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ACOUSTICAL PROPERTIES OF POLYURETHANE OPEN CELLS MATERIALS: EXPERIMENTAL INVESTIGATION AND THEORETICAL MODELS

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Abstract

In this work results about the experimental investigation on polyurethane open cell materials are reported. The materials have shown different acoustical performances, due mainly to non-homogeneity of the tested samples.

In this paper the experimental acoustical parameters will be discussed in terms of some physical quantities both measured (airflow resistivity, open porosity and tortuosity) and inversely determined from those acoustical data (viscous and thermal characteristic lengths) by using genetic algorithms. Furthermore correlations between some physical parameters will be shown and discussed.

Finally the application of the phenomenological model proposed by Johnson-Champoux and Allard will be presented.

1. INTRODUCTION

The present paper reports the results of an experimental and theoretical investigation on polyurethane foam materials. These materials are widely used for automotive applications and to control the sound quality of machines.

The materials used in this research have been provided by five different Italian companies. It is worth emphasizing that because of the absence of adequate foaming process controls, these materials can exhibit high variability in acoustical performances, even when they are nominally identical.

As a consequence, a physical characterization of these materials turns out to be necessary in order to better understand their acoustical behaviour and to determine those parameters which can influence the absorption mechanisms taking place within them.

Furthermore, the knowledge of the internal structure of the materials could be useful for manufacturers to achieve a better understanding of the foaming processes and eventually for their optimization.

2. A PHENOMENOLOGICAL MODEL FOR THE SOUND PROPAGATION WITHIN RIGID FRAME POROUS MEDIA

In most cases, the porous material is assumed to behave like a visco-thermal equivalent fluid , i.e. supposed to have a rigid frame, much more rigid and heavier than air. In this situation the acoustic waves may only propagate through the air within the pores of the material and the absorption mechanisms then result from thermal and viscous effects occurring in those pores.

In particular, viscous and inertial effects are taken into account by introducing a complex dynamic density, $\rho_e(\omega)$ [kg/m^3], whereas thermal exchanges are described by a complex dynamic compressibility $K_e(\omega)$[Pa].

For the calculation of the effective properties the Johnson and Champoux and Allard [1] proposed the following expressions respectively:

$$\rho_e = \alpha_\infty \rho_0 + \frac{\sigma\phi}{i\omega}\sqrt{1+\frac{4i\alpha_\infty^{\ 2}\eta\rho_0\omega}{\sigma^2\Lambda^2\phi^2}} \text{ and } K_e = \frac{\kappa \cdot P_0}{\kappa-(\kappa-1)\left[1+\frac{8\eta}{i\rho_0\omega N_p\Lambda'^2}\sqrt{1+\frac{i\rho_0\omega N_p\Lambda'^2}{16\eta}}\right]^{-1}} \quad (1)$$

with ρ_0 and η the density and the viscosity of air, N_p the Prandtl number, κ the specific heat ratio and P_0 the static pressure.

All the acoustical parameters (characteristic impedance and complex wave number) can be deduced from these complex parameters, with:

$$Z_c = \sqrt{\rho_e \cdot K_e} \quad [\text{Ns/m}^3] \text{ and } k_c = \omega\sqrt{\rho_e / K_e} \quad [\text{m}^{-1}] \quad (2)$$

from which is possible to calculate the surface impedance by using the following expression:

$$Z_S = \frac{Z_c}{\phi}\cdot\cot(k_c \cdot l) \quad [\text{Ns/m}^3] \quad (3)$$

when l is the thickness of the material.

From equations (1) it is possible to notice that the complex dynamic density and dynamic compressibility depend on five macroscopic parameters: the airflow resistivity σ, the open porosity ϕ, the tortuosity α_∞, and the viscous Λ and thermal Λ' characteristic lengths. Details about the above mentioned quantities can be found in [1].

3. MATERIALS AND METHODS

3.1 Descriptions of the tested materials and measurement procedures

The experimental tests have been carried out on 13 polyurethane foams with density between 25 and 55 kg/m^3 and thickness between 20 and 40 mm.

Firstly some non acoustical parameters have been experimentally determined. In particular, the airflow resistivity was measured according to ISO Standard 9053 [2] with the alternate flow method. The open porosity was assessed using a method based on Boyle's Law, using isothermal compression of air volume within and external to the tested material [3]. Finally, the tortuosity was determined through a method based on determination of the high frequency limit for the complex phase velocity within the material [4].

