Journal of Sound and Vibration (1998) **216**(3), 495–505
Article No. sv981725

A METHOD OF MEASURING THE DYNAMIC FLOW RESISTANCE AND THE ACOUSTIC MEASUREMENT OF THE EFFECTIVE STATIC FLOW RESISTANCE IN STRATIFIED ROCKWOOL SAMPLES

M. A. Picard, P. Solana and J. F. Urchueguía

Universidad Politécnica de Valencia, E.T.S. Ingenieros Industriales, Edfs, D4–D5 bajo, Camino de Vera, 14 46022 Valencia, Spain

(*Received* 21 *November* 1997, *and in final form* 30 *April* 1998)

In our work we have analyzed different stratified rockwool samples, with considerable differences regarding density, mean pore diameter, and porosity, by means of a new method for the measurement of the dynamic flow resistance based on the electrical analogy. This method enables us to measure this parameter without the need for placing the sample between two microphones. Our experimental results have been compared to those obtained with a different measurement scheme and, from a theoretical point of view, we have examined the extent to which the capillary pore approximation can be utilized in intermediate flow regimes and Poiseuille flow regimes and in real situations. For this purpose, a static flow resistivity, which was also approximated using an acoustic method and a commonly accepted theoretical approximation, was calculated based on a microscopic study of the samples and the fibre's diameter. Regarding the conclusions obtained, the results show that the new experimental procedure for determining the dynamic flow resistance is of interest in the intermediate and Poiseuille flow regimes in which, within the limitation of our experimental set-up, good results were obtained. The acoustic procedure for measuring a static flow resistivity delivered good results only for a regime close to Poiseuille, which was obtained only with higher density samples.

1. INTRODUCTION

Many of the acoustic properties of fibrous materials can be modelled and predicted with the aid of appropriate empirical formulae [1–3]. Among the input parameters that are required by such type of macroscopic models, the flow resistivity σ_0 [4] (which other authors call specific flow resistance [5], or flow resistance per unit thickness of the sample), is a very old and well established quantity and frequent reference is made to its use in the literature [6–9]. As usually this parameter is measured in steady Poiseuille flow conditions, i.e., at comparatively low flow speeds [4, 7], one major concern with respect to such a parameter is the question of its possible frequency dependence. For instance, Kawasima [10], in his

0022–460X/98/380495 + 11 $30.00/0

theoretical model, did not find any remarkable flow resistance versus frequency dependence except at the sample characteristic frequencies. It is considered in practice that in highly porous materials the static value σ_0 is accurate enough for modelling in any acoustic regime, [1, 7, 9].

In the case of fibrous materials, however, Attenborough [11] realized that the fibre orientation, its microscopic structure and its stratification properties can severely affect acoustic behaviour. Moreover, it was observed by Lambert and Tesar [8] that non-negligible flow resistance versus frequency variations can arise in stratified fibrous materials like Kevlar. To account for this dependence authors like Morse and Ingard [12] proposed a dynamic flow resistance parameter. In this context, various authors like Zwicker and Kosten [6], Biot [13] and Lambert and Tesar [8] used a cylindrical pore approximation for fibrous material to quantify the dynamic flow resistance per unit thickness, σ, as a function of the acoustic Reynolds number $\kappa = r(\omega\rho_0/\mu)^{1/2}$. Here r is the equivalent pore radius, μ is the air viscosity, ρ_0 is the air density and ω is the angular frequency of excitation.

The analysis due to Zwicker and Kosten indicates that $\sigma = (k/h)(8\mu/r^2)$ if the flow regime is Poiseuille type ($\kappa \ll 1$), $\sigma = k/(hr)\sqrt{2\mu\omega\rho_0}$ in the Helmholtz flow regime ($\kappa \gg 1$), where k is the structure factor and h is the porosity. In transient regime ($10 > \kappa > 1$), of interest in many practical situations [8], estimation of σ is more involved and there is a lack of theoretical and empirical information. In connection with this shortcoming, comparatively recent work has been devoted to the experimental analysis of the dynamic flow resistance per unit thickness by means of acoustic methods. First to mention is the work of Mingzhang and Jacobsen [14], the results of which (referred to a single sample) show a clear tendency towards lower values of σ for increasing κ. This behaviour is in apparent contradiction with the Re $[F(\kappa)]$ function of Lambert and Tesar [8] which predicts a slightly increasing tendency. This function equals σ/σ_0, upon taking into account that $F(\kappa) = \frac{1}{3}[\sqrt{\mathrm{j}} \tanh(\sqrt{\mathrm{j}}\kappa)]/[1 - (1/\kappa \mathrm{j}) \tanh(\sqrt{\mathrm{j}}\kappa)]$ is Biot's function [13], which is a complex quantity and represents the deviation from Poiseuille friction as κ increases.

