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Indirect Characterization of Fibrous Materials Using In-Situ Acoustic Impedance and JCAL-Based Parameter Optimization

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Abstract

This paper presents a novel indirect methodology for the characterization of fibrous sound-absorbing materials based on in-situ acoustic impedance measurements. The proposed approach relies on the combined measurement of sound pressure and particle velocity to estimate the surface acoustic impedance of the sample under test, enabling material characterization directly in realistic measurement conditions. An inverse identification framework based on the Johnson-Champoux-Allard-Lafarge (JCAL) model is employed to optimize the material parameters that exhibit the strongest influence on the acoustic response, namely airflow resistivity, effective sample thickness, and viscous characteristic length. Other parameters are kept fixed, as a sensitivity analysis showed within a physical feasible range their impact on the measured impedance to be negligible within the investigated frequency range. The optimization procedure is designed to be robust and computationally efficient, making it suitable for automated measurement scenarios. The method is evaluated on a wide variety of fibrous samples, covering different thicknesses and densities, and the extracted parameters are systematically compared against results obtained from standardized laboratory measurement techniques. Experimental results demonstrate good agreement between the proposed indirect approach and reference methods, confirming the validity and reliability of in-situ impedance-based parameter estimation. The study highlights the potential of this technique for fast, non-destructive material characterization and paves the way for its application in industrial and end-of-line quality control environments.

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1. Introduction

Fibrous and porous materials are widely used in noise control applications due to their high sound absorption performance, low weight, and relatively low production cost. Their acoustic behavior is governed by a set of physical parameters, including sample thickness, static airflow resistivity, open porosity, tortuosity, viscous characteristic length, and thermal characteristic length. Accurate knowledge of these parameters is essential for material design, numerical modelling, product development, and quality control.

Among these parameters, airflow resistivity is generally regarded as one of the most influential quantities for describing the acoustic performance of fibrous materials [1]. It controls the viscous losses associated with air motion through the porous frame and therefore has a direct influence on the acoustic impedance and absorption behavior of the material. For this reason, airflow resistivity is commonly used as a key indicator in material specification and production quality assessment.

At present, most standardized airflow resistivity measurements rely on static-flow methods, particularly those described in ISO 9053-1:2026 [2] and ASTM C522-26 [3]. These methods consist of imposing a controlled airflow through a material sample and measuring the resulting pressure decay. Although conceptually straightforward and formally standardized, their practical implementation can be challenging. In particular, the measurement must be performed at sufficiently low airflow velocities while resolving small pressure differences with adequate precision. This difficulty becomes especially relevant for highly permeable or thin fibrous materials, for which the pressure drop may be close to the resolution limit of the instrumentation. As a result, reproducibility between laboratories is limited [4].

In addition, standardized measurements generally require sample preparation, such as cutting a specimen to fixed geometry, and are typically performed under controlled laboratory conditions. These requirements limit their suitability for rapid, non-destructive, or end-of-line material characterization.

The viscous characteristic length, unlike airflow resistivity, does not currently have a dedicated direct standardized measurement procedure [5]. It is therefore commonly estimated indirectly from acoustic, ultrasonic, or impedance-based measurements [6] combined with an appropriate porous-material model. This makes the identification of such parameters model-dependent and sensitive to the choice of measurement configuration, frequency range, and optimization strategy.

Several equivalent-fluid models have been developed to relate the physical properties of porous materials to their acoustic response. Among them, the Johnson–Champoux–Allard–Lafarge (JCAL) [7], [8], [9] model is widely used for fibrous and porous absorbers because it accounts for viscous and thermal dissipation mechanisms through a physically meaningful set of parameters. However, fitting all JCAL parameters simultaneously from sound pressure measurements alone can lead to ill-conditioned inverse problems, parameter correlation, and non-unique solutions [10]. This is particularly problematic when the method is intended for automated or industrial measurement scenarios, where robustness and computational efficiency are essential.