Afterwards the surface properties (i.e. surface impedance and the normal incidence sound absorption coefficient) were measured according to the ISO Standard 10354-2 [5]. Lastly, the complex acoustical parameters (i.e. characteristic impedance and complex wave number) were determined by means of a transfer matrix approach by using a 3 microphones technique [6]. It is worthy of mention that, if compared to the 4 microphones scheme, the aforementioned scheme guarantees the exact agreement between the surface properties directly measured and the same ones calculated once complex acoustical properties are known.

The physical and acoustical parameters have been measured on samples of diameter equal to 45mm. The experimental test-rigs are shown in Figure 1.

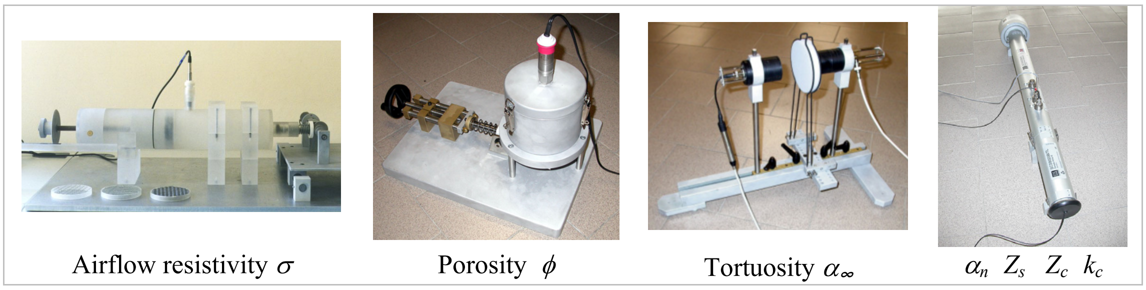

Figure 1 – Experimental devices for the determination of the acoustical and physical quantities

Figure 2 presents the comparison between three samples having the same density (25 kg/m^3) and the same thickness (20mm). In the same graph experimental values of the airflow resistivity are also reported for the tested materials.

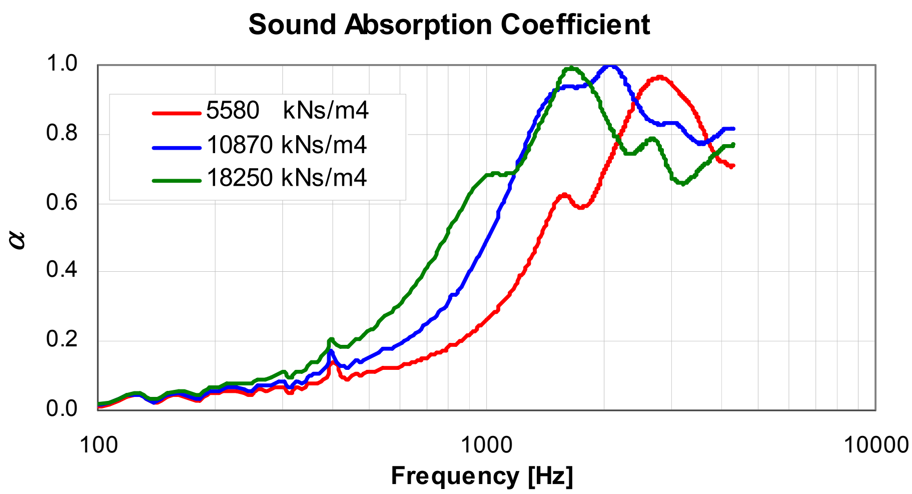

Figure 2 – Sound Absorption curves for three samples having identical density and thickness

Although the samples were nominally identical, they are characterized by different values of the airflow resistivity; moreover, from the figure it is possible to notice that the acoustical performance are extremely diverse (0.3<α<0.7 at 1kHz) and strictly depending on the value of the airflow resistivity. The higher the value of the airflow resistivity the most remarkable is the enhancement at lower frequencies.

A complete description of the tested materials is reported in Table 1. In the same table the experimental values for airflow resistivity, open porosity and tortuosity are shown.

