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A key physical mechanism that controls the sound absorption of aerogel powders

Hasina Begum[1]
Department of Mechanical Engineering, The University of Sheffield, S1 3JD, United Kingdom

Yutong Xue[2]
Midea Corporate Research Center, Foshan, Guangdong, China, 52831

J. Stuart Bolton[3]
Ray W. Herrick Laboratories, School of Mechanical Engineering, Purdue University, 177 S. Russell St., West Lafayette, Indiana 47907-2099, USA

Kirill V. Horoshenkov[4]
Department of Mechanical Engineering, The University of Sheffield, S1 3JD, United Kingdom

ABSTRACT

A key physical mechanism that controls the acoustic absorption and attenuation in a loose, air-saturated aerogel granular mix with the grain diameter being in the order of a few microns is not well understood. A particular challenge here is to understand sound propagation in an aerogel powder composed of highly porous, low-density particles with sub-micron pores. Experimental evidence suggest that a relatively thin layer of an aerogel powder can provide a very high narrow band acoustic absorption at relatively low frequencies. This study presents an attempt to explain this physical phenomenon with two well-known analytical models for the acoustical properties of porous media. The results of this study suggest that an aerogel powder behaves like a viscoelastic layer and its absorption coefficient depends strongly on the sound pressure level in the incident wave, i.e., this acoustic behaviour is non-linear. The loss factor seems to be a key parameter which predicts the observed acoustical behaviour. The loss factor is found to be higher than physically reasonable at low frequencies and decreases with the frequency exponentially. This behaviour is likely to relate to the frictional interaction between the particles in the powder and acoustic fluidisation effect.

1. INTRODUCTION

A majority of previous research has focused on the acoustical properties of millimetric (e.g. [1]) grain mixes with sub-millimeter pore sizes (e.g. [2]). As a result, there is a clear gap in the understanding of the acoustical behaviour of light powders such as aerogels with particle sizes close to a micron and

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[1] hasina.begum@nuron.tech

[2] xyt@alumni.purdue.edu

[3] bolton@ecn.purdue.edu

[4] k.horoshenkov@sheffield.ac.uk

particle density being close to that of air, i.e. ρ_0 = 1.2 kg/m^3. There is evidence that relatively thin (30-50 mm) layers of these powders are able to absorb well at low frequencies (e.g. 100 – 500 Hz) noise. There is also evidence that their acoustical behaviour is non-linear, i.e. it depends on the amplitude of the incident sound pressure. Modelling the acoustical properties of these powders is a challenge because the key physical mechanisms that control their ability to absorb sound are not fully understood.

The aim of this work is to illustrate a connection between the non-acoustical properties of aerogel powder and its normal incidence absorption coefficient through modelling and experiment. It is shown that a key mechanism of absorption in this class of materials relates to the particle oscillation and associated material damping. This behaviour is non-linear.

2. METHODOLOGY

The material studied in this work was Enova IC3100 produced by Cabot Corporation, Alpharetta Georgia, USA. Figure 1 is a scanning electron microscope image (SEM) of this material. The bulk density of this aerogel powder determined using calibrated scales was ρ_b = 38.71 kg/m^3.

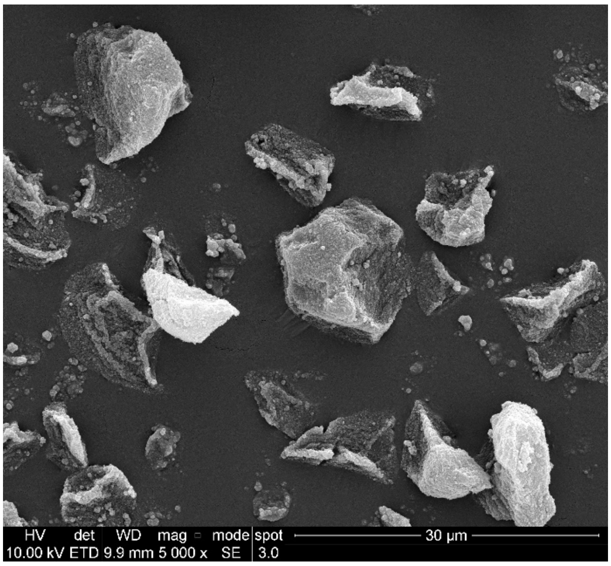

Figure 1: A SEM photograph of Enova IC3100 aerogel powder.

