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Sound absorption provided by an impervious membrane/cavity/activated carbon arrangement

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Abstract

A tensioned impervious membrane at the entrance of an air cavity which is backed by a reflecting end provides high and narrow sound absorption peaks at certain frequencies. In the absence of flexural bending, the sound absorption is mainly due to the vibration energy dissipation in the membrane. The frequencies at which maxima of sound absorption occur are dependent on the membrane resonances and the geometry of the cavity. Inclusion of a porous material inside the air cavity broadens the sound absorption curve at low frequencies making the absorber more efficient. It has been shown that, due to adsorbing and desorbing physical mechanisms, granulated activated carbon exhibits unusually very good low-frequency sound absorption properties. This article presents some experimental and theoretical results of a circular tensioned membrane clamped in a cylindrical cavity that is closed with a reflecting backing. The effects on the normal-incidence sound absorption coefficient of adding a porous layer of activated carbon inside the cavity are reported. The use of an activated carbon layer showed better performance in the low frequency range than traditional fiberglass with the same thickness.

Keywords: Sound absorption, Membrane, Activated carbon

1 INTRODUCTION

Sound absorption can be achieved by different ways. Membrane sound absorbers are typically used to absorb low-frequency noise. Basically, they consist in a vibrating element such as a flexible panel, plate, or tensioned membrane which is fastened over its entire perimeter in front of an air cavity that ends in a rigid wall. The vibrating element is forced by an incident sound wave. The cavity can be either partly or completely filled with a porous material. The case of a tensioned clamped membrane is simpler than that of a plate [1], since we do not have to deal with the plate's bending stiffness and thus the speed of transverse vibration waves does not depend on frequency. Therefore, the sound energy dissipation of an impervious tensioned membrane will be mainly dependent of its mechanical damping which is usually given in terms of a loss factor.

The use of vibrating membranes in acoustics has been studied for many years. Ingard [2] reported the results of absorption and transmission of a circular membrane inside a tube which had sound absorbing material at its end. The velocity distribution of the system was derived by using equivalent circuits. Other authors [3, 4] have studied the sound absorption produced by a single membrane placed in front of a rigid wall which resulted in a mass-spring system. Kiyama et al. [5] presented the results of double-leaf membranes and describe the effects of a double-mass-spring resonance. The effect of placing sound absorption material inside the air cavity was investigated by Bosmans et al. [6].

It seems that Song and Bolton [7] were the first to consider the membrane tension on the sound absorption characteristics of a membrane backed by an air cavity. They developed a theoretical model capable of explaining the effect of membrane tension and the energy dissipated by the motion of the membrane itself. Later, they extended their theory to the case of permeable membranes [8] and to other types of membrane-based sound absorbers [9]. More recently, the sound absorption characteristics of thin microperforated membranes backed by an air cavity have been investigated by considering the spatially varying acoustic impedance due to the membrane perforations [10]. They found good agreement between theoretical and experimental results.

On the other hand, inclusion of a porous material inside the air cavity broadens the sound absorption curve at low frequencies making the absorber more efficient. Usually porous materials placed inside the cavity have been either cellular or fibrous, such as foams, fiberglass and rockwool. The use of fine granular material is less common and may require the use of an impervious membrane. In particular, activated carbon has received much attention as an absorbing material due to its unusually very good low-frequency sound absorption properties. It has been shown that these properties are due to adsorbing and desorbing physical mechanisms [11].

A first stage in manufacturing activated carbon is to carbonize a raw material which can be coconut husk or coal, which is subjected to an inert atmosphere with temperatures between 700 and 1000 °C. Later, the carbonized material is activated with oxidizing gases such as carbon dioxide or water vapor, at temperatures between 800 and 900 °C. The combination of carbonization and activation creates a range of porosities that goes from nanometric pores to micrometric pores inside the grains. This range of porosities produces an increase in its surface area and determines the sorption characteristics of this material [11]. Activated carbon has also been used in filtering and purification applications, among others.

In this article, we present the sound absorption performance of a system composed of a thin tensioned impervious circular membrane backed by an air cavity which is partially filled by activated carbon.

