Reproducibility experiments on measuring acoustical properties of rigid-frame porous media (round-robin tests)

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This paper reports the results of reproducibility experiments on the interlaboratory characterization of the acoustical properties of three types of consolidated porous media: granulated porous rubber, reticulated foam, and fiberglass. The measurements are conducted in several independent laboratories in Europe and North America. The studied acoustical characteristics are the surface complex acoustic impedance at normal incidence and plane wave absorption coefficient which are determined using the standard impedance tube method. The paper provides detailed procedures related to sample preparation and installation and it discusses the dispersion in the acoustical material property observed between individual material samples and laboratories. The importance of the boundary conditions, homogeneity of the porous material structure, and stability of the adopted signal processing method are highlighted. © *2007 Acoustical Society of America.*
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I. INTRODUCTION

Porous materials are widely used to control the sound field in both interior and exterior spaces. Powders, wool, hair, soils, and vegetation are natural forms of porous media which affect sound field incident on the porous surface. Characterization of porous media is now a routine experiment which is carried out in many laboratories worldwide to determine the acoustical absorption performance of these materials and/or to deduce the fundamental nonacoustical data related to their porous microstructure. A standard technique to characterize these materials is the impedance tube method,[1] which typically allows one to measure the surface impedance and absorption coefficient of relatively small (e.g., 29–100 mm) samples of porous media. These data can then be used to deduce some of the nonacoustical (geometrical) parameters of porous materials. As a result, the characterization process relies heavily on the accuracy of experimental data on the acoustic surface impedance or absorption coefficient. The accuracy of this technique is affected by the quality and homogeneity of the material samples, their environmental, and operational conditions during the experiment, the quality of the setup, and the signal processing method. These conditions and measurement apparatus can vary from lab to lab and their effect on the measured values of the sound absorption coefficient is largely unknown.

There have been a number of studies into the accuracy of the standing wave tube method.[2–5] A majority of these studies are concerned with the effect of the mounting conditions on the measured values of the normal incidence acoustical impedance and sound absorption coefficient. Specifically, Pilon *et al.* suggested a practical criteria for the

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assessment of the importance of the frame vibration effect in a sample with given elastic properties and of a given surface area. Song and Bolton[4] and Tsay and Yeh[6] developed advanced finite element models to study the effect of vibration of the sample installed in the impedance tube with arbitrary boundary constraints. Kino and Ueno[7] presented evidence from a series of laboratory experiments which suggests that the frame resonance effect may be overcome if the sample diameter is chosen 0.5–1.0 mm smaller than the inner diameter of the impedance tube. The latter effect will be dependent on the flow resistivity of the material sample.[2,5] These and other related studies suggest that the effects of the mounting conditions and of the circumferential air gap are expected to impact on the values of both the impedance surface and the absorption coefficient. In the case of weak edge constraints, the acoustical response of the sample tends to the response of a sample having infinite lateral dimensions.[3,6,7] The other extreme situation occurs when the sample edges are fixed.[4,5] In this case, the material is artificially "stiffened" and a shear resonance[4] may occur at the frequency which position would depend on the material elastic properties. This results in rapid and sharp variations in the impedance surface data and it corresponds to a sharp dip in the absorption data in the vicinity of the frequency of this resonance.

However, a majority of the relevant studies (e.g., Refs. 2–7) were carried out in individual laboratories and the authors are not aware of any works offering systematic experimental data on the performance of the impedance tube method between individual laboratories (i.e., interlaboratory data) for a particular set of material samples. These data should be obtained using independent sample preparation techniques, standing wave tubes of different diameters, different excitation stimuli, and signal processing methods. We also note that a majority of previous works focused on the acoustical properties of highly porous, light-weight foams and glasswool. As a result, there is a lack of data on the reproducibility of the standard impedance tube experiment on material samples made from granular-like media for which a limited porosity and a relatively low "air" permeability, are characteristic. Here the authors are referring to the static permeability, which is the ratio of the dynamic viscosity of air to the static air flow resistivity, i.e., the ability of a material to transmit continuous flow of air.

The objectives of this work are: (i) to use the standard standing wave tube method[1] to determine the dispersion of normal incidence, plane wave acoustic surface impedance and absorption coefficient data obtained for different samples of the same sheet of material in the same laboratory; and (ii) to determine the dispersion of acoustic surface impedance and absorption coefficient data for samples of the same material obtained between different laboratories. This paper is organized as follows. First, the methodology is detailed. Second, the results from individual laboratories are presented and dispersion in the results within each individual laboratory is discussed. Third, a comparison is made between the interlaboratory results. Finally, conclusions on the dispersion between the results are drawn.

TABLE I. A summary of the averaged characteristics of the investigated porous materials measured independently from the acoustic.