A second proposal related to this issue is the work due to Woodcock and Hodgson [15] who define a (mathematical) frequency dependent function from the inversion of the Delany and Bazley [1] expression of the characteristic impedance versus flow resistivity relation. According to these authors [15], the function so calculated has an average value which is close to the flow resistivity; thus, the question is legitimate whether their mathematical averaged value is a true measure of the flow resistivity of the sample obtained according to other known procedures, like the method by Bies and Hansen [4].

In this work a new method of measuring the dynamic flow resistance of rockwool samples in a wave tube is presented and examined. These samples have considerable differences regarding density, mean pore diameter, rigidity and porosity. In order to confirm the tendency observed by Mingzhang and Jacobsen, the non-dimensionalized dynamic flow resistance σ/σ_0 was compared to the Lambert and Tesar Re $[F(\kappa)]$ function in all cases. Our measurements confirm a tendency which is close to the Lambert and Tesar prediction but different from the results of Mingzhang and Jacobsen. Also the averaged values proposed by

Woodcock and Hodgson are compared to the flow resistivity of Bies and Hansen based on our new experimental results.

2. THEORETICAL FORMULATION

2.1. AN ACOUSTIC MEASUREMENT OF THE DYNAMIC FLOW IMPEDANCE

The dynamic flow impedance is defined for a very thin sample [14, 16] as

$$\breve{Z}_f = \Delta\breve{p}/\breve{v}, \tag{1}$$

where $\Delta\breve{p}$ is the (complex) acoustic pressure difference through the sample and $\breve{v}$ is the complex flow velocity throughout the sample. It is implied in this definition that the sample is supposed to be so thin compared to the wavelength that the flow velocity can be regarded as constant throughout the sample (i.e., if $\lambda \approx 15$ mm, thicknesses of the sample in the range of 2–4 mm can be chosen). This parameter has been measured by Mingzhang and Jacobsen [14], by means of an extension of the Ingard and Dear method [16].

The method proposed to measure $\breve{Z}_f$ is based on the electrical analogy.

The specific acoustic impedance measured for a sample "1" $\breve{Z}_1$, with material of characteristic impedance $\breve{Z}_C$ and thickness l backed by a second sample "2" of specific acoustic impedance $\breve{Z}_2$, and subject to a plane-wave incidence normal to the wall, is, according to Zwikker and Kosten [6] and Beranek [5]

$$\breve{Z}_1 = \breve{Z}_C \coth(\breve{\gamma} l + \breve{\psi}), \tag{2}$$

where $\breve{\gamma}$ is the propagation constant and $\breve{\psi} = \coth^{-1}(\breve{Z}_2/\breve{Z}_C)$. In samples of very low thickness, the surface impedance will be almost independent of sample thickness and can be considered as a concentrated or localized quantity. Following this idea, in our method we have measured the impedance of small 1–4 mm thickness samples backed with air and an acoustic tube terminated with an absorbing wedge which ensures fairly free field propagation of the transmitted wave [14]. At ideal conditions, it would be allowable to replace $\breve{Z}_2$ by the characteristic air impedance $\rho_0 c_0$. However, in our experimental set-up this is not possible and $\breve{Z}_2$ is the acoustic impedance of the tube that is measured without the test sample but with the same absorbing termination. In this approximation the sample flow impedance can be deduced therefore from the measured values as

$$\breve{Z}_{12} = \breve{Z}_1 - \breve{Z}_2 = (\breve{p}_1/\breve{v}_1) - (\breve{p}_2/\breve{v}_2). \tag{3}$$

Hence, if the sample thickness is very small, $\breve{v}_1 = \breve{v}_2$ and $\breve{Z}_{12} = \breve{Z}_f = \Delta\breve{p}/\breve{v}$, of which the real part gives the dynamic flow resistance. The dynamic flow resistance per unit thickness is $\sigma = \mathrm{Re}[\breve{Z}_f]/l$, where l is the thickness of the sample.