2 THEORY

The sound absorption of a combination of a circular membrane and an air cavity backed by a rigid termination which is partially filled with a porous material can be determined by using the impedance translation theorem [12]. For this, the governing equation of a thin tensioned clamped membrane of radius a which is forced by a periodic force $f(r,\theta,t)$ acting uniformly on the membrane is [13]

$$T\nabla^2 W(r,\theta,t) + f(r,\theta,t) = \rho_s \frac{\partial^2 W(r,\theta,t)}{\partial t^2}, \tag{1}$$

where $W(r,\theta,t)$ is the transverse displacement of the membrane and ρ_s is the membrane's mass per unit area. The effect of membrane damping is included by the complex tension $T = T_0(1+j\eta)$, where T_0 is the membrane's tension (N/m), η is the damping loss factor of the membrane and $j=\sqrt{-1}$. The velocity amplitude for harmonic excitation can be expressed as $u = j\omega W$.

Since the membrane is excited by the action of a uniformly distributed pressure (a plane sound wave) only axisymmetric modes need to be considered. The membrane average surface impedance is determined as the ratio between the sound pressure and the spatially averaged velocity on the surface of the membrane $\langle u \rangle$ which is given by

$$\langle u \rangle = \frac{1}{S}\int\int_S u(r)dS = \frac{1}{\pi a^2}\int_0^{2\pi}\int_0^a u(r)rdrd\theta = \frac{2\pi}{\pi a^2}\int_0^a u(r)rdr. \tag{2}$$

A simplified expression of such membrane spatially averaged surface impedance is [10]

$$Z_m = -j\omega\rho\left[\frac{2}{k_m a}\frac{J_1(k_m a)}{J_0(k_m a)} - 1\right]^{-1}, \tag{3}$$

where J_0 and J_1 are Bessel's functions, ρ is the air density, and $k_m = \omega\sqrt{\rho_s/T}$.

The total impedance Z of the absorber shown in Figure 1 is determined by including the effect of the air cavity and the infill porous material using the impedance translation theorem [12]. An identical methodology is applied in [1], but here D is the cavity depth and d_p is the thickness of the infill porous material. Thus, the normal-incidence sound absorption coefficient is obtained as $\alpha = 1 - |R|^2$, where R is the complex reflection coefficient obtained from the total surface impedance of the absorber $R = (Z - Z_0)/(Z + Z_0)$, where Z_0 is the characteristic impedance of the air.

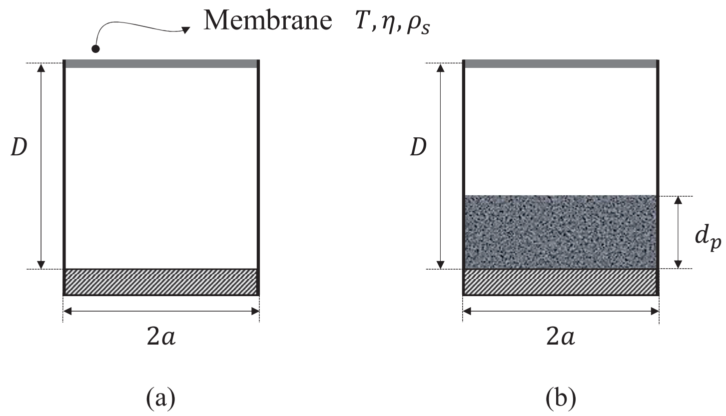

Figure 1. Schematics of the sound absorber. (a) empty; (b) partially filled with a porous material

3 EXPERIMENTAL METHOD

A series of experiments were performed for assesing the sound absorption properties of the absorber. A rigid vertical impedance tube of inner diameter 100 mm was adapted to implement a circular membrane absorber at one end and a loudspeaker at the opposite end (see Figure 2). The standardized two-microphone technique described in ISO 10534:2001 Part 2 was used to measure the normal-incidence sound absorption coefficient of the absorber. The loudspeaker was driven with white noise signal that varied from 0 to 2 kHz. The signals were generated and processed by a two-channel real-time fast Fourier transform analyzer, which was connected to a computer for data analysis.

Figure 2. Experimental setup for measuring the normal-incidence sound absorption coefficient of the membrane absorber

Because of the random characteristics of the noise signal, a total of 200 averages were taken for each measurement. The transfer functions were measured between the signals of two 1/4-inch microphones at increments of 1 Hz. In light of the diameter of the standing wave tube and the center-to-center spacing between two microphones (100 mm), the measurements according to the ISO standard were assumed valid in the frequency range 200 to 1500 Hz. Care was taken to ensure a good sealing of all the elements of the experimental setup.