In this work, an indirect in-situ methodology is proposed to characterize fibrous sound-absorbing materials from acoustic impedance measurements. Sound pressure and particle velocity are measured close to the material surface using an in-situ impedance device [11], [12]. On the resulting surface impedance, the JCAL model is fitted to estimate selected material parameters without the need of cutting the sample or removing it from its environment. To improve robustness and convergence, only the parameters with the strongest influence on the measured impedance in the investigated frequency range are optimized, namely airflow resistivity, effective sample thickness, and viscous characteristic length, while the remaining JCAL parameters are kept fixed. The method is validated on fibrous materials with different densities and thicknesses by comparing the estimated airflow resistivity with a standardized measurement.

2. Theoretical framework

The proposed in-situ characterization method is based on the estimation of the acoustic surface impedance of the material from local pressure–velocity measurements. First, a free-field measurement of impedance is obtained from pointing the in-situ device to an open space, $Z_{\mathrm{ff}}(\infty)$. Then, a second impedance measurement is performed while keeping the sensor located over the sample at a close distance, $Z_s(h)$. Taking a ratio between both measurements, the normalized specific impedance at the sensor is obtained,

$$Z_r(h) = \frac{Z_s(h)}{Z_{\mathrm{ff}}(\infty)}, \qquad (1)$$

Assuming that the sound field above the material can be approximated by a normally incident plane wave and its reflected component [13], the normalized specific impedance measured at a distance (h) from the material surface can be solved to extract the material reflection coefficient at the surface such as

$$R = \frac{Z_r(h) - 1}{Z_r(h) + 1} e^{2\mathrm{j}kh}. \qquad (2)$$

The normalized surface impedance of the material is then obtained by evaluating the impedance at the surface, i.e. for $(h = 0)$,

$$Z_{\mathrm{meas}} = \frac{1 + R}{1 - R}. \qquad (3)$$

The acoustic response of the fibrous material is modeled using the JCAL model, in which the porous layer is represented as an equivalent fluid with a rigid frame. For a given set of material parameters, including airflow resistivity (σ), open porosity (ϕ), tortuosity (α_∞), viscous characteristic length (Λ), thermal characteristic length (Λ'), and sample thickness (d), the model provides the equivalent dynamic density $(\rho_{eq}(f))$ and equivalent bulk modulus $(K_{eq}(f))$. These quantities, that depend on the frequency (f) define the complex characteristic impedance and wavenumber of the porous layer as

$$Z_{c,\mathrm{JCAL}} = \sqrt{\rho_{eq} K_{eq}}, \qquad (4)$$

$$k_{c,\mathrm{JCAL}} = 2\pi f \sqrt{\frac{\rho_{eq}}{K_{eq}}}. \qquad (5)$$

For a porous layer backed by a rigid surface, the modeled surface impedance is

$$Z_{\mathrm{JCAL}} = -\mathrm{j}\, Z_{c,JCAL} \cot\left(k_{c,JCAL} d\right). \qquad (6)$$

3. Inverse characterization procedure

The inverse characterization problem is formulated as the minimization of the discrepancy between the measured complex surface impedance and the surface impedance predicted by the JCAL model over the selected frequency range

$$CF(\boldsymbol{\theta}) = \sum_{i=1}^{N} \left| \mathrm{Z}_{\mathrm{meas}}(f_i) - Z_{JCAL}(f_i, \boldsymbol{\theta}) \right|, \qquad (7)$$

where (f_i) are the frequencies included in the fitting range and ($\boldsymbol{\theta}$) is the vector of optimizable parameters. To improve the robustness of the optimization, only the parameters that most strongly affect the measured impedance are identified: airflow resistivity, effective sample thickness, and viscous characteristic length. The remaining JCAL parameters are kept fixed using independently estimated or physically representative values. An alternative objective function based on the absorption coefficient was also evaluated; however, the cost function based on complex surface impedance provided more accurate and stable results as suggested in [10] and [14]. The vector of optimizable parameters is defined as