2.2. DETERMINATION OF THE STATIC FLOW RESISTIVITY

The flow resistivity is [9]

$$\sigma_0 = \Delta p/vl, \tag{4}$$

where Δp is the static pressure drop through the sample divided by its thickness l and v is the flow velocity across it. It is often characterized by means of non-acoustic methods by using the expression of Bies and Hansen [4],

$$\sigma_0 = 3{\cdot}18 \times 10^{-9} \times \rho_m^{1{\cdot}53}/d^2, \tag{5}$$

in which ρ_m is the mean sample density and d is the mean diameter of its fibres, expressed in I.S. units. The flow resistivity σ_0 is also referred too by other authors as static flow resistance per unit thickness [5]. In any case, it is always measured in static Poiseuille flow conditions with flow velocities in the range 5×10^{-4} to 5×10^{-2} [4] and 3×10^{-3} m/s [7].

Woodcock and Hodgson [15] point out the possibility of approximating this quantity with acoustic techniques. The (complex) characteristic impedance $\breve{Z}_C = Z_{\mathrm{Re}} + \mathrm{j}Z_{\mathrm{Im}}$ is then given as a function of the flow resistivity σ_0, according to the expression by Delany and Bazley [1], where its real part is

$$Z_{\mathrm{Re}} = \rho_0 c_0[1 + 0{\cdot}051(\sigma_0/f)^{0{\cdot}75}], \tag{6}$$

$\rho_0 c_0$ being the characteristic impedance of air and f the frequency. This suggests, as was noticed in reference [15], that a mathematical flow resistivity σ_m can be related to some measured impedance values by inversion of equation (6),

$$\sigma_m = [(Z_{\mathrm{Re}} - \rho_0 c_0)/0{\cdot}051\rho_0 c_0 f^{-0{\cdot}75}]^{1/0{\cdot}75}, \tag{7}$$

where an apparent dependence on frequency can be observed. The measurement of Z_{Re} is performed by determining the surface impedance of two samples, “1T” and “2T”, of thicknesses l and $2l$, respectively, both backed with a rigid wall, which is related to the material characteristic impedance [17] by

$$\breve{Z}_C = [\breve{Z}_{1T}(2\breve{Z}_{2T} - \breve{Z}_{1T})]^{1/2}. \tag{8}$$

The real part of the foregoing expression is then substituted into equation (7) to give a mathematical function σ_m, whose average value should approximate the flow resistivity: $\bar{\sigma}_m \approx \sigma_0$.

3. EXPERIMENTAL RESULTS

Our experimental method proceeds in two steps. The first step consists of determining the dynamic flow impedance of very thin samples. From these data the dynamic flow resistance per unit length, σ, is calculated from Re $[\breve{Z}_f]/l$. Second, an effective static flow resistivity is obtained from the measurement of the characteristic impedance of the sample. The measurement of the characteristic impedance follows the outlines of the method proposed by Smith and Parrot [17]. From there, following Woodcock and Hodgson [15], a value of the flow resistivity at any frequency, σ_m, of which the arithmetic mean, $\bar{\sigma}_m$, determines the effective static flow resistivity of the sample, is calculated. This value can be compared to the Bies and Hansen equation (5) estimation, if the mean fibre diameter is previously calculated. A comparison of both values can be found in Table 1.

The measured dynamic flow resistance per unit length, σ, and the values obtained for σ_0 in Table 1 can finally be related to each other in the form of the

TABLE 1

The main characteristics and relevant parameters of the rockwool samples tested

ρ_m (kg m^{-3})	Porosity	σ_0 (N m^{-4} s) [4]	$\bar{\sigma}_m$ (N m^{-4} s) [15]	f (Hz)	κ (400 Hz)	κ (3200 Hz)
30	0·98	9041	24 849	500–3000	1·85	4·5
70	0·97	33 055	44 376	500–3000	0·97	2·4
120	0·948	75 404	104 158	500–3000	0·65	1·58
175	0·924	134 306	123 529	500–3000	0·5	1·2