The absorber was made of milled stainless steel cylinders that perfectly fitted the impedance tube inner diameter. Two kinds of porous materials were used in the experiments: 1) a fiberglass sample of thickness 20 mm and flow resistivity of 12848.2 Ns/m^4 and 2) granular activated carbon kindly supplied by Salford Research and Development, UK. The activated carbon was compacted inside the air cavity. The elastic membranes were made of silicone with a thickness of 0.623 mm, constant $\eta = 0.005$, surface densities between 0.237 and 0.265 kg/m^2, and subjected to different tension values. The acoustic characteristics of both the fiberglass and the activated carbon were measured independently in the impedance tube before being used as infill materials in the absorber.

4 RESULTS AND DISCUSSION

Figure 3 shows the results for two absorbers without absorbing material in the air cavity. It can be observed that this kind of absorber exhibits narrow maxima of sound absorption coefficient. It is noted that the frequency of these maxima are close to the natural frequencies of the membrane and located at frequencies at which the surface reactance becomes zero. We observe that there are a good correlation between the theoretical and experimental results. In addition, these findings agree well with those reported in the literature [7].

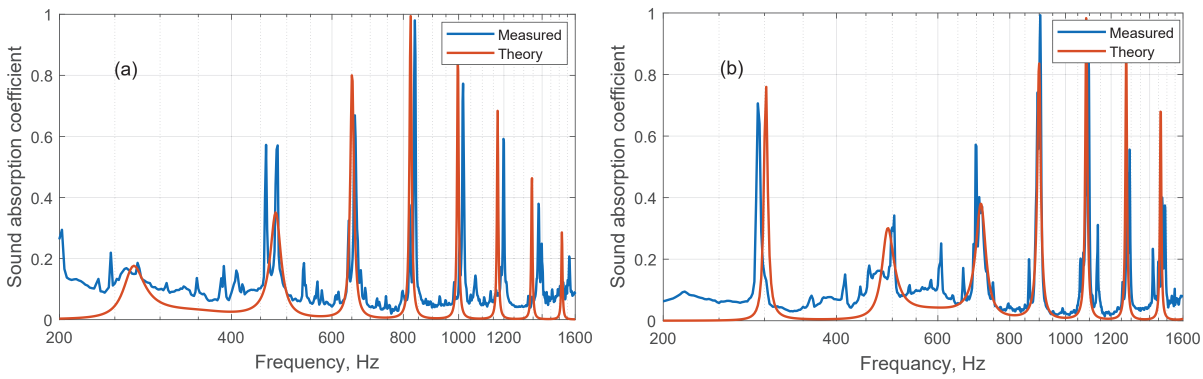

Figure 3. Sound absorption coefficient for a membrane absorber without porous material in its cavity. (a) $D = 100$ mm, $T = 76.53$ N/m^2, $\rho_s = 0.265$ kg/m^2; (b) $D = 40$ mm, $T = 81.04$ N/m^2, $\rho_s = 0.237$ kg/m^2

In Figure 4 we can observe the effect of introducing a 20 mm thick porous material in the cavity. Figure 4a shows the effect of fiberglass in the cavity where the sound absorption values are increased for frequencies below 600 Hz. The measured sound absorption coefficient (blue line) has a first maximum around 250 Hz, which increases its sound absorption value by about 0.1. In addition, a second broad maximum in sound absorption appears, which is not present in the empty absorber (gray line). The correlation between these measured values (blue line) and those calculated (red line) below 300 Hz is less accurate compared to what is observed in Figure 3, where the theoretical values overestimate the measured ones. Above 300 Hz there is little difference between the measured and estimated results.

Figure 4b shows the corresponding results using activated carbon in the cavity. We see that, for this case, there is a better agreement between theoretical and measured values, observing three maxima of sound absorption that increase the bandwidth in comparison to the empty absorber. By comparing Figures 4a and 4b, it is verified that the sample of activated carbon exhibits better sound absorption than the fiberglass sample, increasing the value of the sound absorption coefficient for the first two maxima by 0.4 approximately. It is noted that over 600 Hz, the sound absorption behaves quite similar independently of the type of porous material in the cavity.