$$\boldsymbol{\theta} = [d, \sigma, \Lambda]. \tag{8}$$

The effective sample thickness is included in the optimization to attempt to correct the uncertainty in its direct measurement. The remaining JCAL parameters, namely open porosity, tortuosity and thermal characteristic length, are kept fixed using independently estimated or physically representative values. This reduced formulation is adopted because fitting all JCAL parameters simultaneously may lead to non-unique solutions and sensitivity to the initial parameter estimates. By limiting the optimization to the parameters that most strongly affect the measured impedance in the investigated frequency range, the inverse problem becomes better conditioned and more suitable for automated measurements.
The optimization is performed under physically admissible lower and upper bounds for each fitted parameter. The minimization algorithm used is the Nelder-Mead Simplex Method [15]. To reduce the likelihood of convergence towards a local minimum, the method is initialized from multiple starting points. At each iteration, the JCAL surface impedance is computed for the current parameter set and compared with the measured impedance through the cost function. The final identified parameters correspond to the parameter set that yields the minimum discrepancy between measured and modeled impedance, i.e., the minimum value of the cost function.
The output of the procedure is therefore the fitted impedance curve together with the effective thickness, estimated airflow resistivity, and viscous characteristic length for each sample or measurement position. Since the method relies only on the in-situ surface impedance, it can be applied without cutting the sample or using an impedance tube, making it suitable for non-destructive laboratory measurements as well as production-line characterization.

4. Experimental campaign

The proposed methodology was evaluated on a set of fibrous materials covering different densities, thicknesses, and airflow resistivity ranges. The experimental campaign included in-situ measurements and laboratory standardized tests.

Reference airflow resistivity values were obtained using a conventional Air Flow Resistivity (AFR)-meter procedure based on standardized static-flow measurements. Cylindrical specimens were prepared and inserted into the measurement tube, where a controlled airflow was imposed through the sample and the resulting pressure drop was measured. These values were used as reference data for comparison with the parameters identified from the in-situ impedance measurements. The in-situ impedance measurements were done before cutting the samples and in the center of the circle that was later cut. It is important to note that the in-situ measures one point of the sample, while the AFR-meter measures a cylindrical area. Figure 1 illustrates a measurement using the in-situ device.

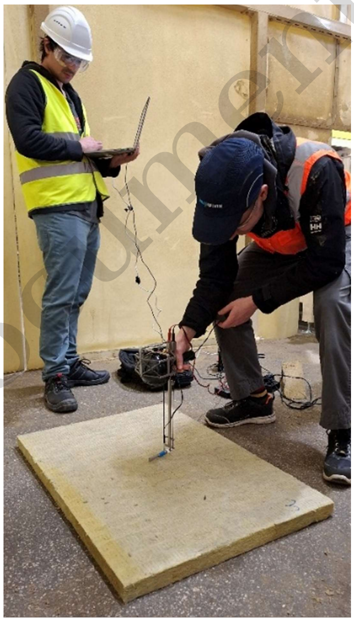


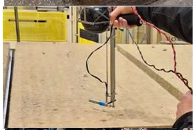
Figure 1. Picture of the in-situ testing measurement procedure.

For each sample, a free-field reference measurement was first acquired. The material was then placed on a rigid backing and the probe was positioned close to the sample surface. Sound pressure and normal particle velocity were measured over the investigated frequency range, and the resulting surface impedance was used as input for the inverse JCAL-based characterization.
Additional measurements were performed under production-line conditions using the same in-situ impedance-based procedure. The line results were compared with laboratory in-situ measurements and AFR-meter reference values to evaluate the robustness of the method in a realistic industrial environment. Spatial measurements were also performed on selected samples to investigate local airflow resistivity variations and material inhomogeneity.

5. Results and Discussion

The overall experimental results are summarized in Table 1, which presents the four tested material types in increasing order of mass density, together with representative images and the average airflow resistivity obtained from the standardized AFR-meter method (σ_{Standard}) and from the proposed in-situ approach (σ_{PU}). Measurements were repeated on 5 different positions of each sample from which the mean and standard deviation have been computed.

Table 1. Image of the sample tested, mass density, and airflow resistivity measured with the AFR-meter and in-situ approach.