Material	Description	Mean porosity	Mean flow resistivity (kPa s m^{-2})	Mean density (kg/m^3)	Mean layer thickness (m)
A	Reconstituted porous rubber	0.80±0.02	141.4±44.0	242.0	0.0245
B	Reticulated foam	0.98±0.01	9.9±0.8	8.8	0.0197
C	Fibreglass	0.97±0.03	11.7±1.9	21.0	0.0290

II. METHODOLOGY

In total seven acoustic research centers were involved in this work. These are: University of Perugia (Italy), Katholieke Universiteit Leuven (Belgium), ENTPE (Lyon, France), Gesellschaft für Akustikforschung (Dresden, Germany), University of Bradford (UK), University of Ferrara (Italy), and Sherbrooke University (Canada). The paper reports the results for three porous media of different classes: reconstituted porous rubber, reticulated foam, and fiberglass, denoted, respectively, material A, B, and C. These materials were chosen to cover the range from relatively low (1.28×10^{-10} m^2) to relatively high (1.81×10^{-9} m^2) air permeability and to be representative of typical, commercially available acoustic porous materials. Table I provides a summary of some physical and geometrical characteristics of these materials. The values of parameters presented in Table I were averaged over all the range of data provided by all the partners for all the material specimens studied in this round-robin test. Table I also presents the standard deviation for the measured flow resistivity and porosity data. The criterion for the selection of the optimal sample area proposed by Pilon[5] was not adopted in this work because a detailed characterization of the elastic properties of the tested material was outside the scope of this investigation.

Each partner has been provided with a 400 mm $\times$ 400 mm sheet of the above-mentioned materials. Specimens of these materials have been cut individually by the partners using a circular cutting tool or water jet cutting machine to fit the diameter of the standing wave tube. The diameter of the standing wave tube, the measurement method, the sample preparation procedure, and the mounting method for the sample used by the partners are detailed in Table II.

TABLE II. Equipment and sample preparation procedures (HM—home-made tube; H—horizontally installed tube; V—vertically installed tube).

Partner	Tube diameter (m/tube manufacturer)	Tube length/microphone spacing (m)	Material preparation method
1	44 mm/HM/V	1/0.03	Water jet/circular tool
2	46 mm/HM/H	1.32/0.02	Rotating blade
3	38 mm/HM/H	1/0.02;0.03;0.05	Rotating blade
4	29 mm/BK4206/H	0.4225/0.02	Rotating blade
5	29 mm/BK4206/H	0.4225/0.02	Rotating blade
6	29 mm/HM/H	0.4225/0.02	Rotating blade
7	45 mm/HM/H	0.37/0.025	Water jet

TABLE III. A summary of the number of material specimens tested by individual laboratories and condition for specimen constraint (TF—tight fit; TC—tape constraint; GB—glue bonded; PF—perfect fit; R—repeated measurements with the reversed samples).

Partner	Material A	Material B	Material C	Method of support
1	6	4	6	TF/TC
2	6	6	3	TF/TC
3	1	1	1	GB
4	5	4	4	TF
5	10(R)	9(R)	10(R)	TF/TC
6	6	6	6	TF/TC
7	3	4	3	PF/TF

The measured properties were the surface impedance z_s and the absorption coefficient α of the material sample backed by a rigid wall, i.e.,

$$z_s = z_b \coth(-ik_b h), \quad \alpha = 1 - \left| \frac{z_s - \rho_0 c}{z_s + \rho_0 c} \right|^2, \tag{1}$$

respectively. Here ρ_0 and c are the equilibrium density and the sound speed in air, respectively, z_b is the characteristic impedance, k_b is the wave number within the material, and h denotes the material thickness.

Either of the following methods of sample mounting conditions were adopted (see Table III): (i) the diameter of the cut samples was 1 to 2 mm larger than the diameter of the tube in order to ensure their tight fit (TF); (ii) the diameter of the cut samples was close or slightly smaller than the diameter of the tube and the samples were wrapped in tape to prevent any leakage around the edge—tape constraint (TC); (iii) the diameter of the sample was exactly equal to that of the tube—perfect fit (PF); (iv) the diameter of the sample was exactly equal to that of the tube and the sample was glue bonded to the rigid backing—glue bonded (GB).

The partners used a range of commercially available impedance tube apparatus and impedance tubes especially designed and constructed for their laboratories. The characteristics of the impedance tube and the type of the acoustic stimuli used by individual partners are summarized in Tables II and IV. All the microphones used in these experiments were standard measurement 1/4 in. microphones. Six out of seven partners used identical or similar types of microphones provided by Brüel and Kjær. Partner 6 used specialized 1/4 in. microphones supplied by Microtech Gefell. The type of the acoustic stimulus was mainly restricted to random noise. Partners 1, 2, and 7 used maximum length[8] or phase-modulated random noise sequences.[9] The number of averages was adapted to the type of the acoustic stimulus and the signal-to-noise ratio observed during the experiment. This number varied from 8 in the case of the maximum length sequences to 100 in the case of random noise. The type of electronic hardware used for data acquisition varied from a specially dedicated commercially available Brüel and Kjær PULSE system (partners 5 and 6), general purpose A/D analyzers (partners 2 and 3), and high-quality sound cards (1 and 4). Each impedance tube was driven by a single loudspeaker which was adapted to the size and the frequency range of the impedance tube (typically in the range of 100–6000 Hz). It was assumed that the nonlinearity in the speaker response and tube vibration effect could be neglected. The sampling frequency and the sequence length used in the Fourier analysis were chosen so that to cover the desired frequency range and provide adequate frequency resolution in the transfer function spectrum as suggested in Ref. 1. The equipment was properly calibrated prior to the start of the experiments to compensate for the microphone channel mismatch using the procedure suggested in Ref. 1 for those partners who used two independent microphone channels. The effects of temperature and atmospheric pressure variations were compensated as suggested in Ref. 1. The material thickness was measured to ±0.1 mm using a set of calibrated calipers.

