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A comparison of two acoustical methods for estimating parameters of glass fibre and melamine foam materials

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ABSTRACT

Using the Bies–Allard and Kino–Allard models, parameters including porosity, flow resistivity and characteristic lengths of glass wool, polyester fibre, melamine foam and compressed melamine foam materials have been deduced from knowledge of the mean fibre diameter, bulk density and density of the raw solid material from which the fibres are made. Also these parameters have been deduced from ultrasonic measurements and inverted from impedance tube measurements using commercial software Foam-X. It has been found that the ultrasonically-measured viscous and thermal characteristic lengths are in good agreement with the predictions from fibre diameters and densities. However the values of tortuosity, flow resistivity and characteristic lengths inverted from impedance tube data using the commercial software differ significantly from the values obtained by the ultrasonic slope method.

Differences between bulk densities of materials predicted by the Bies–Allard and Kino–Allard models using viscous characteristic length values derived from the Foam-X and values deduced by the slope method are explored in detail. In particular it is shown that the outputs from the commercial software do not distinguish between materials with similar flow resistivity but rather different microstructures.

1. Introduction

Flow resistivity, viscous characteristic length and thermal characteristic length are important parameters for the acoustical properties of porous media. Recently a commercial software for inverting these parameters from acoustical measurements made with plane waves at normal incidence has become available (Foam-X software [1]). The software has four model options that depend on the pore structure ("General" or "Fibre") and frame elasticity ("Rigid" or "Limp") of the material of interest i.e. "General-Rigid" "General-Limp" "Fibre-Rigid" and "Fibre-Limp". This paper explores the reliability of the parameter deduction using the Foam-X method for three types of materials. The software, which is based on the Johnson–Champoux–Allard model (detailed in Section 2.2), minimises the cost function defined as the difference between measured surface acoustic impedance and predicted surface acoustic impedance using the non-linear least squares [2].

For fibre glass products Bies and Hansen [3] have developed the relationship in Eq. (1) between flow resistivity, the diameter of a glass fibre and the bulk density.

$$\sigma d^2 \rho_1^{-1.53} = \begin{cases} 3.18 \times 10^{-9} & \text{Glass fibre} \\ 15.0 \times 10^{-9} & \text{Polyester fibre} \\ 11.5 \times 10^{-9} & \text{“Illtec” melamin e foam} \\ 8.0 \times 10^{-9} & \text{“Basotect TG” melamin e foam} \end{cases}, \tag{1}$$

where σ is the flow resistivity, d is the mean fibre diameter, ρ_1 is the bulk density of the porous medium, the constant 3.18×10^{-9} for the glass fibre was proposed by Bies, and the other three values for polyester fibre and melamine foam were proposed by Kino. Champoux and Allard [4] have shown that sound propagation in rigid-framed fibrous materials depends on the total length of fibres per unit volume of material (see Eqs. (2)–(4)). Values of the constant in Eq. (1) and ρ_m in Eq. (2) for various materials are listed in Table 1.

$$L_{Allard} = 4\rho_1/\pi d^2 \rho_m, \tag{2}$$

$$\wedge_{Allard} = 1/2\pi R L_{Allard}, \quad \text{where } R = d/2, \tag{3}$$

$$\wedge'_{Allard} = 2\wedge_{Allard}, \tag{4}$$

where ρ_m is the density of the raw solid material from which fibres are made, L_{Allard} is the total length of fibres per unit volume of a material, $\wedge_{Allard}$ is the viscous characteristic length, and $\wedge'_{Allard}$ is the thermal characteristic length.

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Table 1
The values of the constant (Eq. (1)) and the densities of the raw solid materials for various porous media.

Porous media	Constant	ρ_m(kg m^{-3})
Glass fibre	3.18×10^{-9}	2500
Polyester fibre	15.0×10^{-9}	1380
"Illtec" melamine foam	11.5×10^{-9}	1570
"Basotect TG" melamine foam	8.0×10^{-9}	1570

The relationship between the two characteristic lengths shown in Eq. (4) is applicable where the velocity of the air is perpendicular to the direction of the fibres. Eq. (1) together with Eqs. (2)–(4) constitute the Bies– and Kino–Allard models.

The Bies model has been modified for the polyester fibre [5], "Illtec" melamine foam [6,7] and "Basotec TG" melamine foam [7] materials. Also Garai et al. have modified the Bies model for polyester fibre [8].

The flow resistivity and characteristic lengths of glass wool are predicted accurately by using a combination of the Bies and the Allard models [5]. Also the flow resistivity and characteristic lengths of polyester fibre, melamine foam and compressed melamine foam materials are predicted accurately by using the Kino and Allard models [5–7].

In Section 2, measurements of the parameters (including tortuosity, the characteristic lengths and the flow resistivity) and the acoustical properties of glass fibre, polyester fibre, melamine foam and compressed melamine foam materials are described. The parameters are deduced from acoustical properties by means of acoustical models which are described also. Outputs of inverse calculations for compressed melamine foam using the Foam-X software are also shown. Subsequently, in Section 3, the bulk densities using the Bies–Allard and Kino–Allard models are predicted using the inverted values and values obtained by the slope method. The discrepancies between measured and deduced parameter values are explored using the predicted bulk densities, together with the normal incidence absorption coefficient based on predictions using the Johnson–Champoux–Allard model [9].