Table 1 – Description of the tested materials

Sample	***Density*** *[kg/m³]*	***Thickness*** *[mm]*	σ *[Ns/m⁴]*	ϕ	α_∞
P1	30	30	4370	0.98	1.08
P2	30	40	3923	0.98	1.08
P3	25	40	19270	0.97	1.59
P4	25	20	10870	0.97	1.41
P5	55	20	6412	0.97	1.50
P6	30	20	5993	0.96	1.41
P7	25	20	5581	0.96	1.47
P8	25	20	18255	0.98	1.37
P9	25	25	12697	0.98	1.76
P10	33	20	15754	0.97	1.35
P11	33	20	8869	0.97	1.44
P12	33	20	12842	0.98	1.38
P13	33	20	7672	0.98	1.41

From the table, it is possible to notice a variation of the airflow resistivity between 4 and 20 kNs/m^4, whereas the values of the porosity vary between 0.96 and 0.98. Finally, the tortuosity values are between 1 and 1.76.

The values of airflow resistivity as a function of tortuosity are shown in Figure 3.

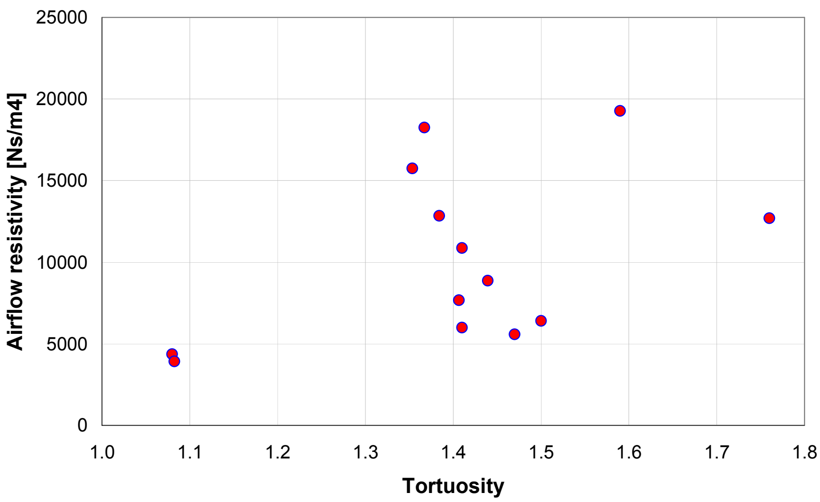

Figure 3 - Correlation between airflow resistivity and tortuosity

From the previous figure it is interesting to underline that the values of tortuosity are not sufficient to justify the high values of the airflow resistivity.

3.2 Inversion methods

Inverse techniques for determining the physical parameters from acoustical data have been widely investigated in recent years.

Different approaches have been proposed and they are based on the minimization of the experimental characteristic or surface acoustical properties with respect to the same quantities, determined by applying a theoretical prediction model. Regarding the minimization procedures, methods based on high frequency behaviour of porous media [7], genetic algorithms [8] and neural network schemes [9] have been proposed in literature.

In this work a genetic algorithm has been used to inversely determine the viscous and thermal characteristic lengths. The procedure is based on the minimization of experimental and theoretical surface impedance curves, calculated by using equation (3). The cost function to be minimized was:

$$CF\left(f,\phi,\sigma,\alpha_{\infty},\Lambda,\Lambda'\right)=\sum_{i=1}^{n}\left(\left|Zs_{\mathbf{exp}}\left(f_i\right)-Zs_{\mathbf{mod}}\left(f_i\right)\right|\right)^2 \tag{4}$$

The procedure has been implemented in Matlab®. It is important to remark that it has been applied the non linear constrain $\Lambda' \geq \Lambda$, physically expected.

4. RESULTS

The inversely determined values for the characteristic lengths are reported in Table 2.

Table 2 – Values of the VCL and TCL determined through the inversion procedure

Sample	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**P13**
Λ [µm]	143	114	18	20	107	114	61	13	23	14	24	19	34
Λ' [µm]	234	250	357	437	254	239	314	263	471	251	309	272	256

From the table it is possible to observe that the inverse procedure provided values for the viscous and thermal characteristic lengths between 13 and 143 µm and 234 and 471 µm, respectively. In particular, it is interesting to notice that only materials P1, P2, P5 and P6 are characterized by values of Λ higher than 100µm.