TABLE IV. Summary of the acoustic stimuli and the hardware used in the round-robin experiments (MLS—maximum length sequence; PRN—pseudorandom noise; RN—random noise; WN—"white" noise).

Partner	Type of acoustic stimulus	Number of averages	Electronic hardware	Microphone type
1	MLS	8	Marc-8 sound card	BK4187
2	PRN	16	NI card PXI-4461	BK4187
3	RN	30	HP-35060A analyzer	BK4135
4	WN	100	VX-Pocket PCMCIA	BK4187
5	RN	100	BK PULSE	BK4187
6	RN	100	BK PULSE	Microtech Gefell Type M360
7	PRN	6	MNS Tube-X	BK4187

III. RESULTS

A. Individual laboratory tests

The exact number of samples tested in the individual laboratories is presented in Table III. Up to ten sets of data for each of these materials were analyzed. In the case of laboratories 2 and 5 this number includes the data sets obtained when the tested samples were reversed. Figures 1–3 present the measured data for the real and imaginary parts of surface impedance together with their standard deviation obtained by each partner for materials labeled A, B, and C, respectively. The results obtained by laboratory 3 have been omitted from these figures since no statistics are available from a single set of data.

The results for the acoustic surface impedance obtained for material A indicate that the dispersion in both the real and imaginary part is considerable. Specifically, the maximum dispersion in the real part of the impedance is ±31% in the frequency range below 1000 Hz. The dispersion in the imaginary part of the impedance in this frequency range is limited and increases with the increasing frequency. This phenomenon is consistent in the results obtained in other laboratories as indicated in Fig. 1. This is a highly resistive material and the dispersion is likely to be attributed to dispersion in the values of the flow resistivity (σ) of the investigated material samples. The standard deviation in the measured values of the flow resistivity obtained for this material using the direct measurement[10] is relatively high (see Table