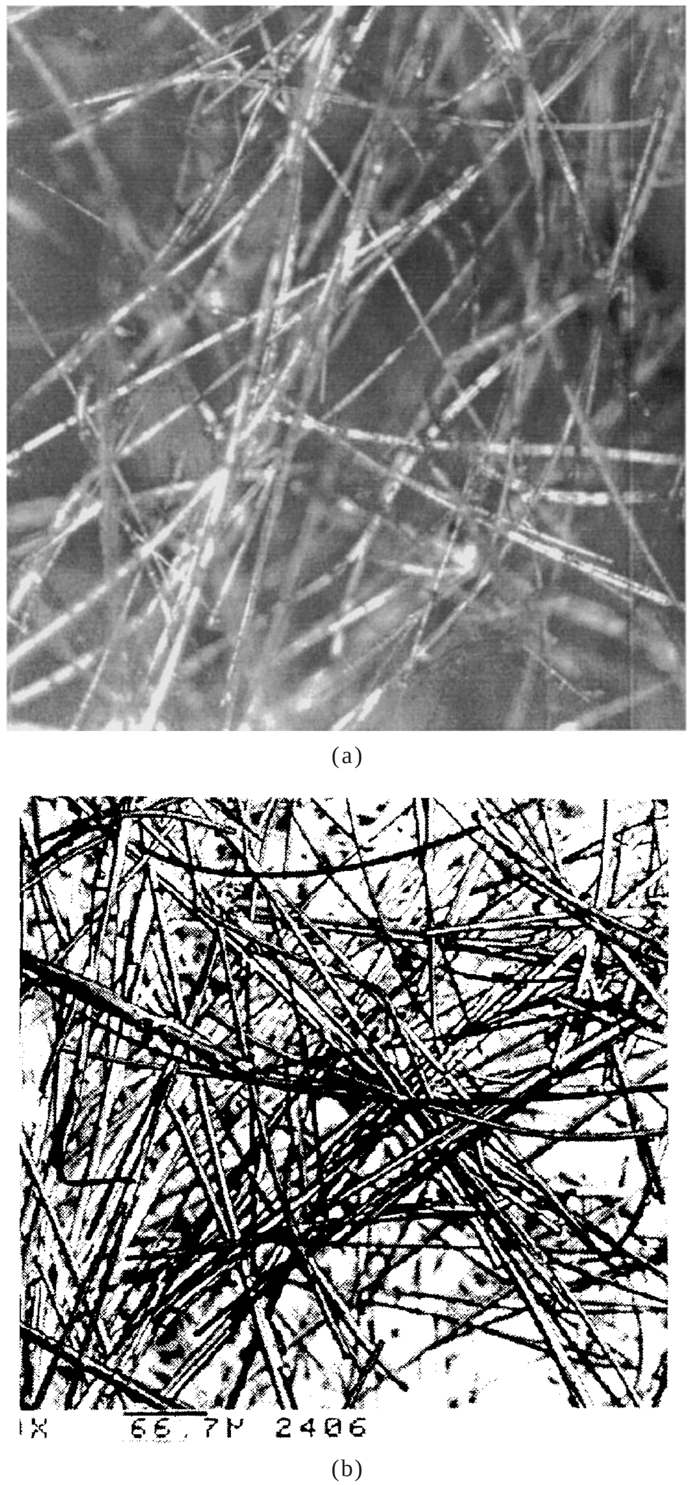

Figure 1. (a) Photo of a sample of rockwool ($100\times$); (b) electronic microscope photo.

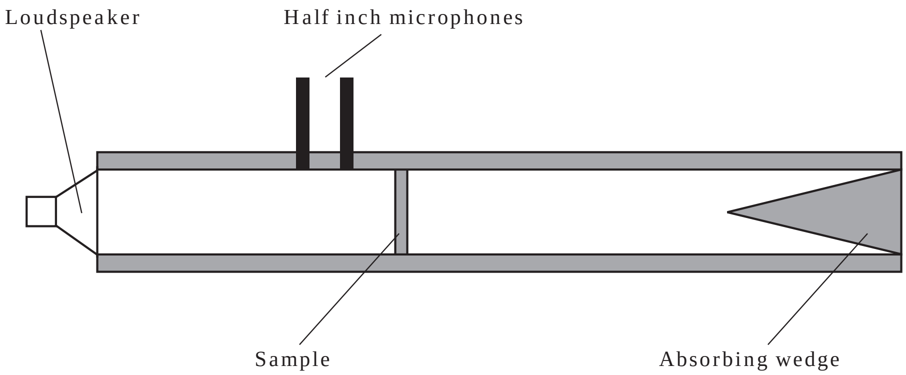

Figure 2. Experimental arrangement for the measurement of the flow resistance of a fibrous sample.

ratio σ/σ_0, which itself is related to the Lambert and Tesar function $\sigma/\sigma_0 = \mathrm{Re}\,[F(\kappa)]$.