By comparing the experimental physical parameters listed in Table 1 and the characteristic lengths, it is possible to underline a decrease of the airflow resistivity when the viscous characteristic length increases. The correlation between the above-mentioned parameters is depicted in Figure 4.

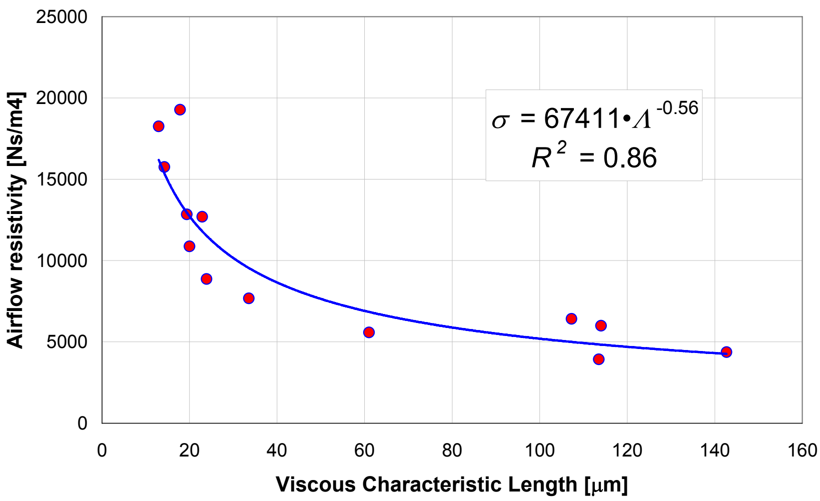

Figure 4 - Correlation between Airflow resistivity and Viscous Characteristic Length

From the regression curve shown in Figure 4 it is possible to notice that the trend of the airflow resistivity as a function of the viscous characteristic length is governed by a relation similar to the theoretical law that establishes the dependence of the energetic losses in cylindrical circular ducts from the inverse of their squared radius [1].

No significant correlations seem to exist between Λ' and the values of σ and α_∞.

The results could be explained in the following way: tortuosity and airflow resistivity, and consequently the acoustical performance, are not related to the size of the pores (for all the tested materials $\Lambda' > 200\mu m$) but they depend on the dimension of the connections between pores, which are linked to the level of "explosion" of the cells during the processes leading to the formation of the foam itself. If during these processes the cells remain partially closed then the energy losses increase and consequently the acoustical performance enhances.

It is worthy of mention that these considerations can be utilized to justify differences highlighted in Figure 2. In fact, when the value of the viscous characteristic length becomes lower, then the airflow resistivity increases leading to higher values of sound absorption coefficient at lower frequencies.

The comparison between experimental and theoretical values of the normalized surface impedance and the normal incidence sound absorption coefficient for material P1 are reported in figure 5 and 6. The theoretical curves have been determined by applying the J-C-A model using the experimental values of σ, ϕ and α_∞ and the values of the characteristic lengths determined through the inversion procedure.

