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Acoustic characterization of silica aerogel clamped plates for perfect absorption

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ABSTRACT

A multiobjective optimization procedure is employed to retrieve the viscoelatic parameters of silica aerogel clamped plates. This retrieval method preserves the aerogel sample integrity and, in contrast to the existing ones, relies on the minimization of two different cost functions. The first one, namely J_1, is related to the reflective properties of clamped plates backed by a rigid cavity, while the second one, namely J_2, concerns both the reflectance and transmittance spectra measured in transmission configuration. The recovered parameters are in agreement with previously reported values in the literature. In addition, they are also supported by designing structures for perfect absorption (100% of absorption), which has been validated experimentally. Aerogel plates can be therefore used as innovative building units of artificial structures for the broadband absorption of sound.

1. Introduction

Silica aerogels have been mainly developed for thermal and acoustic insulation purposes [1;2]. Therefore, their manufacturing process has been widely studied to improve their bulk properties and they present an extremely low density [3], an ultra low thermal conductivity [4], and a subsonic sound velocity [5;6]. The extremely low static density is directly related to their high porosities. The frame of silica aerogel effectively consists of an assembly of connected small cross-sections beam-like elements resulting from fused nanoparticles. This particular assembly additionally provides silica aerogel a very low elastic stiffness when compared to rigid silica structure of identical porosity [6]. Silica aerogels are then nanoporous lightweight materials [2]. Beyond these soft bulk material properties, silica aerogel plates or membranes are excellent candidates to design original acoustic metamaterials, because they exhibit subwavelength resonances and present efficient absorption capabilities [7].

Recently, membrane-type metamaterials have shown an increasing interest to control acoustic waves. While a single membrane presents negative mass density [8] as well as may be used as a perfect subwavelength absorber [9;10], the periodic arrangement of plates combined with other kind of resonators presents single and double negativity [11]. More recently, periodic arrangement of clamped plates has been used to control the harmonic generation [12] and the solitary wave generation in the nonlinear acoustic regime [13].

The characterization of the elastic properties of the silica aerogel plates is therefore primordial to design efficient aerogel-based acoustic metamaterials. Two types of test have been yet proposed to characterize their elastic properties: mechanical destructive tests and ultrasonic non-destructive tests. On the one hand, Woignier et al. [14;15;16] used 3-point bending and uniaxial compression while Haj-Ali et al. [17] used digital image correlation technique to determine the mecanical behavior of aerogel. On the other hand, ultrasonic tests [5;6;18;19] provide acoustic properties but are limited in terms of frequencies and by definition do not provide information in the audible regime.

This work aims at providing the viscoelastic properties of silica aerogel plates in the audible frequency range thanks to a novel signal processing method based on usual impedance tube measurements which have the advantage to preserve the sample integrity. The silica aerogel, being nanoporous, can be approximated by a viscoelastic material in this low frequency regime; i.e. in the audible frequency range. In this work we also show that clamped plates of silica aerogel can be used to design ultralight acoustic metamaterials for the perfect absorption of sound.

The article is divided in four Sections. In Section 2, the proposed method to retrieve the elastic properties is presented. A genetic optimization algorithm is used with two objective (or cost) functions to estimate Young modulus, loss factor, Poisson's ratio and mass density of

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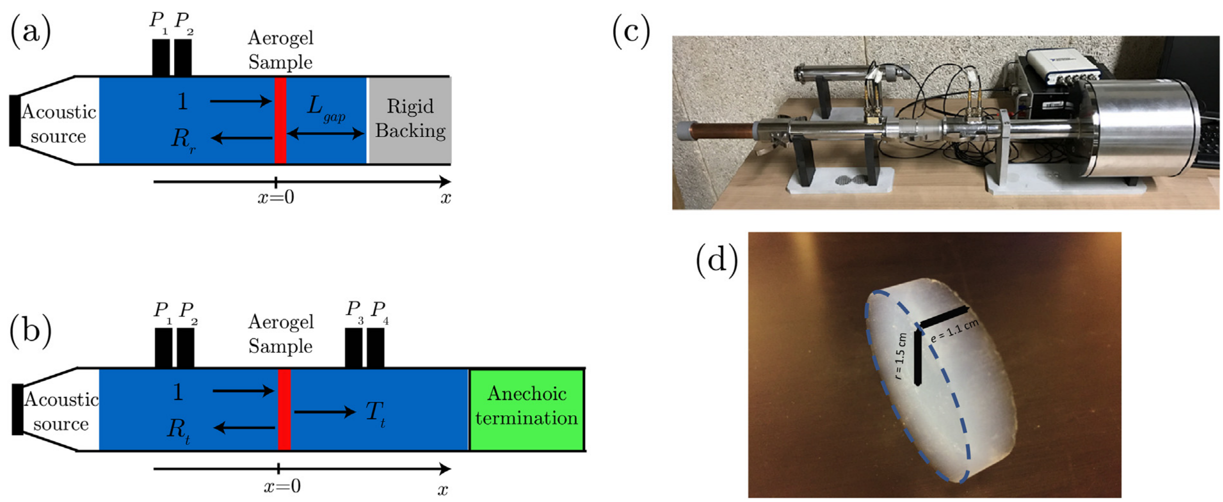