The acoustical absorption coefficient of aerogel powder was measured in a specially made 10 mm diameter standing wave tube in accordance with the ISO 10534-2 standard. The aerogel powder layer thickness was set to 50 mm. This 2-microphone setup enables measurement of hard-backed porous layers in the frequency range from 100 to 4999 Hz. Two models were used to predict the complex effective density and bulk modulus of aerogel powder: (i) the 5-parameter Johnson-Champoux-Allard (JCA) model [1]; and (ii) the 3-parameter Páde approximation (3P) model [3]. The Biot theory (also see Chapter 11 in reference [1]) was then applied to account for the frame elasticity in the presence of air. These predictions were then used to estimate the frequency-dependent absorption coefficient and to fit it to the data measured in the 2-microphone impedance tube. This fitting process was based on the MATLAB built-in numerical optimization subroutines.

3. RESULTS

Figure 2 presents the measured and modelled absorption coefficient spectra for the 50 mm hard-backed layer of aerogel powder for a range of excitation levels. Tables 1 and 2 list the parameters of these two models used to predict the absorption coefficient spectra shown in Figure 2. The meaning of the parameters shown in Tables 1 and 2: σ is the flow resistivity; ϕ is the porosity; α_∞ is the tortuosity; Λ is the viscous characteristic length; Λ' is the thermal characteristic length; E_1 is the Young's modulus; ν is the Poisson's ratio; η_m is the frequency-dependent loss factor; s_b is the median pore size; σ_s is the standard deviation in pore size.

Table 1: The values of non-acoustical parameters in the JCA model [1] used to predict sound absorption coefficient spectra shown in Figure 1.

σ [Pa s m^{-2}]	ϕ	α_∞	Λ [μm]	Λ' [μm]	ρ_b [kg/m^3]	E_1 [Pa]	ν	η_m
10.5×10^6	0.999	3.0	36.1	36.1	35.5	775	0.396	Eq. (1)

Table 2: The values of non-acoustical parameters in the 3-parameter model [2] used to predict sound absorption coefficient spectra shown in Figure 1.

Material	ϕ	s_b [μm]	σ_s [ϕ-units]	ρ_b [kg/m^3]	E_1 [Pa]	ν	η_m
Type 1	0.999	14.7	0.756	35.5	775	0.396	Eq. (1)

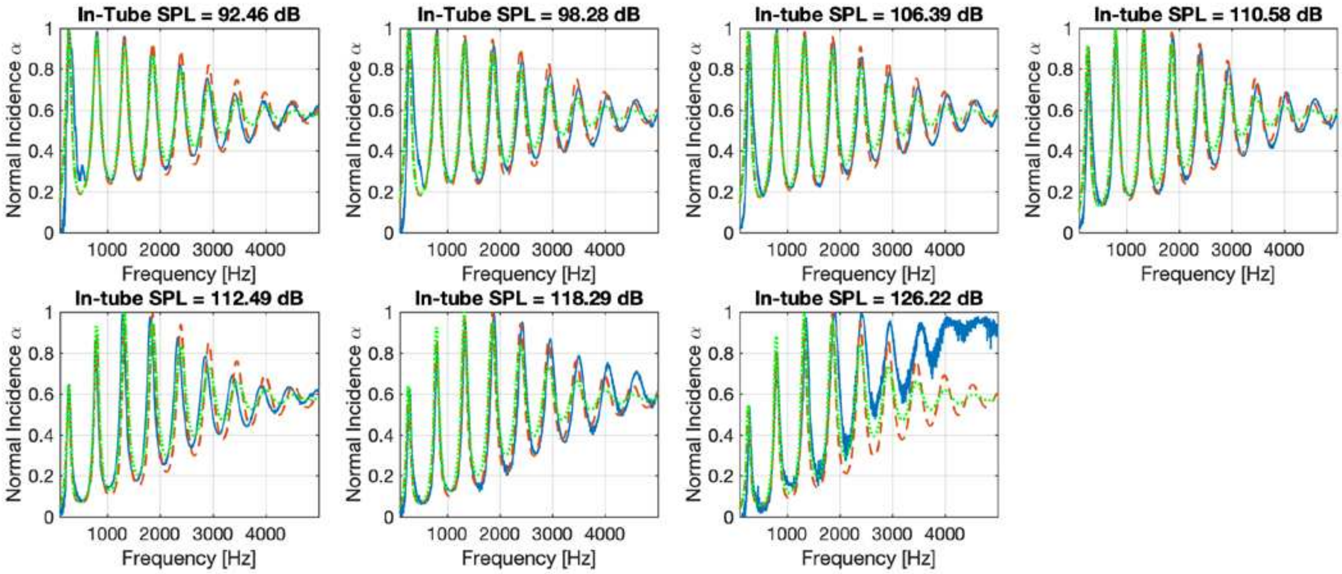

Figure 2: The normal incidence absorption coefficient spectra of aerogel powder at different incident sound pressure levels. Experiment (blue-solid lines), JCA model prediction (orange-dashed lines), 3-parameter model (green-dotted lines).