The fibre mean diameter of available samples was first measured by performing a statistical study on 100 Nikkon Microphot pictures; see Figure 1(a). Additional confirmation measurements were done with the aid of an electronic microscope, as exemplified in Figure 1(b). Following Nichols [18], the shots are considered not

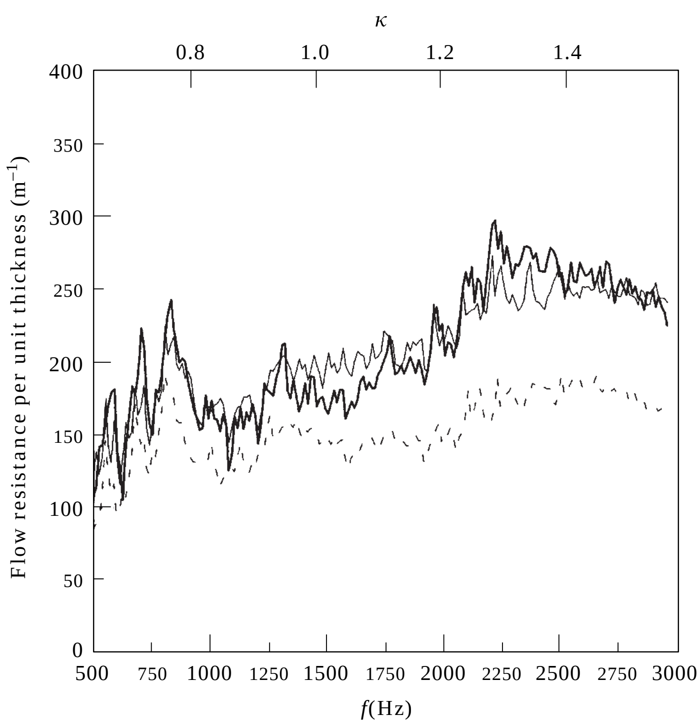

Figure 3. Comparison of measurements of dynamic flow resistance per unit thickness, normalized to ρc units. ——, Measurements of samples of 3 and 4 mm thickness; –––, measurements of a sample of 7 mm thickness.