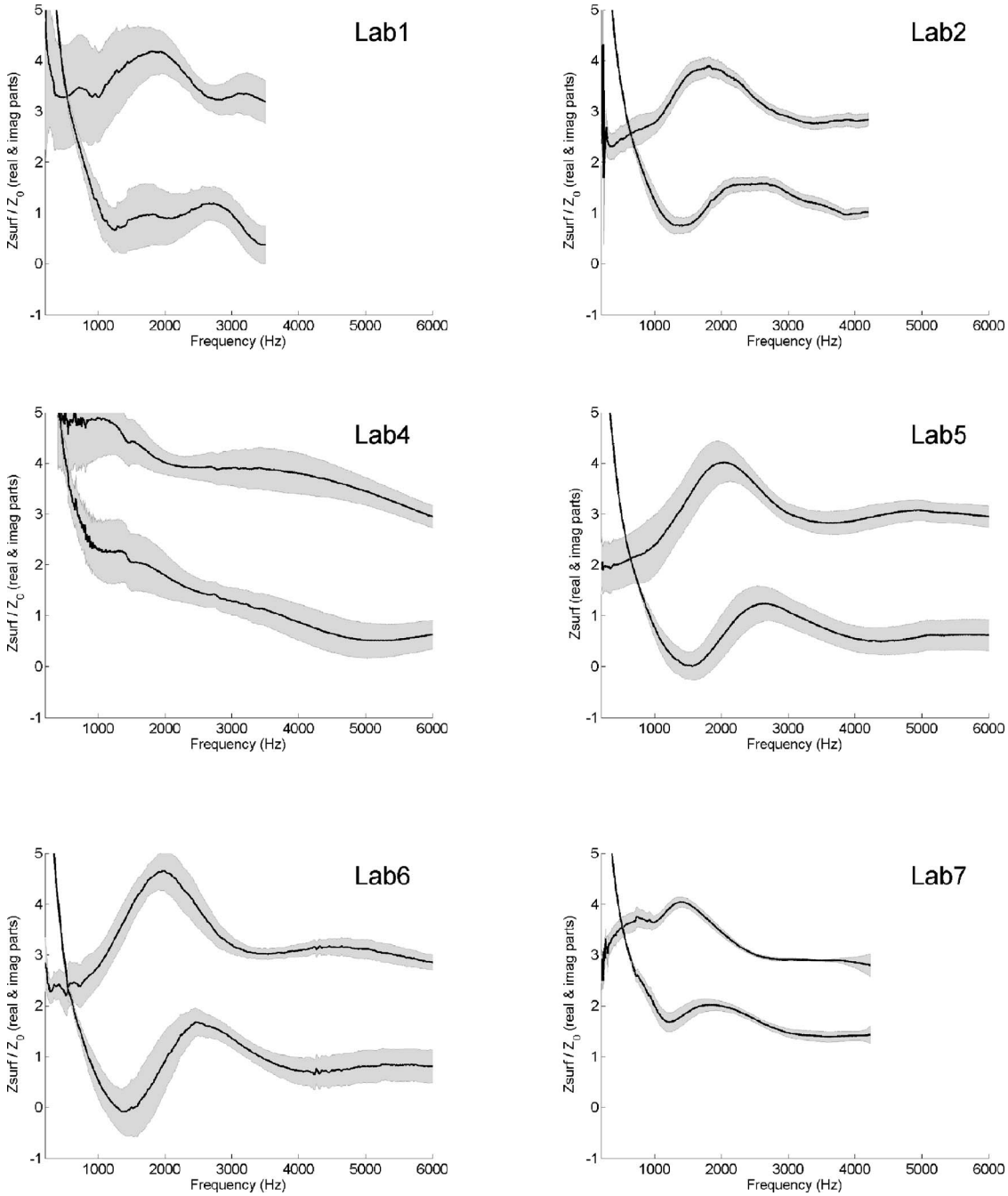

FIG. 1. Individual results of the measurements of the real and imaginary parts of the normalized surface impedance for material A for all partners.

I) and compares well with that observed in the measured data for the real part of the surface impedance ($\Delta\sigma$=31% vs Δ Re z_s=31%). This effect is expected and explained by the dominant $\sigma/3$ term in the expression [see exp. (4.4.5) in Ref. 11]

$$z_s \approx \frac{\sigma}{3} + \frac{i}{\phi\gamma kh}, \quad k \to 0, \tag{2}$$

where k is the wave number in air, γ is the ratio of specific heats, and ϕ is the material porosity.

The interlaboratory examination suggests that there is a similarity in the behavior of the mean impedance between laboratories 1, 2, and 7 but there are noticeable differences in the dispersion. These laboratories used the impedance tubes of similar diameter (44–46 mm) and similar type of acoustic excitation. The maximum dispersion in these results is observed in the case of laboratory 1 and the minimum is in the case of laboratory 7. This is likely to be attributable to the quality of the sample mounting conditions and the number of tested specimens (see Table III). The behavior of the results from laboratories 5 and 6 is comparable both in terms of the dispersion and mean values of the acoustic surface impedance. These two laboratories used identical type of the impedance tube (Brüel and Kjær 4206), signal analysis hardware (Brüel and Kjær PULSE), and the same software setup. The behavior of the impedance data obtained in laboratory 4 differs from that obtained in the other laboratories, but the level of dispersion is similar to that observed in the results