Samples	Mass Density [kg/m^3]	σ_{Standard} [kPa · s/m^2]	σ_{PU} [kPa · s/m^2]
	17	10.8 ± 2.1	11.9 ± 1.5
	37	27.8 ± 9.4	43.4 ± 5.8
	89	39.9 ± 6	41.6 ± 7.9
	140	92.6 ± 12.4	89.5 ± 10.2

Overall, the in-situ estimates follow the same increase of airflow resistivity with mass density as the standardized measurements. Good agreement is observed for the lowest-density material ($\rho \approx 17$ kg/m^3), for the intermediate-high-density material ($\rho \approx 89$ kg/m^3), and for the highest-density material ($\rho \approx 140$ kg/m^3). The corresponding average values are close for both methods, indicating that the proposed impedance-based characterization is able to reproduce the expected airflow resistivity over a broad range of fibrous materials.
As an example of the individual tests, for the highest-density material, a direct comparison between four cut samples shows a very good correlation between the standardized AFR measurements and the in-situ estimates. The agreement is consistent from sample to sample, which supports the robustness of the proposed method for this material type and confirms that the JCAL-based inverse fitting can provide reliable airflow resistivity estimates when the material structure is sufficiently stable and homogeneous.

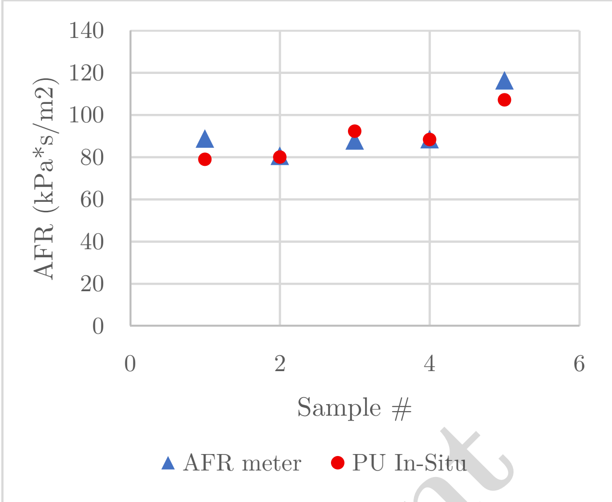


Figure 2. AFR measurement comparison of the 140 kg/m^3 sample.

In contrast, the largest discrepancies were observed for the material with density around 37 kg/m^3. In this case, some samples show clear differences between the AFR method and the in-situ estimation, whereas others are in much closer agreement. This behaviour suggests that the discrepancy is not systematic, but rather linked to sample-dependent variability. A plausible explanation is the combination of two effects: first, the practical difficulty of cutting low-density fibrous samples in a repetitive and controlled way for the standardized AFR measurement; and second, a potentially higher spatial variability of the material itself. Both effects can increase the scatter of the AFR reference results and make direct point-to-point agreement more difficult.

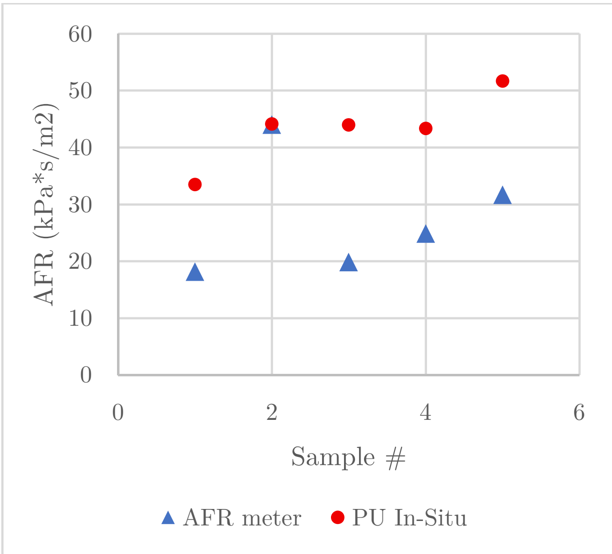


Figure 3. AFR measurement comparison of the 37 kg/m^3 sample.