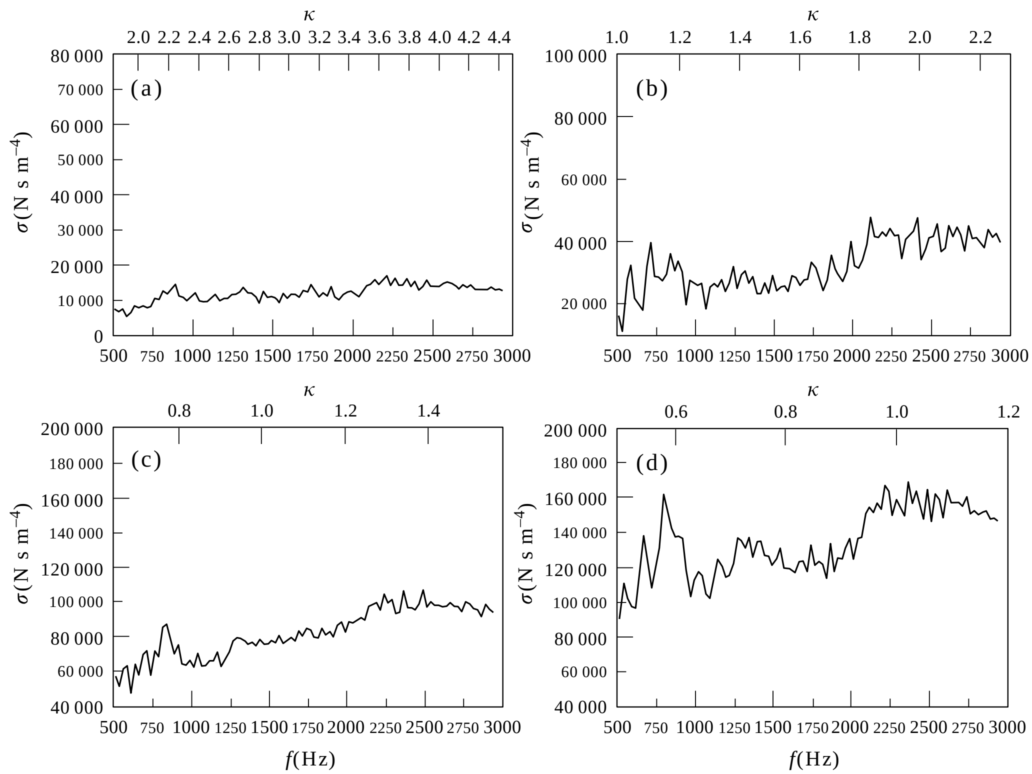

Figure 4. Measurement of dynamic flow resistance per unit thickness σ on a stratified rockwool sample of (a) 30 kg/m^3, (b) 70 kg/m^3, (c) 120 kg/m^3 and (d) 175 kg/m^3.

to significantly affect the static flow resistivity, σ_0, and therefore the value obtained for the effective mean fibre diameter, of about 8 μm, is in full accordance with values obtained by Voronina [19] on similar rockwool samples.

The samples for measuring the characteristic impedance were cut with the aid of a device, as used by Chung and Blaser [20], adapted to our tube diameter. Thin samples for measuring the dynamic flow resistance, as described in section 2.1, were cut with a special knife delivered by the manufacturer.

The sample was attached (see Figure 2) to the junction between two tube segments upstream and downstream to avoid displacement during measurements [21]. The 57-mm diameter tube and measurement equipment was set up following ASTM E 1050 norm [22], with a cut-off frequency, up to which the plane wave approximation can be applied, of 3500 Hz.

Table 1 shows characteristic parameters of the rockwool samples tested. It can be observed that, in the frequency range considered, neither Poiseuille nor Helmholtz flow conditions are to be expected. A strong discordance can be observed between the static flow resistivity of Bies (equation (5)), calculated with a fibre diameter of 8 μm, and the values obtained following the method of Woodcock and Hodgson.

In Figure 3, results of measurements on samples of the same density but different thicknesses are shown. It may be observed, that when the thickness is in the range of the values allowed by the method (as outlined in section 2.1), results obtained are in full accordance, whereas if thickness cannot be considered small, results differ substantially.

Figures 4(a, b) show the dynamic flow resistance per unit thickness value, σ, as a function of frequency for samples of density 30, 70 kg/m^3, respectively. In Figures 5(a, b), the quotient σ/σ_0 for the same samples is represented and compared to the Lambert's theoretical prediction. It can be seen that $10 > \kappa > 1$ in all cases, consequently measurements correspond to intermediate flow regimes. In both samples the prediction of Lambert and Tesar, showing increasing