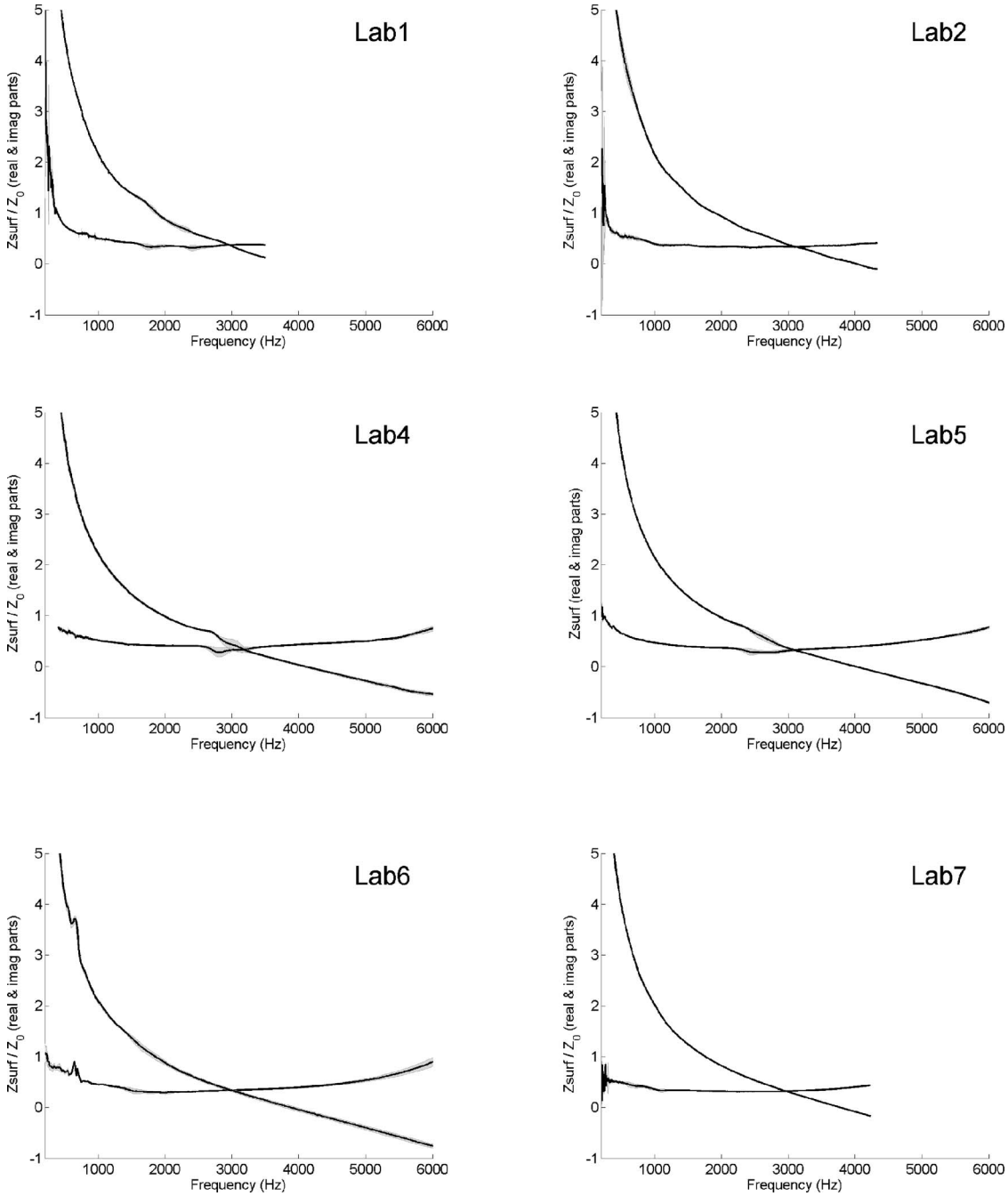

FIG. 2. Individual results of the measurements of the real and imaginary parts of the normalized surface impedance for material B for all partners.

from laboratories 5 and 6. These three laboratories use the identical impedance tubes but laboratory 4 uses a specialized sound card instead of a PULSE analyser (see Table IV).

Sample B (see Fig. 2) represents the case of a high permeability, relatively homogeneous foam for which the standard deviation in the airflow resistivity is within ±8% (excluding laboratory 7, for which this information is not available). The results show that the dispersion of the acoustic absorption spectra for this material is considerably less ($<$10% except around the frame resonance) than that in the case of material A, which relates to the consistent airflow resistivity values and the constant material thickness. Here the largest values of the standard deviation, reaching locally more than 30% for laboratory 4, occur near the structural resonance in the material frame which frequency depends on the mounting conditions attained during the measurement.[3–7] It is clear from the results obtained in laboratories 2 and 7 that the selected mounting conditions using the appropriate sample constraints enabled one to move the structural resonance frequency out of the measurement spectral range. Measured data from laboratories 1, 4, 5, and 6 suggest that the investigated samples were inconsistently mounted which resulted in the higher values of the standard deviation observed at frequencies of the frame resonance between 1500 and 3500 Hz (see also Fig. 4).

Sample C represents the case of a transversely isotropic fibrous material. The mean value of static permeability of this material measured in the direction normal to the fiber

