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A FITTING METHOD TO ESTIMATE THE AIR FLOW RESISTIVITY OF POROUS MATERIALS

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Abstract

The air flow resistivity can be considered as a key characteristic to study the acoustic performance of porous materials. In the laboratory the absorption coefficient or the acoustic impedance in a standing wave tube are the quantities usually measured. Both parameters are related to the air flow resistivity through well proven empirical models. In this work one of these models is used to estimate the air flow resistivity based on absorption coefficient measurements by an inverse fitting method. Some examples are given.

INTRODUCTION

Sound absorbing materials are used in almost all areas of noise control engineering. The use of mineral wools is especially extended in building acoustics because their physical properties are especially suited in noise and thermal problems, and also fire protection.

The mineral fibers are manufactured in the form of mats, boards or performed elements. Most mineral wools used in building acoustics are constituted of fibres of statistically distributed diameters between 1 and 10µm. In the case of mineral wools their diameters can reach up to 100µm.

The goal of the acoustical characterization of these materials is the prediction of the complex characteristic impedance Z_c and propagation constant k_c, being the experimental procedures to determine these parameters deeply investigated and standardized.

The intrinsic characteristics of these materials related with their acoustic absorptive capabilities are: *porosity* (related as the ratio of pore volume to total volume), *fiber diameter* (microscopic examinations are necessary to establish the distribution statistics), *structure factor* (takes into account the effect of the pores and cavities placed perpendicular to the sound wave) and *flow resistivity*.

The flow resistivity, R_1 (specific flow resistance per unit thickness of the sample) is the most important physical characteristic of a fibrous material, and it can be measured following the instructions described in ISO 9053:1991 [1]. For these types of materials the R_1 value allows the complete prediction for the acoustic behaviour of the projected devices, using the well known mathematical models mentioned above.

Many efforts have been made in order to predict k_c and Z_c for fibrous materials on the basis of their physical intrinsic characteristics. Several authors [2-6] developed empirical algorithms based in the regression analysis of careful experimental data.

Other models based in the diameter of the fiber materials and the density has been developed [7] but in this work has not been considered.

Microstructural models have been also developed, as the Garay & Pompoli [8] that solve the wave equation in function of the mticrostructure of the material. This type of approximation is based on the Biot theory; that by Allard [9] being one of the most used. Allard simplifies the model assuming a rigid structure, excluding the structural waves that propagate throughout the skeleton of the material.

In the literature, models based on can also be found such as numerical calculus, as finite element models [10]. These techniques cannot be easily generalized.

All the empirical algorithms use a single parameter, proposed by Delany: the non dimensional variable, E, resulting from the product of the frequency with the air density over the flow resistivity of the bulk material at the density at which the absorption coefficient will be measured.

The design and implementation of a device for the measurement of the air flow resistivity, R_1, based on the ISO standard are not within reach of many laboratories. The alternative procedure described in this paper allows the determination of R_1 through impedance measurements in standing wave tubes or impedance tubes that are commonly available in acoustic material laboratories. Furthermore, it is applicable to the calculation of R_1 in samples of glass fiber wools as well as in mineral wools.

The validity range of the procedure and the precision will be stated in the summary and conclusions.

ABSORPTION OF FIBROUS MATERIALS

In applied acoustics the most used parameter to define the capabilities of this type of materials is the sound absorption coefficient, α. It is well extended the use of impedance tubes in the processing step of the selection or implementation of absorbing devices, and for the measurement of α.

The surface acoustic impedance Z_s of a layer of absorbing material, with thickness d, characteristic impedance Z_c and propagation constant k_c, placed in an impedance tube with rigid end (normal incidence) is:

$$Z_s = -Z_c \coth(k_c d) \tag{1}$$

The reflection coefficient in the external surface of the porous layer is:

$$R = \frac{Z_s - Z_o}{Z_s + Z_o} \tag{2}$$

being Z_o the characteristic impedance of the surrounding fluid, in our case (air) $\rho_o c$.

Finally, the absorption coefficient is:

$$\alpha = 1 - |R|^2 \tag{3}$$

In this way, starting from the values of k_c and Z_c the calculation of α is straightforward.

