 - |r|^2 , \quad (5)$$

This allows to do all the measurements without exchanging the microphone positions, obtaining directly the value of H_{12} in each case: Also, measurements considering the thickness of the air cavity, d, behind the study sample from 1cm to 5cm have also been done with the purpose of studying the effect of the air layer between the SC and a rigid termination placed behind it. Experimental set-up is shown in Figure 1b.

2.1 The Resonant Sonic Crystals

A SC made of an arrangement of Ti-6Al-4V parallel bars acting as scatterers (two-dimensional periodicity) with squared transverse section and squared lattice is set as a test sample. The structure has a lattice constant, a = 1.45mm and a filling fraction, ff = 9.6% (see Figure 1a).

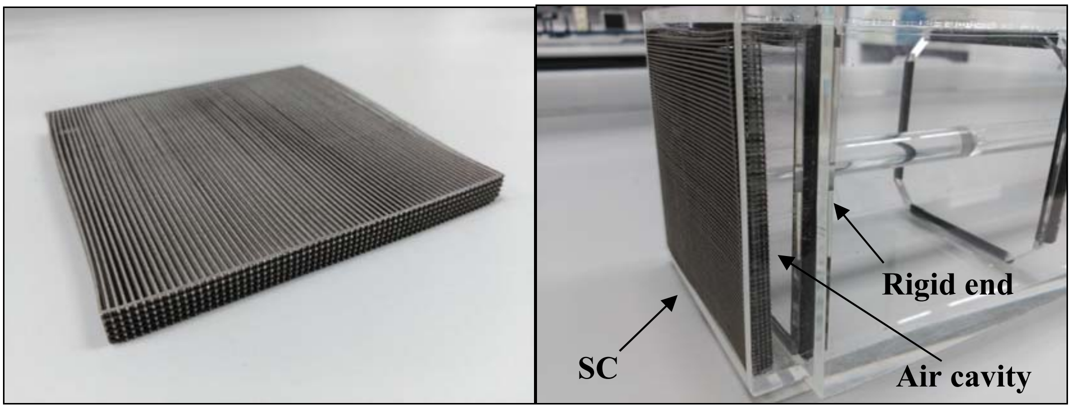

Figure 1 – a) SC with square lattice. b) Placement of the SC into the impedance tube.

As it was mentioned above, one of the most important properties of SCs is the existence of band gaps. The Bragg's frequency, f_B, of the SC is at the middle of the band gap and depends on the lattice constant and the speed of sound in the host medium. This frequency can be calculated as follows

$$f_B = \frac{c}{2a} = 118275.9 Hz \ , \tag{6}$$

As can be seen, the Bragg's frequency of the analysed SC is placed in the ultrasound regime, at much higher frequencies than those used in the impedance tube. Due to this, the system will behave as a homogeneous material with slightly different properties to those of the host medium (air), acting as an equivalent fluid [12]. The normalized effective parameters of the SC are calculated as follows [4]

$$\overline{\rho}_{eff} = \frac{1+ff}{1-ff} = 1.21 \ , \tag{7}$$

$$\overline{c}_{eff} = \frac{1}{\sqrt{1+ff}} = 0.96 \ , \tag{8}$$

Where $\overline{\rho}_{eff}$ and $\overline{c}_{eff}$ are the effective density and effective sound speed propagation in the SC and the host medium, respectively.

This similarity with the effective parameters between air and the SC is due to the low filling fraction of the structure. For this reason, the SC is coupled with the air in terms of impedance and viscothermal losses are not effectively acting.

3 Results and discussion

All the measurements shown in this work have been performed in the working frequency range of the impedance tube [192Hz to 1732Hz] in order to study the vibroacoustic properties of SC in sound absorption. The first step has been to study the behaviour of the SC by itself and, thus, placing the rigid ending immediately behind the sample (d=0cm). In this configuration, the measured reflection coefficient is close to one for all the frequency range, meaning that the crystal is completely transparent to acoustic waves. However, a peak of absorption appears at 800Hz caused by the vibration of the scatterers at its resonant frequency, and also producing a phase change of the incident waves (see Figure 2).

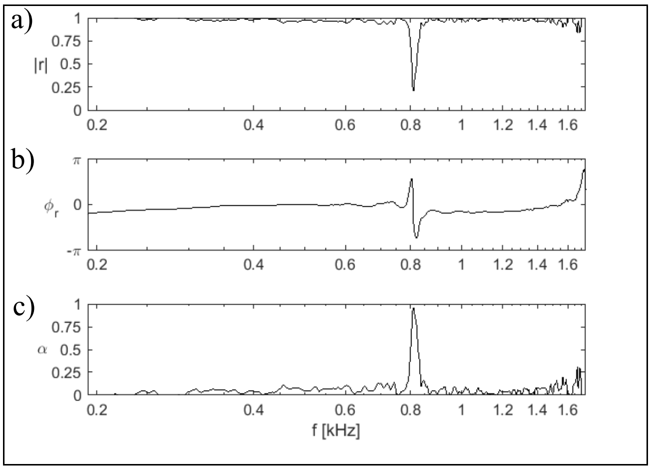

Figure 2 – Experimental measurements considering the air cavity of d=0cm (|r|). a) Sound reflection coefficient (ϕ_r), b) Phase of the sound reflection coefficient, c) Sound absorption coefficient (α).

Furthermore, the effect of different lengths of the air cavity behind the SC has been considered, as shown in Figure 3.

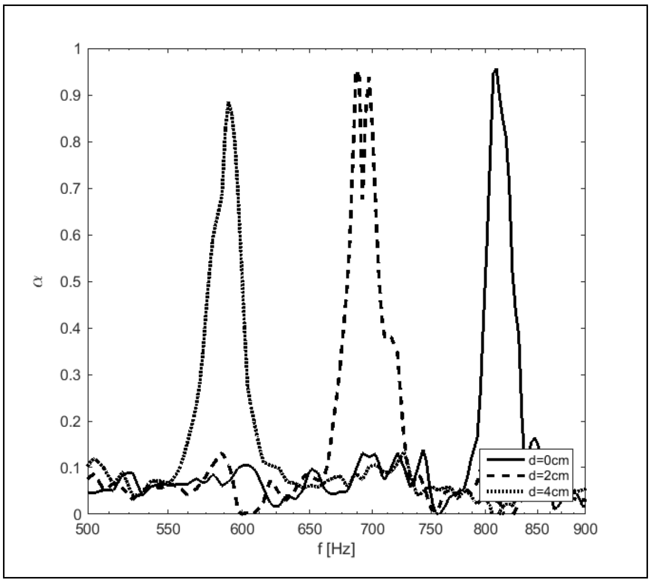

Figure 3 – Sound absorption coefficient considering a thickness of the air layer of 0cm (solid line), 2cm (dashed line) and 4cm (dot line).

When experimental results are analysed (Figure 3), it is observed that peaks in the sound absorption coefficient in all the cases decresases in frequency as the thickness of the air layer is increased, being all of them close to 0.8. This effect may be due to the influence of the air volume below the SC, that acts as a spring with stiffness inversely dependent on the size of the cavity.

4 Conclusion

Damped flexural vibrations of the scatterers of a resonant SC is the mechanism proposed for sound absorption in the homogeneization regime. Measurements with an impedance tube show very high dissipation with values of the sound absorption coeficient around 0.8. The maximum of absorption can be controlled by changing the size of the air cavity between the SC and the rigid end.

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