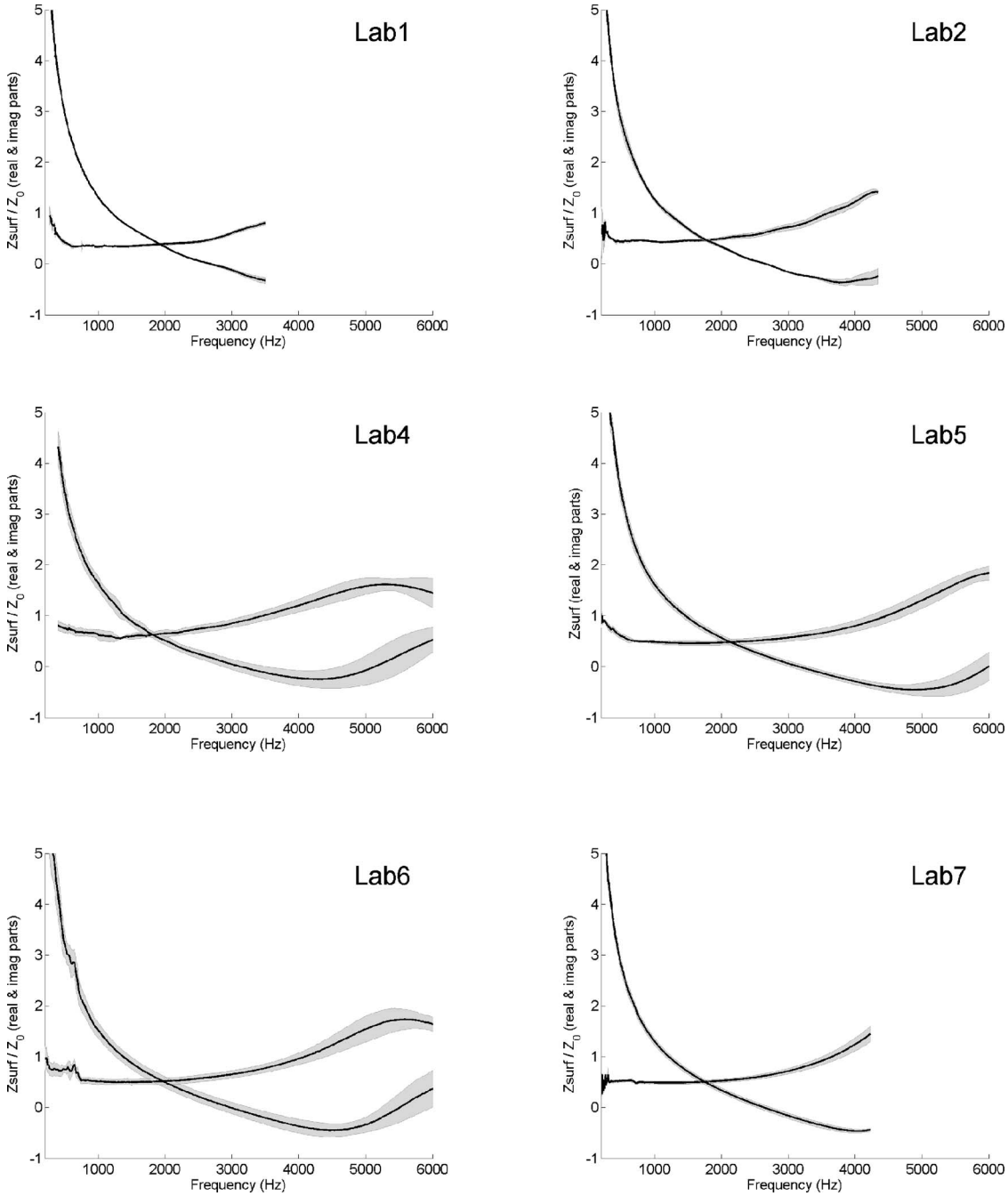

FIG. 3. Individual results of the measurements of the real and imaginary parts of the normalized surface impedance for material C for all partners.

orientation is similar to that measured in material B, but its standard deviation is higher being at ±16% (excluding laboratory 7, for which the individual value is given in the following). There is a greater thickness dispersion between individual specimens of material C. The density of this material is approximately 2.5 times greater than that of material B and the material exhibits a relatively low bulk modulus of approximately 100 kPa. The latter characteristics seem to drive the resonance frequency toward the lower spectral end so that none of the presented results show the distinctive frame resonant behavior. The dispersion in the presented data is less noticeable than that observed in the case of materials A but higher than that observed in the case of material B. The dispersion in the real part of the surface impedance lies between 10% and 20% on the frequency range from 1000 to 6000 Hz. The dispersion in the imaginary part of the acoustic surface impedance is noticeably greater across the considered frequency range. At the lower frequencies this behavior is explained by dominant effects of the material thickness as suggested by expression (2). In the higher frequency limit this behavior is governed by the oscillatory term $\coth(-ik_b h)$ in which the material thickness dispersion is likely to be dominant for low airflow resistivity glasswool. The value of the standard deviation is generally greater at the frequencies above 3000 to 4000 Hz, which is confirmed by the results from laboratories 2–6. The results from laboratory 1 do not extend to sufficiently high frequencies to demonstrate this effect. The results from laboratory 7 also show the

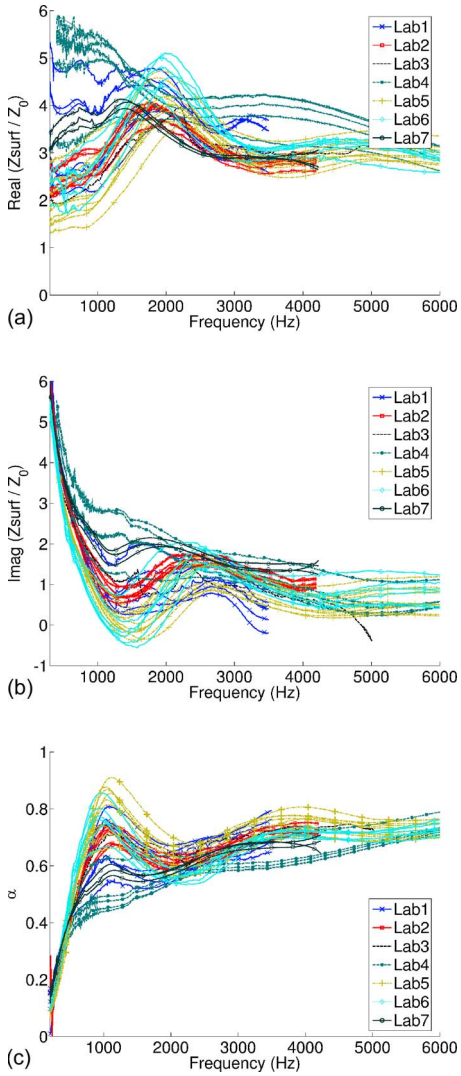

FIG. 4. (Color online) Interlaboratory measurements of the real part (top), imaginary part (middle), and the sound absorption coefficient (bottom) for material A.