In this work we have used the empirical algorithms developed by Mechel [4], because we have found this gives the best correlation between experimental measurements and empirical predictions for the materials studied (several types of glass and mineral wools). As Z_c and k_c are functions of R_1, an inverse method has been implemented to get R_1 values from α data.

CALCULUS PROCEDURE

The equations that relate propagation constant and the characteristic impedance of the material with its air flow resistivity are (Mechel [4]):

$$\begin{aligned} k_c &= \frac{1}{k_o}\left\{a' E^{-\alpha'} + j(1 + a'' E^{-\alpha''})\right\} \\ Z_c &= \frac{1}{Z_o}\left\{1 + b' E^{-\beta'} - jb'' E^{-\beta''}\right\} \end{aligned} \tag{4}$$

In these equations the normalized frequency parameter $E = \dfrac{\rho_o f}{R_1}$ is a universal descriptor of fibrous porous sound absorbing material, firstly used by Delany & Bazley [2]. The regression parameters a’, a’’, b’, b’’, α’, α’’, β’ and β’’ are given in table 1. In the table different regression parameters for the normalized frequency regions below and above E=0.025 are shown.

Material	E Region	a’	α’	a’’	α’’	b’	β’	b’’	β’’
Mineral & basalt wool	$E \geq 0.025$	0.322	0.502	0.136	0.641	0.081	0.699	0.191	0.556
	$E \leq 0.025$	0.179	0.663	0.103	0.716	0.056	0.725	0.127	0.655
Glass fiber	$E \geq 0.025$	0.396	0.458	0.135	0.646	0.067	0.707	0.196	0.549
	$E \leq 0.025$	0.179	0.674	0.102	0.705	0.024	0.887	0.088	0.770

Table 1. Parameters for Mechel’s model of Z_c yk_c.

The direct method to determine R_1 values starting from the absorption measurements and solving with the aid of equations 1 to 4 is not straightforward, due to the exponential dependence in eq. 4.

An alternative way is the use of an inverse method, consisting on measuring the absorption coefficient, $\alpha(f)$, in impedance tube, comparing these results with those obtained by equations 1-4 for a set of values of *R1* and thicknesses centred in the nominal value of the material thickness. The computer program minimizes the quadratic sum of the distances between each calculated value and its corresponding experimental value (fitting residue).

In the measurement of the air flow resistivity following IS0 9053, the measured parameter is the acoustic resistance of the test sample, that, divided by the thickness of the sample the value of R_1 is obtained. The measurement of samples with very low densities is very complicated due to the delicate positioning in the sample holder, which can be compressed during manipulations, giving as a result higher values of R_1. The same situation will be found when the sample is positioned in the sample holder of the impedance tube. This manipulation increases the uncertainties of the measurements.

RESULTS

With the aim of verifying the above described procedure an experimental set up was implemented, measuring R_1 and α from a series of samples of mineral wools (from several manufacturers), whose characteristics are described in table 2

Direct method

The resistivity of the fibrous layers was obtained using ISO 9053:1991, following method A: “Direct airflow method”. A unidirectional air flow, φ, is forced through the sample to be tested, and the flow rate and the pressure drop, Δp, across the test sample are measured. The total flow resistance of the sample is obtained from the ratio of the pressure drop and the flow velocity. The resistance per unit length is obtained dividing by the sample thickness. Defining *A* the cross sectional area of the sample (perpendicular to the flow), and *d* the thickness, then the air flow resistivity of the test specimen is:

$$R_1 = \frac{\Delta p}{\varphi} \cdot \frac{A}{d} \qquad \text{Nm}^{-4}\text{s} \quad \text{(SI Rayls/m)}$$

Several samples of each fibrous type have been measured. We must emphasize that for this paper we have selected several types of mineral wools that have in common their stratified constitution, presenting several problems in the measuring that are not found with other types of fibre materials as glass wools. Three or four samples have been obtained at random locations in the layer material, for both sizes of diameters.

In table 2 are included the average of the measured air flow resistivity, with the standard deviation. The averaged values correspond of three samples random selected for a mat of material, measured three times turning over the sample between each consecutive measurement (so as to reverse the faces).