The dependence of the loss factor on the frequency was the most significant factor that enabled good fitting of the model to the measured absorption coefficient spectra. It allowed the non-linearity in the absorption coefficient behaviour to be numerically captured. More specifically, it was found that:

$$\log_{10} \eta_m = a(SPL)f + b(SPL). \tag{1}$$

where a and b are coefficients that depend on the sound pressure level, SPL. Their dependence on the sound pressure level is illustrated in Table 3. These coefficients have a clear physical meaning. The absolute value of coefficient a is the rate with which the loss factor decreases with increasing frequency. The value of the coefficient b is the low-frequency limit of the loss factor, i.e., the greater it is, the greater the losses associated with the frame vibration excited by the incident sound wave. Aerogel powder studied in this work was relatively low density. As a result, the value of a does not depend much on the sound pressure level. The behaviour of the coefficient b on the sound pressure level is much more pronounced. Below 105 dB the value of this coefficient does not depend significantly on the sound pressure level. Above this threshold the value of b drops suddenly and then continues to reduce slowly with increasing sound pressure level, i.e. there is a sudden reduction in the loss factor.

The analysis of data presented in ref. [4] suggests that the drag force applied to the particles of this relatively light aerogel powder almost always exceeds the gravity force at the applied levels of excitation, i.e., the aerogel particles are likely to vibrate at a range of frequencies, particularly at resonance frequencies. These resonance frequencies coincide with the maxima in the absorption coefficient spectra shown in Figure 2. When the sound pressure level is relatively small, e.g., 92 dB, then the displacement in the incident sound wave is well below that of the particle diameter. The relatively light particles in this powder aerogel can be excited by the incident sound wave, particularly in the lower frequency range, but their movements are likely to be much smaller than their diameter. These particles interact mechanically with each other losing energy through contact friction so that the acoustic absorption coefficient peaks close to 100% at frequencies below 1000 Hz (see Figure 2 for 92 dB). As the level of excitation increases, the amplitude of the particle movement increases progressively. This amplitude generally reduces with the increased frequency. When this amplitude becomes comparable with the particle diameter, e.g., 1 μm at 250 Hz for 112 dB excitation, the particle contact can begin to break, i.e., they lose contact with each other, so that the losses reduce below 1000 Hz as illustrated by the standing wave tube data in Figure 2. At this level, the amplitude of the displacement of air molecules in the medium and high frequency regime (1000–3000 Hz) is close to the 1-10 nm range (around 1/1000th of the particle diameter) which seems to result in an increase in the absorption coefficients, particularly around the resonance peaks as shown in Figure 2.

Table 3: The coefficients in equation (1) for the dynamic loss factor.

In-tube SPL [dB]	a	b
92.46	-5.511×10^{-4}	1.353
98.28	-5.520×10^{-4}	1.335
106.39	-6.328×10^{-4}	1.318

110.58	-6.328×10^{-4}	1.141
112.49	-6.328×10^{-4}	0.761
118.29	-6.736×10^{-4}	0.768
126.22	-6.940×10^{-4}	0.649

4. CONCLUSIONS

A relatively thin layer of a light aerogel powder can provide a very high (almost 100%) acoustic absorption at relatively low frequencies, e.g., below 250 Hz. The behaviour of this material is non-linear, i.e., it depends on the amplitude of the incident sound wave. The agreement between the predicted and measured absorption coefficient obtained with the adopted models was close, with root mean squared errors below 0.1, for most of the sound pressure levels in the tube.

A small but finite elasticity expressed in terms of the Young's modulus of the material's solid frame structure needs to be introduced in the modelling process in order to realise a good fitting to the measured sound absorption over a broad range of frequencies. Different groups of dynamic loss factors were needed to yield the best fit at different in-tube sound pressure levels. This indicates that the dynamic loss factor is dependent on both frequency and incident sound pressure level. An additional sound absorption mechanism could not be captured by the Biot-type poro-elastic model and needs to be considered to provide a better fit in the higher frequency region (i.e., above 2000 Hz) especially when the incident sound pressure level is relatively large. The loss factor required to fit the measured data at the lower frequencies (i.e., below 2000 Hz) is relatively high, i.e. higher than is physically reasonable for an elastic porous medium. This suggests that there is an additional loss mechanism working at low frequencies to contribute to the non-linearity of the sound absorption.

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