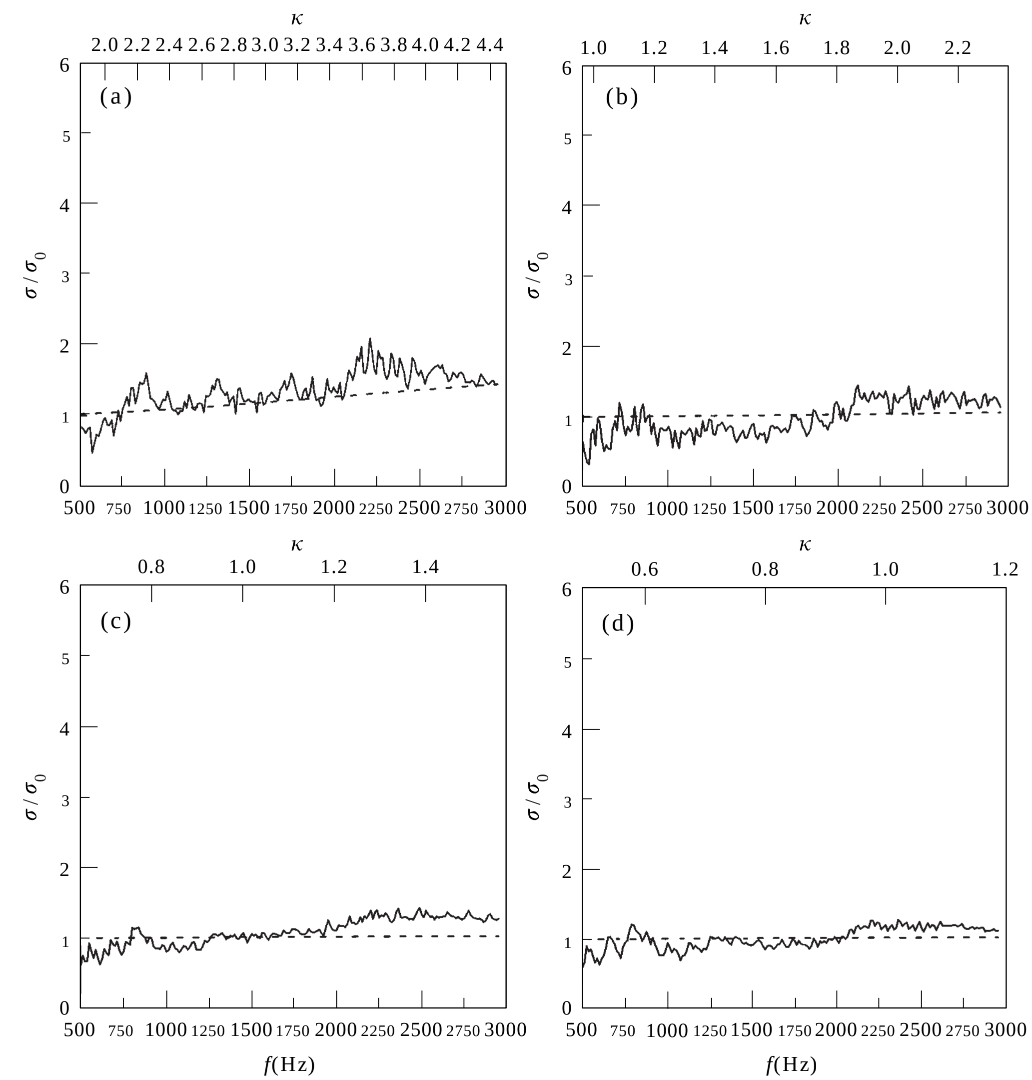

Figure 5. (a) Quotient σ/σ_0 between the measured dynamic flow resistance per unit thickness and the static flow resistivity as a function of frequency (——) on a stratified rockwool sample of 30 kg/m^3, quotient σ/σ_0 calculated from Lambert's relation applied to a rockwool sample of a 30 kg/m^3 (–––); (b) as (a) but for 70 k/m^3 sample; (c) as (a) but 120 kg/m^3 sample; (d) as (a) but 175 kg/m^3 sample.

resistance for increasing κ, are in good accordance with the measured flow resistance per unit thickness values.

Figures 4(c, d) and Figures 5(c, d), show the results for the samples of 120 and 175 kg/m^3, respectively. In contrast to the former results of lower density samples, now the flow regime is close to Poiseuille. The theoretical prediction of Lambert and Tesar is close to the determined values when $\kappa < 1$ in Poiseuille's flow regime. While if $\kappa > 1$, there is a significant tendency towards values higher than the predicted ones, especially in Figure 5(c).

Measurements by Mingzhang and Jacobsen presented in Figure 2 of reference [14], show similar values of flow resistance per unit length in Poiseuille's regime, as in our samples; however there is a clear difference in the tendency on increasing κ if $\kappa > 1$.

4. CONCLUSIONS

From the available data, the following conclusions can be drawn.

The measurement procedure outlined in section 2.1 allows one to obtain values for the dynamic flow resistance in a simple and fast way in Poiseuille and intermediate flow regimes. The limitations of the method are similar to those imposed by "the two microphone method", as well as the necessity of cutting thin samples of fibrous materials with precision and without deteriorating them.

The value of flow resistivity σ_0 obtained by means of the Woodcock and Hodgson procedure (see Table 1) is far from the value obtained with the Bies and Hansen formula (equation (5)) except in the sample of highest density. Only in this last sample were measurements almost fully in agreement with the Poiseuille regime, which could explain this fact (see the last column in Table 1).