Fig. 1. Reflection and transmission configurations and experimental set-up. (a) acoustic reflection configuration to determine reflection coefficient from the evaluated pressure P_1, P_2. (b) acoustic transmission problem to assess reflection and transmission coefficients from the pressures P_1, P_2, P_3, P_4. (c) Acoustic impedance tube mounted for the experimental characterization of the transmission problem. (d) Photograph of a Silica aerogel plate with thickness $e = 1.1$ cm and radius $r = 1.5$ cm.

the sample. The two objective functions arise from two complementary acoustic configurations: the reflection problem, where the aerogel membrane is backed with a rigid cavity, and the transmission problem. Section 3 make use of the recovered parameters to derive the perfect absorption (PA) condition [9;20] (i.e. $\alpha = 1$, where α is the acoustic absorption) when the silica-aerogel plate is backed by a rigid cavity of a specific length. By varying the cavity length from 0.5 cm to 6.5 cm, the positions of both zeros and poles of the reflection coefficients are studied in the complex frequency domain. Section 4 provides the concluding remarks and comments.

2. Acoustic characterization of the silica aerogel plate mechanical properties

The characterization of the viscoelastic properties of the silica aerogel plate is based on the analysis of data acquired in the two configurations shown in Fig. 1. In the first one, depicted in Fig. 1(a), the reflection coefficient of the aerogel plate when rigidly backed with an air cavity is measured. In the second one, depicted in Fig. 1(b), both the reflection and transmission coefficients of the aerogel plate in a transmission problem are measured. In addition, Fig. 1(c) shows a photograph of the experimental setup used for the characterization.

In this Section, we present the retrieval procedure which consists in minimizing the difference between the experimental and the theoretical coefficients.

2.1. Direct modeling

Assuming a Kirchhoff-Love plate [21], the transverse displacement w_s satisfies the equation of motion

$$D\nabla^4 w_s + e\rho \frac{\partial^2 w_s}{\partial t^2} = 0, \tag{1}$$

where e is the plate thickness, ρ is the plate density and D is the flexural rigidity. $D = \frac{Ee^3}{12(1-\nu^2)}$, where E is the Young modulus and ν is the Poisson coefficient. Considering the temporal convention $e^{i\omega t}$, with ω the angular frequency, the silica aerogel viscoelastic behavior implies a complex Young modulus of the form $E = E_r(1 + i\eta\omega)$, where E_r is the real part of the Young modulus and η is the loss factor. Assuming a subwavelength regime, the silica aerogel disk is considered as a punctual resonant element. The acoustic impedance Z_p of a clamped circular cross-section plate was derived [7] and takes the form,

$$Z_p = \frac{-i\omega\rho e}{S} \frac{I_1(k_p r)J_0(k_p r) + J_1(k_p r)I_0(k_p r)}{I_1(k_p r)J_2(k_p r) - J_1(k_p r)I_2(k_p r)} \tag{2}$$

where $S = \pi r^2$ is the cross-section surface of the plate, J_n and I_n are the regular and modified Bessel functions of the first kind of order $n \in \{0, 1, 2\}$ and $k_p^2 = \omega\sqrt{\rho e/D}$ is the plate wavenumber.

In the impedance tube, the aerogel clamped plate acoustically behaves as a point resonator mounted in series, implying sound velocity continuity and pressure discontinuity. Therefore, the clamped plate can be represented by a matrix M_p when using the transfer matrix method, [22] which reads as

$$[M_p] = \begin{bmatrix} M_{p11} & M_{p12} \\ M_{p21} & M_{p22} \end{bmatrix} = \begin{bmatrix} 1 & Z_p \\ 0 & 1 \end{bmatrix}. \tag{3}$$

The reflection and transmission coefficients for this symmetric and reciprocal transmission problem are then directly obtained from the elements of M_p as [22],

$$T = \frac{2e^{ikL}}{M_{p11} + M_{p12}/Z_t + Z_t M_{p21} + M_{p22}}, \tag{4}$$

$$R = \frac{M_{p11} + M_{p12}/Z_t - Z_t M_{p21} - M_{p22}}{M_{p11} + M_{p12}/Z_t + Z_t M_{p21} + M_{p22}}, \tag{5}$$

where $Z_t = \rho_t c_t/S$ is the impedance of the surrounding medium, i.e. in our case the effective fluid occupying in the impedance tube, S is the characteristic cross-sectional area of the tube, k is the wavenumber in the air and L is the length of the sample, in our case $L = e$. Viscous and thermal losses are effectively accounted for in the tube thanks to the formulae provided by Stinson [23].

The aerogel plate system being symmetric and reciprocal, the modeled coefficients in the transmission problem are given by,

$$T_{mod}^t = \frac{2}{2 + Z_p/Z_t}, \quad R_{mod}^t = \frac{Z_p/Z_t}{2 + Z_p/Z_t}. \tag{6}$$

In the reflection problem, the system is composed of an aerogel plate in front of a closed cavity. In this case, the transfer matrix method reads as,

$$\begin{bmatrix} P \\ V \end{bmatrix}_{x=0} = [M_p][M_c]\begin{bmatrix} P \\ 0 \end{bmatrix}_{x=L_{gap}}, \tag{7}$$