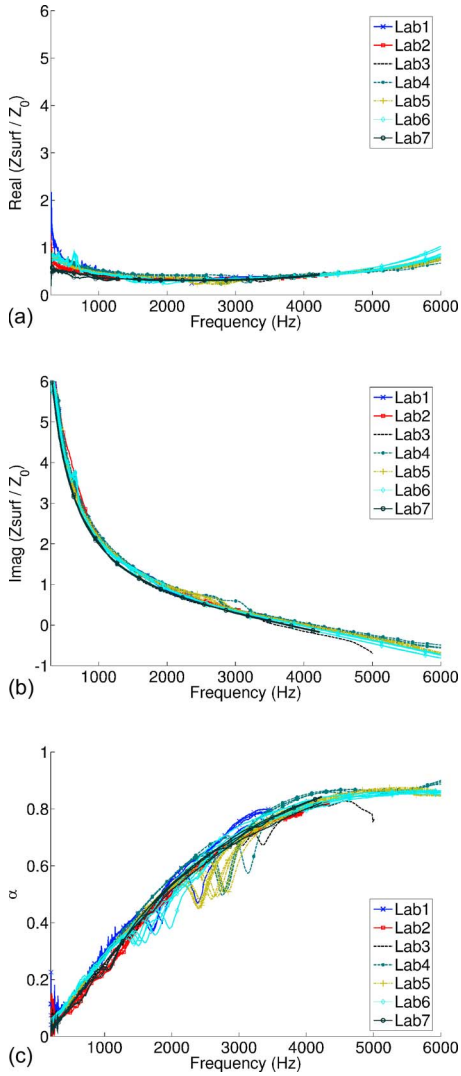

FIG. 5. (Color online) Interlaboratory measurements of the real part (top), imaginary part (middle), and the sound absorption coefficient (bottom) for material B.

increase in the dispersion in the real part of the acoustics surface impedance in the higher frequency range. This is explained by a relatively large standard deviation in the flow resistivity data for the batch of glasswool material presented to laboratory 7 ($\Delta\sigma$=27% for laboratory 7 vs $\Delta\sigma$=16% for all other laboratories) which is a consequence of the presence of the protection skin on the specimens tested by this laboratory. Note that partners 3, 4, and 7 did not remove the microperforated film covering the front surface of the fiberglass sample. The presence of the film slightly affects the measured data on the whole frequency range. This has been verified experimentally and numerically by comparing the acoustical properties for the material with and without the film. However, it is not possible to separate the effect of the screen and the sample thickness which can contribute similarly to the observed dispersion in the measured data.

B. Interlaboratory tests

Figures 4–6 present the combined results from all seven laboratories for all the specimens of materials A, B, and C. respectively. These figures (a)–(c) display data from the measurements of the real part (a) and the imaginary part (b) of the normalized acoustic surface impedance and the normal incidence, plane wave absorption coefficient (c).

The results obtained for material A show that there can be a maximum of five- to sixfold dispersion in the value of the real part of the surface impedance in the low frequency limit below 1000 Hz [Fig. 4(a)]. The agreement between the imaginary part data is poor in the medium frequency range of 1000–2000 Hz [Fig. 4(b)]. In this frequency range the imaginary part can take either negative (e.g., data from laboratory 6) or positive (e.g., data from laboratory 4) values. This dispersion is reflected in the erratic behavior of the absorption coefficient which values are summarized in Fig. 4(c). The data suggest that around these frequencies the absorption coefficient can vary within the 40%–95% range. This phenomenon is unlikely to be due to the quality of the impedance tube experiment and can rather be attributed to the dispersion in the airflow resistivity of the material specimens observed in the independent airflow resistivity tests.[10] The high flow resistivity and the acoustic penetration depth,

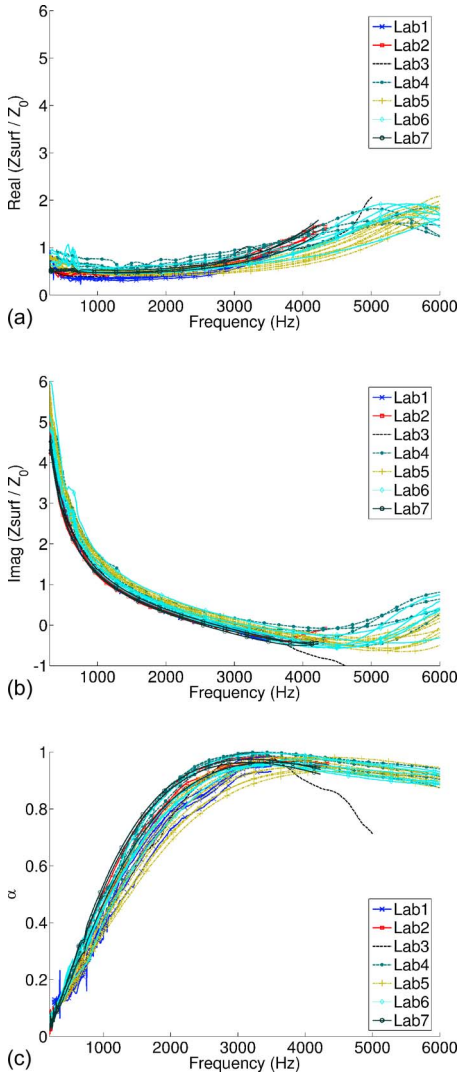

FIG. 6. (Color online) Interlaboratory measurements of the real part (top), imaginary part (middle), and the sound absorption coefficient (bottom) for material C.