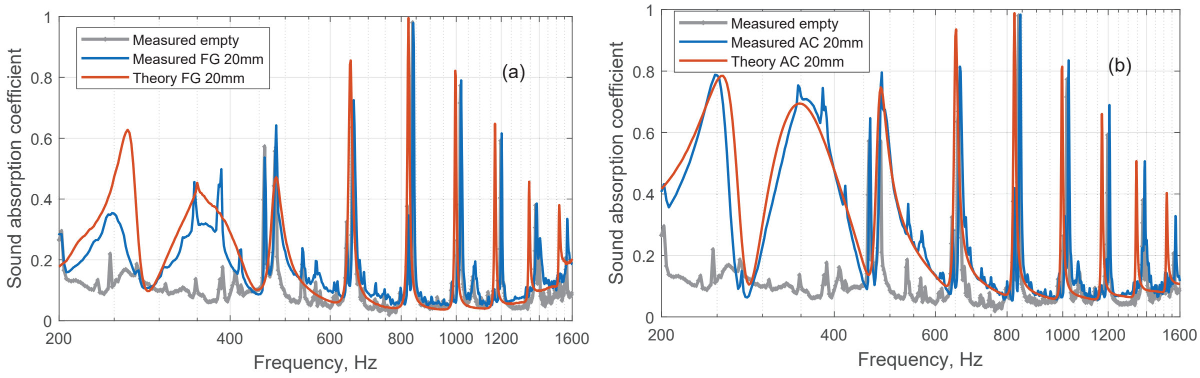

Figure 4. Sound absorption coefficient for a membrane absorber ($D = 100$ mm, $T = 76.53$ N/m^2, $\rho_s = 0.265$ kg/m^2) partially filled with a porous material of thickness $d_p = 20$ mm in its cavity. (a) fiberglass (FG); (b) activated carbon (AC)

The effect of filling the cavity with porous material on the sound absorption coefficient and on the total surface impedance is observed in more detail in Figure 5. Figure 5b shows the experimental results of the real and imaginary part of the total surface impedance of the absorber as a function of frequency. It can be seen how the total surface resistance increases by the presence of both materials, which is much higher for the activated carbon than for the fiberglass of the same thickness.

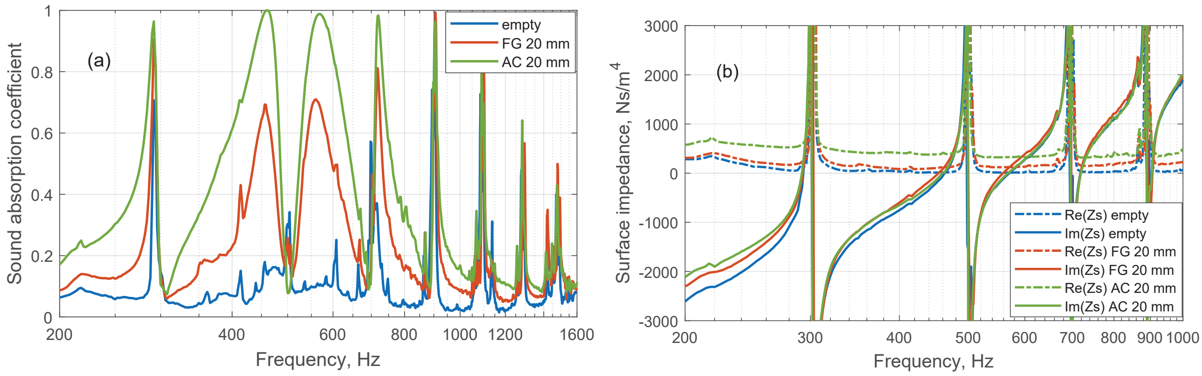

Figure 5. Experimental results for a membrane absorber ($D = 40$ mm, $T = 81.04$ N/m^2, $\rho_s = 0.237$ kg/m^2) partially filled with either fiberglass (FG) or activated carbon (AC) of thickness $d_p = 20$ mm in its cavity. (a) sound absorption coefficient; (b) real and imaginary parts of its surface impedance