Sample	**d1(mm)**	**ρ (Kg/m^3)**	**R_1 SI Rayls/m**	**std(R_1), (%)**
R01	40	110	43148	1358 (8.6)
R02	80	56.1	16896	1669 (9.8)
R03	40	70	25627	6160 (24)
R04	60	29	5934	1523 (25.6)
R05	40	38.2	14488	2040 (17.7)
R06	40	52	15761	1358 (8.6)

Table 2. Characteristics of the used fibre layers

Inverse method

For each type of material a set of α – curves was obtained, for 10 cm diameters and for 3cm diameter. An algorithm was implemented to adjust experimental curves to theoretical following the different empirical equations [2-6]. After preliminary calculus with all the cited empirical equations applied to the several types of mineral wools studied, we decided to restrict the study to the proposals of Delany, Allard and Mechel.

Each sample was measured at least three times reversing the orientation between measurements as described above.

The absorption coefficient, α, of the samples was measured in an impedance tube using two microphone method, following ISO 10534-2:1998 [11]. The impedance tube has a diameter of 10 cm, determining a measurement range from 100 to 1600 Hz. In order to increase the frequency range up to 6400 Hz a smaller tube with a diameter of 3 cm was used.

As an example, figure 1 shows the experimental curves of the 10 cm samples of the set R01.

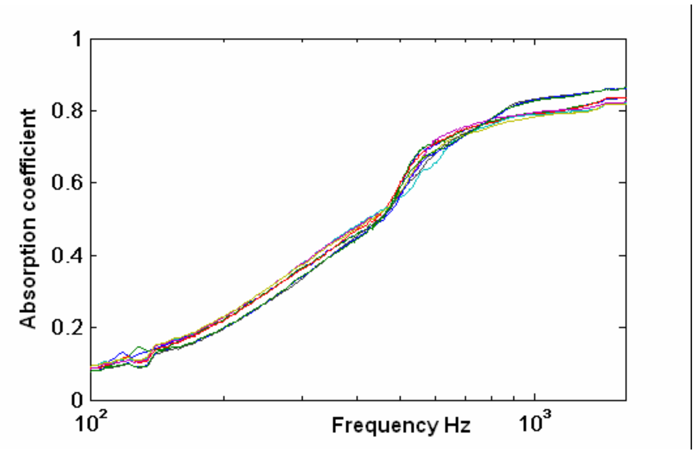

Figure 1. Experimental absorption curves of the set R01 measured in impedance tube. Diameter of the samples 10 cm, thickness 6 cm.

Figure 2 shows the difference of the experimental α – curves minus the corresponding obtained after the best adjustment with each of the three cited algorithms, for the R04 (big tube) set of values:

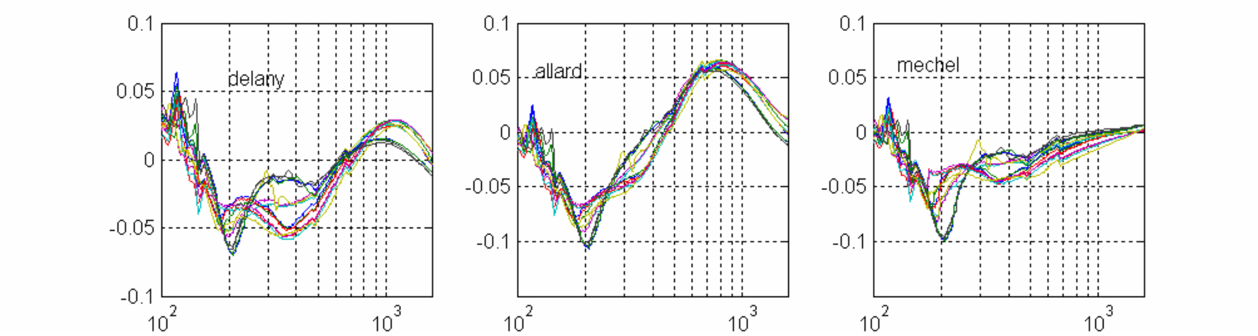

Figure 2. Differences between experimental absorption curves and the corresponding theoretical, using the formulations of Delany, Allard and Mechel, after the better approximation of R_1 for each curve for the sample of 10 cm enclosed in the set R01.

A quality single number index was implemented (based on the fitting residue) in order to simplify the election of the best empirical formulation for our proposals, through great number of samples.

Figure 3 shows superimposed, as an application example, the calculated R_1 values for the experimental curves using the algorithms of Delany, Allard and Mechel (10 cm. samples of R01).