2. Experimental method and results

Values for flow resistivity (σ), tortuosity (α_∞), characteristic lengths ($\wedge$ and $\wedge'$) for six glass fibre, six polyester fibre and 11 melamine foam samples have been obtained by direct non-acoustical measurements (flow resistivity) and from ultrasonic data (tortuosity and characteristic lengths). Deductions of these parameters for glass wool sample 1[5] and "Illtec" melamine foam sample 32 [6] of similar flow resistivity have been made using the Foam-X method. Deductions for compressed "Illtec" melamine foam sample 53 [7] have been made also. The melamine foam samples have been compressed by a heat press processing. Samples 51 and 61 listed in Tables 4 and 5 are reference (uncompressed) materials. The others listed in Tables 4 and 5 are compressed materials.

2.1. Measurements of the flow resistivity (σ)

Measurements of the flow resistivity (σ) were made in accordance with the ISO 9053 [10] and the resulting values are listed in Tables 2–5.

2.2. Measurements of the tortuosity (α_∞) and the characteristic lengths ($\wedge$ and $\wedge'$)

Values of tortuosity corresponding to saturation of the materials by air at room temperature have been deduced from ultrasonic measurements [5–7]. Measurements of the characteristic lengths ($\wedge$ and $\wedge'$) have been made using the ultrasonic slope method [11] involving saturation by two different gases, in this case air and argon [12]. A linear approximation has been fitted to the measured data in the frequency range between 100 kHz and 800 kHz. Characteristic lengths have been deduced from two linear approximations of ultrasonic data for porous samples saturated by air and argon [5–7]. The deduced values of tortuosity and characteristic lengths are listed in Tables 2–5.

The squared refraction index for compressed "Illtec" melamine foam sample 53 is plotted as a function of the square root of the inverse frequency in Fig. 1a. The accuracy of the measurements of tortuosity and characteristic lengths has been tested [5–7] by using the ultrasonically-measured values to predict the sound velocity through Eqs. (5) and (6) which is obtained by transforming the wave number equation at high frequencies [11,13]. Subsequently the predicted and measured sound velocities have been compared as shown in Fig. 1b. The temperature was 21.5–21.8 °C during these experiments.

$$c_{high} = \frac{c_0}{\sqrt{\alpha_\infty}}\left[1 - \frac{\delta}{2}\left(\frac{1}{\wedge} + \frac{\gamma - 1}{\sqrt{P_r}\wedge'}\right)\right] \Big/ \left[1 - \frac{\delta^2}{4}\left(\frac{1}{\wedge} + \frac{\gamma - 1}{\sqrt{P_r}\wedge'}\right)^2\right], \quad (5)$$

$$\delta = \sqrt{\frac{2\eta}{\omega\rho_0}} \quad (6)$$

where c_{high} is the sound velocity in the materials at high frequencies, and δ is the viscous skin depth.

The discrepancy between measured and predicted sound velocities shown in Fig. 1b is calculated as follows:

$$100 \times \left|c_m - c_{high}\right| / c_m, \quad (7)$$

where c_m is the measured frequency-dependent sound velocity and c_{high} is the predicted frequency-dependent sound velocity.

For the compressed "Illtec" melamine foam sample 53 in air, the mean value of the sound velocity discrepancy between measurement and prediction in the frequency range between 100 kHz and 800 kHz was 0.087%. For the sample 53 in air, the maximum value of the sound velocity prediction difference was 0.78 m s^{-1} (see Fig. 1b).

For the compressed "Illtec" melamine foam sample 53 in argon, the mean value of the sound velocity discrepancy between measurement and prediction in the frequency range between 100 kHz and 800 kHz was 0.122%. For the sample 53 in argon, the maximum value of the sound velocity prediction difference was 0.79 m s^{-1} (see Fig. 1b).

Since the predicted sound velocities are very close to the measured values, the ultrasonically-measured values of the tortuosity and the two characteristic lengths in Tables 2–5 are judged to be highly accurate.

By using Eq. (1) with measured flow resistivities (σ) and measured bulk densities (ρ_1), the fibre diameters (d_{Bies} and d_{Kino}) in Tables 2–5 were predicted. The fibre diameters (d_{Bies} and d_{Kino}) predicted from Eq. (1), $d = d_{Bies}$ and $d = d_{Kino}$ were substituted for Eq. (2) so that the total length of fibre equivalents per unit volume ($L_{Allard(\sigma)}$) was obtained. The total length of fibre equivalents per unit volume was substituted in Eq. (3) so that the characteristic lengths ($\wedge_{Allard}$ and $\wedge'_{Allard}$) were predicted.

The ultrasonically-measured values of $\wedge$ shown in Table 2 have been compared with the predictions of $\wedge_{Allard}$ shown in Table 2. For the viscous characteristic lengths of the 6 glass wool samples shown in Table 2 the discrepancy was represented as $100 \times |\wedge_{Allard} - \wedge|/\wedge$. The mean value for the glass wool data was 4.85%. Similarly for the viscous characteristic lengths of the 6 polyester fibre samples the discrepancy was represented as