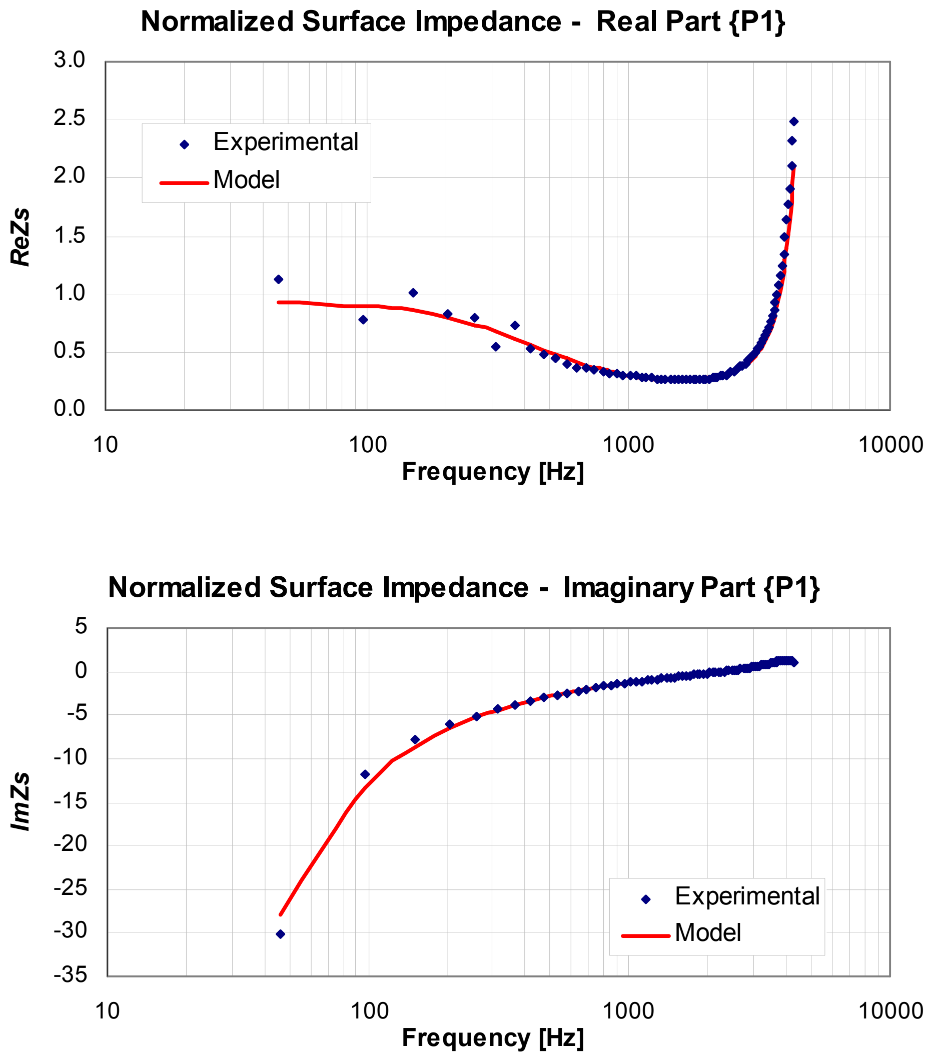

Figure 5 - Normalized Surface Impedance for material P1

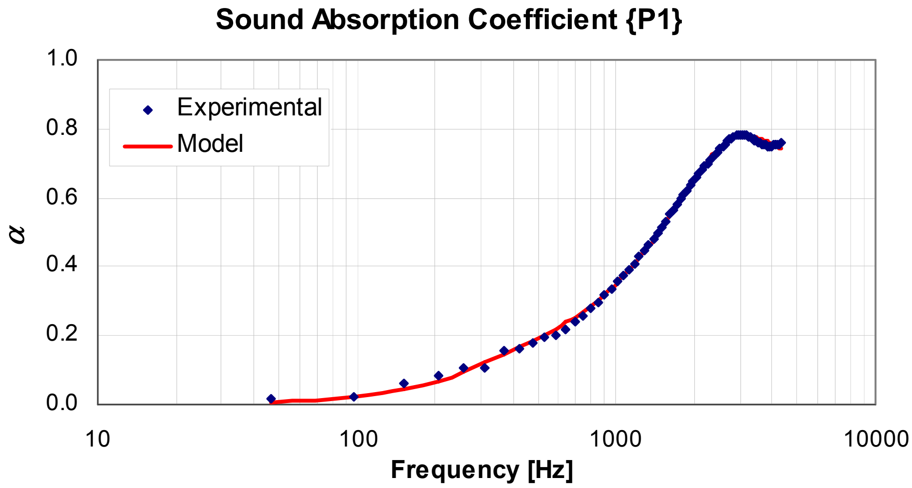

Figure 6 – Sound Absorption Coefficient for material P1

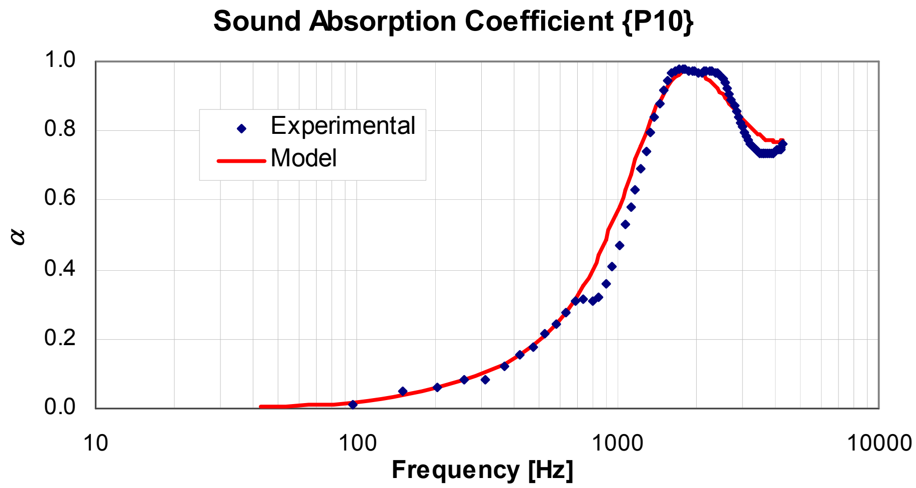

Figure 7 - Sound Absorption Coefficient for material P10

The comparison between the experimental and theoretical curves of sound absorption coefficient for material P10 is shown in Figure 7. From the figure it can be noticed that the model is able to represent the trend of the curve, but it does not predict resonances occurring for frequencies higher than 700 Hz, caused by the elastic behaviour of the structure of the tested material. It is worthy of mention that this aspect makes the inversion procedure less efficient. The aforementioned elastic behaviour has been noticed for many of the tested materials.

5. CONCLUDING REMARKS

In the present work an experimental and theoretical investigation has been presented for polyurethane foam materials. Tested materials have been experimentally characterized by measuring characteristic and surface acoustical properties

From the experimental tests carried out on those materials, they have shown an high variability in the acoustical performance, even for sample nominally identical.

As a consequence a physical characterization turned out to be necessary and some physical quantities, (that are the airflow resistivity, the open porosity and the tortuosity) have been directly determined.

Furthermore, a genetic algorithm based inverse approach has been applied for the determination of the viscous and thermal characteristic lengths from the minimization of the theoretical values of the surface impedance, obtained by using Johnson-Champoux-Allard model, with respect to the values of the same quantity, experimentally measured.

Results have shown a remarkable correlation between values of the airflow resistivity and viscous characteristic length. The analysis of this correlation highlights the dependence of the acoustical performance of such materials on the dimensions of the connections between the open pores.