$\mathrm{Re}(1/k_b)$, in this material are rather sensitive to the fluctuation of the material pore size distribution and the mounting conditions. The latter are likely to affect the thickness of the circumferential air gap and the compression rate of the investigated sample. These effects are reflected in the position and amplitude of the first interference maxima and minima in the absorption coefficient spectra which can disappear completely due to the low value of the penetration depth (e.g., data from laboratory 4).

Further examination of the obtained data suggests that the agreement between the imaginary part data for material A improves significantly in the low (e.g., below 500 Hz) and high frequency (above 5000 Hz) limits [see Fig. 4(b)] where the behavior of the absorption coefficient spectra appears much more consistent [within ±5% as illustrated in Fig. 4(c)]. This consistency in the measured acoustic absorption performance can be explained by a relatively small measured standard deviation in the material porosity [expression (2)] and by a relatively constant material layer thickness [Eq. (1)] (see also Table I) which dominate the behavior of the imaginary part.

The surface impedance and absorption coefficient spectra for material B are shown in Figs. 5(a)–5(c). There is good (approximately 10%–20%) agreement in all the results for the impedance obtained in the seven laboratories. The maximum dispersion in the real part of the impedance (within ±25%) is observed in the low and medium frequency range up to 3000 Hz [see Fig. 5(a)]. The dispersion in the imaginary part data for the impedance is limited and relatively independent of frequency [see Fig. 5(b)]. A noticeable increase of the dispersion in the absorption coefficient data can be observed around the frequency of the frame resonance in the range of 1500–3000 Hz [see Fig. 5(c)]. This suggests that the quality of the mounting conditions can control the position of the frame resonance frequency within 25% of the considered frequency range. The dispersion in the absorption coefficient due to the frame resonance can amount to more than 20% (see data from laboratories 1, 4, and 5).

Figures 6(a)–6(c) shows the results for material C measured by all seven partners. The maximum dispersion in the real part of the surface impedance can reach 100% at frequencies around 500 Hz. The dispersion in the imaginary part is comparable in this frequency range and the imaginary part can also fluctuate between the positive and the negative values [see Fig. 6(b)]. However, these fluctuations are not reflected in the dispersion of the absorption coefficient ($<10\%$) at frequencies above 4000 Hz [except data from laboratory 3 in Fig. 6(c)]. Although the behavior of the real and imaginary parts of the impedance is more consistent in the low and medium frequency range, the dispersion in the absorption coefficient is relatively large ($>20\%$). This relates to the strong dependence of the absorption coefficient of high-permeability fibrous material to the specimen thickness, which is straightforward to predict using a simple semi-empirical model (e.g., Ref. 12). There can be other complementary factors which can explain this phenomenon: (i) the quality of the material samples submitted to individual partners may not be consistent; (ii) the condition of the specimens can differ because of the damaged fibers or contamination which can occur during the transportation or cutting process; (iii) the microstructure of the sample in the standing wave tube can be affected when the sample is inserted.

IV. CONCLUSIONS

Interlaboratory standing wave tube measurements have been performed on samples of three commercial porous products which represent low- and high-permeability porous media. One standard method of testing has been used, namely the ISO 10534-2.[1] The maximum dispersion in the measured spectra for the surface impedance (five- to sixfold) and acoustic absorption coefficient (two fold) has been observed in the results between individual samples and individual laboratories in the case of low permeability, low homogeneity, broad pore size distribution, and reconstituted porous rubber (material A). The least dispersion ($<20\%$) in the data was observed in the case of high permeability porous foam (material B). This material is consistent in terms of its thickness and airflow resistivity values. Laboratories 2 and 7 demonstrated that it is possible to use the appropriate

sample constraints to move the structural resonance frequency out of the measurement spectral range to minimize the dispersion in the measured acoustical data. This effect can be predicted and avoided using the methods suggested in Refs. 4–6. However, similar mounting conditions for this material are difficult to reproduce in independent acoustic laboratories which results in the drift in the frequency of the frame resonance affecting the local value of the absorption coefficient spectrum. Intermediate level of dispersion in the measured acoustical absorption data ($>20\%$) is observed in the case of fibrous media (material C). This behavior has been attributed to the dispersion in the specimen thickness.

The current standard does not provide enough details on the procedure for sample preparation and the optimum method for sample support. In the view of the present and previous works,[2–7] it is suggested that the existing ISO10534-2[1] should be revised to define more precisely: (i) the procedure for sample preparation and minimum number of tested specimen; (ii) the minimum size of the sample as a function of the material density, bulk modulus of the material skeleton and flow resistivity; (iii) the sample mounting conditions; (iv) the type of stimuli and signal processing method; and (v) the procedure for merging material data obtained in tubes of different diameters, a procedure that has not been discussed here. The revised standard procedure should enable quantification of the intrinsic experimental errors.

This paper deals with the reproducibility of the acoustic measurements. It is proposed that a more systematic analysis of the results obtained should be carried out to investigate the dependence of the dispersion in the measured data on the geometrical and elastic properties of the porous structure and on the method of sample mounting. This will be the subject of a separate publication, which will be based on interlaboratory tests performed on the same samples of material.

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