After this preliminary work, we decided to use Mechel's equations due to the better agreement between experimental results and theoretical approximations.

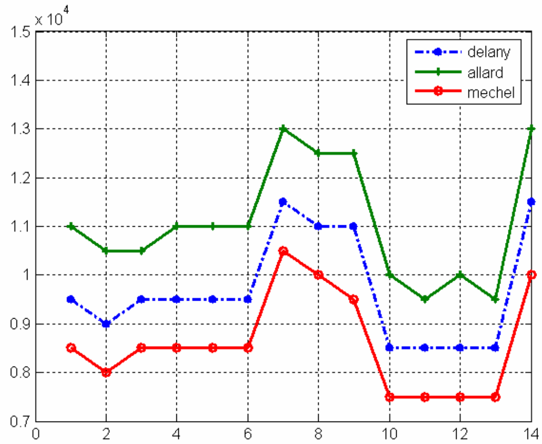

Figure 3. Best approximation of R_1 values of the big samples using the empirical equations of Delany, Allard and Mechel

In the samples with very low bulk density, the measurement of R_1 can be troublesome due to the variations in their thickness, *d*, during successive manipulations. For this reason two series of calculi were made: one with their nominal thickness and other with the values that correspond to the best approximation to the experimental data.

Starting from this data an algorithm was implemented in function of R_1 and *d*, that gives the better approximation to the respective experimental curve.

Figure 4 shows, as a survey summary, the results obtained for the set of measurements R01 for the 10 cm. tube (TG) and the 3 cm. The bars correspond to one standard deviation .

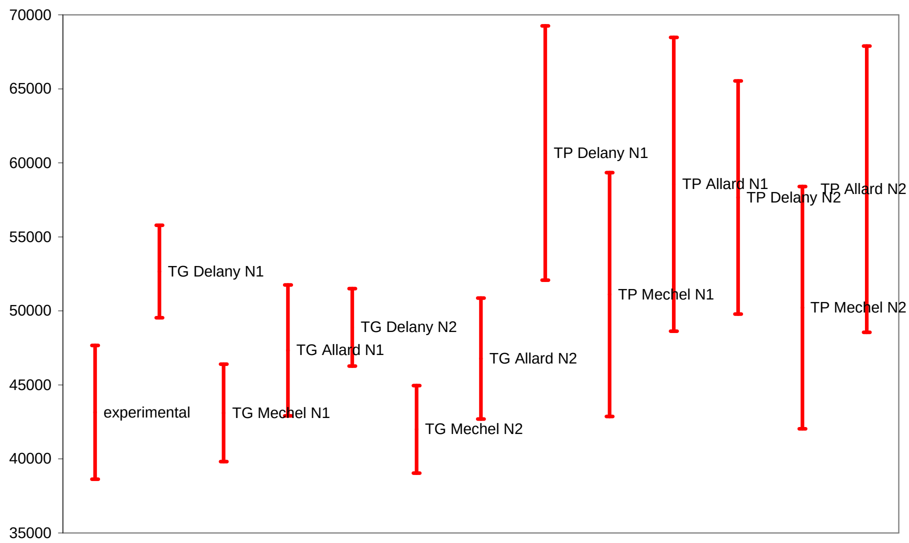

Figure 4. Airflow resistivity, R_1 of R01 obtained through experimental measurements according to ISO 9053, and those obtained with the empirical equations throughout α determination with 10 cm impedance tube (TG) and 3cm (TP). Bars correspond to one standard deviation

CONCLUSIONS

In this paper an alternative procedure to the ISO 9053 is presented. The new procedure allows calculating the flow resistivity, R_1 from experimental measurements of the acoustic absorption coefficient, α, in an impedance tube

The procedure allows detecting thickness variations of the samples due to manipulations during the measuring process.

For sufficiently rigid materials, the procedure can be simplified by neglecting the influence of thickness variation.

The compatibility index between the direct and inverse methods indicates that the differences between both methods are not significative.

It would be very interesting to investigate the effect of the bulk density of the samples in the used procedure, in order to define possible dependences.

The uncertainty due to the applicability of the method in several types of fibrous wools is of the same order than those obtained with the direct method described in ISO 9053

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