Moreover a satisfactory agreement between experimental acoustical data and the same determined by using Johnson-Champoux-Allard model, when the directly measured airflow resistivity, open porosity and tortuosity and the inversely determined characteristics lengths values are used.

In conclusion, the proposed investigation has shown that the combined use of experimental techniques and inversion procedures for determining physical parameters could allow to comprehend the internal structure of porous media and to understand their acoustical performance.

REFERENCES

[1] J.F. Allard, "Propagation of sound in porous media", Elsevier, Applied Science, London and New York, 1993.

[2] ISO 9053 , "Acoustics - Materials for acoustical applications - Determination of airflow resistance", 1991.

[3] Champoux Y., Stinson M.R., Daigle G.A., "Air-based system for the measurement of porosity", Journal of Acoustical Society of America, 89, pp.910 (1991).

[4] Allard J. F., Castagnède B., Henry M. and Lauriks W., "Evaluation of the tortuosity in acoustic porous materials saturated by air", *Review of Scientific Instruments* 65, 7654-7655 (1994).

[5] ISO 10354-2, Acoustics-Determination of sound absorption coefficient and impedance in impedance tubes-Part 2: Transfer-function method, 1996.

[6] Mcintosh J. D., Zuroski M.T. and Lambert R. F., "Standing wave apparatus for measuring of acoustic materials in air fundamental properties of acoustic materials in air", J.Acoust. Soc. Am. 88(4) pp.1929-1938 (1990).

[7] Panneton R., Olny X., "Acoustical determination of the parameters governing viscous dissipation in porous media", Journal of Acoustical Society of America 119(4) pp.2027-2040 (2006).

[8] Atalla Y. and R. Panneton, "Inverse characterization of the geometrical macroscopic parameters of porous materials", Canadian Acoustics 28 (2000).

[9] Tran-van J., Olny X., Sgard F.C. and Gervais Y., "Global Inverse Methods for determining the Acoustical Parameters of Porous Materials", Proceedings ICA 2001 Rome.

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