An important outcome of the comparison is that the repeatability of the proposed in-situ method is, overall, higher than that of the AFR method. This can be observed from the generally lower spread of the in-situ estimates for several of the tested materials. The improved repeatability is especially relevant for low-density materials, where sample preparation for the standardized method may introduce additional uncertainty.
The global comparison between airflow resistivity and density further shown in Figure 4 supports these observations. As shown by the overall dataset, both methods exhibit a similar increasing trend of airflow resistivity with density, and the fitted trends are closely aligned. This indicates that the proposed in-situ methodology not only provides comparable absolute values in most cases, but also captures the expected physical dependence between material density and airflow resistivity.

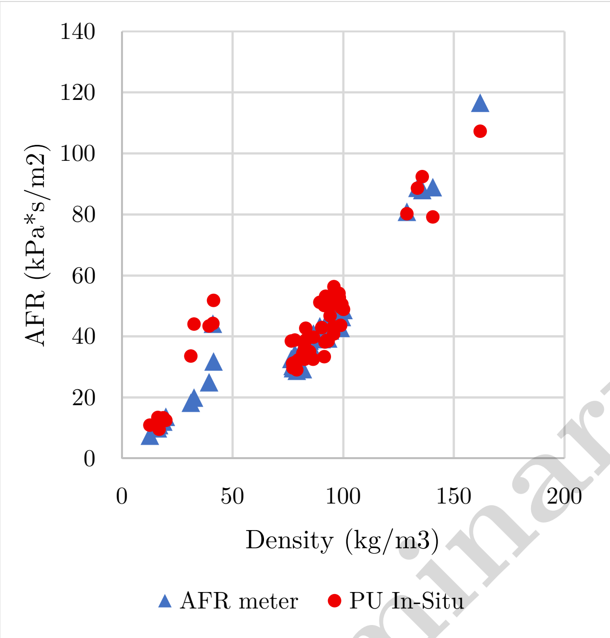


Figure 4. Comparison of airflow resistivity estimates against material density.

Taken together, these results show that the proposed in-situ impedance-based characterization provides airflow resistivity estimates that are generally consistent with the standardized method, while offering improved repeatability and avoiding destructive sample preparation. The remaining discrepancies appear to be mainly associated with low-density materials, for which both higher spatial variability and sample preparation effects are expected to play a stronger role. Further research will be done to investigate spatial variability in more detail and clarify the validity of this assumption.

6. Conclusion

This paper presented an indirect methodology for the characterization of fibrous sound-absorbing materials based on in-situ acoustic impedance measurements and JCAL-based parameter optimization. The method uses pressure–velocity measurements close to the material surface to estimate the surface impedance, which is then fitted with a reduced JCAL parameter set. To improve the robustness of the inverse problem, only the effective sample thickness, airflow resistivity, and viscous characteristic length were optimized, while the remaining parameters were kept fixed.
The method was evaluated on four fibrous material types with mass densities ranging from approximately 17 kg/m^3 to 140 kg/m^3. The airflow resistivity values obtained with the proposed in-situ approach followed the same increasing trend with density as the standardized AFR measurements. Good agreement was obtained for the lowest-density, intermediate-density, and highest-density materials, showing that the proposed method can reproduce the expected airflow resistivity over a broad range of fibrous samples.
The highest-density material showed a particularly good sample-by-sample correlation between the standardized AFR method and the in-situ estimates, confirming the reliability of the inverse fitting procedure for materials with stable and relatively homogeneous properties. The largest discrepancies were observed for the material with density around 37 kg/m^3, where some samples agreed well while others showed significant differences. These differences are likely related to sample-dependent variability, including the practical difficulty of cutting low-density fibrous samples in a repeatable way and the possible presence of spatial variations within the material.
Overall, the proposed in-situ method showed higher repeatability than the standardized AFR method for several of the tested materials. This is a relevant advantage for fibrous materials, where sample preparation can introduce additional uncertainty in conventional airflow resistivity measurements. The results therefore indicate that in-situ impedance-based inverse characterization is a promising non-destructive alternative for estimating airflow resistivity in fibrous materials.
Future work will focus on investigating spatial variability in more detail, assessing the influence of local measurement position, and extending the validation to a wider range of material types. This will help clarify the origin of the remaining discrepancies and further define the applicability of the method for robust material characterization and quality-control applications.

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