Figure 6 shows the results of the sound absorption coefficient for another absorber ($D = 40$ mm, $T = 55.2$ N/m^2, $\rho_s = 0.265$ kg/m^2) with $d_p = 20$ mm of porous material within the air cavity, i.e., fiberglass (Figure 6a) and activated carbon (Figure 6b). It is observed that the sound absorption maxima are broadened between 300 and 800 Hz for both materials. It is also observed that a 20 mm thick activated carbon provided better improvement of the sound absorption than fiberglass. By comparing the sound absorption measured values for the absorber reported in Figure 4 with that of Figure 6, it can be noticed that the same samples of porous material (20 mm of fiberglass and activated carbon) increase differently the total sound absorption. For the absorber in Figure 6 the porous material fills 50% of the air cavity and the sound absorption becomes more effective, reaching about 100% sound absorption with 20 mm of activated carbon. In the case of the absorber in Figure 4, these porous materials only filled 20% of the cavity, reaching a maximum of about 80% in sound absorption with the same sample of activated carbon. When comparing the results of Figures 4 and 6, it can be said that the agreement between the measurements and predictions of sound absorption of the absorber with porous material within its air cavity is satisfactory. A common observation is that for both absorbers, the frequency range for which an increase in sound absorption is achieved is limited, and outside this range of frequencies the sound absorption maxima remain with a narrow bandwidth.

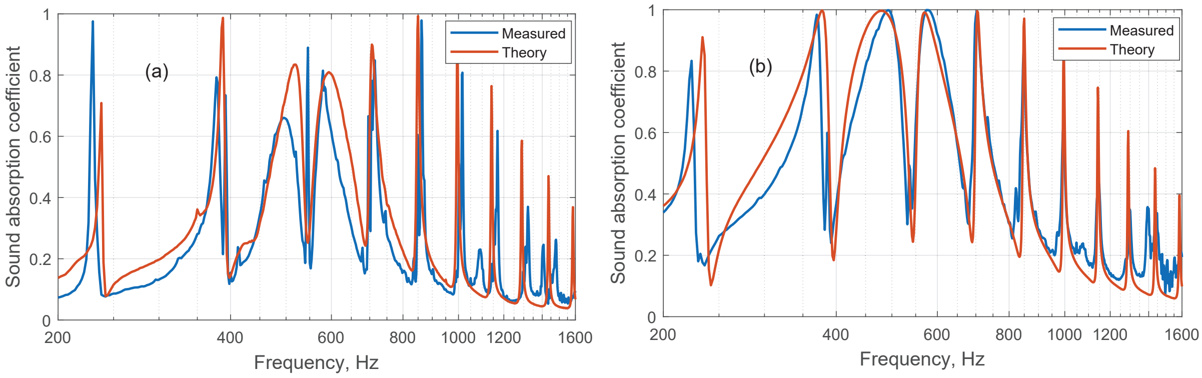

Figure 6. Sound absorption coefficient for a membrane absorber ($D = 40$ mm, $T = 55.2$ N/m^2, $\rho_s = 0.265$ kg/m^2) partially filled with a porous material of thickness $d_p = 20$ mm in its cavity. (a) fiberglass (FG); (b) activated carbon (AC)

It is interesting to note that, although the 20 mm thick fiberglass and the 20 mm thick activated carbon do not exhibit a large sound absorption coefficient at very low frequencies, both increase the sound absorption performance of the membrane absorber at frequencies below 1000 Hz. A similar result was reported by Venegas [11] for two Helmholtz resonators filled with activated carbon. In this case, an increase of approximately three times the maximum in sound absorption was observed. The device did not improve the sound absorption properties at high frequencies. Using a microperforated membrane with 1% of perforation rate also did not report improvement when compared with the empty resonator. These observations also agree with the findings reported in this article.

5 CONCLUSIONS

In this article an absorber made of a tensioned impervious membrane at the entrance of an air cavity which is backed by a reflecting end has been presented. It was observed that this absorber provides high and narrow sound absorption peaks at certain frequencies that are related to the natural frequencies of the membrane. These sound absorption values are mainly due to the vibration energy dissipation in the membrane. Inclusion of a porous material inside the air cavity increases and broadens the sound absorption curve at low frequencies making the absorber more efficient. It was observed that the use of activated carbon as an infill porous material reported better performance in the low frequency range than traditional fiberglass of the same thickness. It was also observed that the improvement in sound absorption is also related to the amount of volume of the air cavity that is filled by the material. Although quite simple, theoretical estimations of the sound absorption coefficient by using the average surface membrane impedance and the impedance translation theorem, show good agreement with the experimental results.

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