The observed tendency of increasing dynamic flow resistance per unit thickness with increasing acoustic Reynolds number is in agreement with the former results of Biot [13], Lambert and Tesar [8] as well as Ingard and Dear [16]. Moreover, our measured σ/σ_0 values are in good accordance with the theoretical predictions by means of Lambert's Re $[F(\kappa)]$ function in Poiseuille as well as in intermediate flow regimes. This differs from the results obtained by Mingzhang and Jacobsen in Figure 2 of reference [14], who observed a negative slope at higher frequencies; we believe this difference could be due to the frame of the samples, as indicated by Attenborough [11]. In our work we used only stratified rockwool samples.

REFERENCES

1. M. E. Delany and E. N. Bazley 1970 *Applied Acoustics* **3**, 105–116. Acoustical properties of fibrous absorbent materials.
2. F. P. Mechel 1976 *Acustica* **35**, 210–213. Ausweitung der absorberformel von Delany und Bazley zu tiefen frequenzen.
3. Y. Miki 1990 *Journal of the Acoustical Society of Japan* **E11**, **1**, 19–24. Acoustical properties of porous materials—modifications of Delany–Bazley models.
4. D. A. Bies and C. H. Hansen 1980 *Applied Acoustics* **13**, 357–391. Flow resistance information for acoustical design.
5. L. L. Beranek 1960 *Noise Reduction*. New York: McGraw-Hill.

6. C. ZWICKER and C. W. KOSTEN 1949 *Sound Absorbing Materials*. Amsterdam: Elsevier.
7. D. J. SIDES and K. ATTENBOROUGH 1971 *Journal of Sound and Vibration* **19**, 49–64. Application of a generalized acoustic propagation theory to fibrous absorbents.
8. R. F. LAMBERT and J. S. TESAR 1984 *Journal of the Acoustical Society of America* **76**, 1231–1237. Acoustic structure and propagation in highly porous, layered, fibrous materials.
9, J. F. ALLARD 1993 *Propagation of Sound in Porous Media Modelling*. *Sound Absorbing Materials*. Amsterdam: Elsevier.
10. Y. KAWASIMA 1960 *Acustica* **10**, 208–217. Sound propagation in a fibre block as a composite medium.
11. K. ATTENBOROUGH 1971 *Journal of Sound and Vibration* **16**, 419–442. The influence of microestructure on propagation in porous fibrous absorbents.
12. P. M. MORSE and K. U. INGARD 1968 *Theoretical Acoustics*. New York: McGraw-Hill.
13. M. A. BIOT 1956 *Journal of the Acoustical Society of America* **28**, 179–191. Theory of propagation of elastic waves in a fluid saturated porous solid II Higher frequency range.
14. R. MINGZHANG and F. JACOBSEN 1993 *Applied Acustics* **39**, 265–276. A method of measuring the dynamic flow resistance and reactance of porous materials.
15. R. WOODCOCK and M. HODGSON 1992 *Journal of Sound and Vibration* **153**, 186–191. Acoustic methods for determining the effective flow resistivity of fibrous materials.
16. K. U. INGARD and T. A. DEAR 1985 *Journal of Sound and Vibration* **103**, 567–572. Measurement of acoustic flow resistance.
17. C. D. SMITH and T. L. PARROT 1983 *Journal of the Acoustical Society of America* **74**, 1577–1582. Comparison of three methods for measuring acoustic properties of bulk materials.
18. R. H. NICHOLS 1947 *Journal of the Acoustical Society of America* **19**, 866–871. Flowresistance characteristics of fibrous acoustical material.
19. N. VORONINA 1994 *Applied Acoustics* **42**, 165–174. Acoustic properties of fibrous materials.
20. J. Y. CHUNG and D. A. BLASER 1980 *Journal of the Acoustical Society of America* **68**, 914–921. Transfer function method of measuring in-duct acoustic properties. II Experiment.
21. D. MILO DAHL, EDWARD J. RICE and DONALD E. GROESBECK *Journal of the Acoustical Society of America* **87**, 54–66. Effects of fibre motion on the acoustic behavior of an anisotropic, flexible fibrous material.
22. *ASTM E* 1050–90 1990. Standard test method for impedance and absortion of acoustical materials using a tube, two microphones, and a digital frequency analysis system.
23. L. L. BERANEK 1947 *Journal of the Acoustical Society of America* **19**, 556–568. Acoustical properties of homogeneus, isotropic rigid tiles and flexible blankets.