In-situ sound absorption of ground surfaces: Innovative processing and characterisation methods

Jacques Cuenca, Laurent De Ryck
Siemens Industry Software, Interleuvenlaan 68, B-3001 Leuven, Belgium.

Summary
The present paper proposes refined methods for the in-situ measurement of ground sound absorption and their use for the estimation of the physical properties of porous pavements. A first part of the work is devoted to the development of two sound absorption measurement techniques using line arrays of several microphones, optimally spread. The validation of the methods is performed by numerically evaluating their robustness to physical uncertainty and measurement variability, and through their application on specifically-designed test setups. In particular, it is shown that the new methods considerably improve the accuracy of the estimation and that the frequency range of validity can be extended by controlling the spatial distribution of the microphones. When limiting the setup to two sensors, both processing methods fall back to the ISO standard specifications, thus guaranteeing compliance with well established methods. The second part of the paper focuses on the extraction of four intrinsic parameters of porous ground surfaces as defined in the Hamet-Bérengier model, namely the porosity, the tortuosity, the flow resistivity and the thickness. These parameters are estimated by fitting the model on the sound absorption coefficient by means of an optimisation approach. The method benefits from the reduced uncertainty of the proposed measurement techniques and is applied to different ground surfaces such as gravel and outdoor road asphalts. One of the main benefits of such an inverse estimation methodology is the replacement of direct measurements of asphalt properties.

PACS no. 43.20.Jr, 43.20.Ye

1. Introduction

The measurement of the sound absorption coefficient of ground surfaces is required for the assessment and regulation of noise levels in urban areas, in particular through specific applications such as vehicle pass-by noise measurements [1]. In-situ sound absorption measurement is required in cases where material samples cannot be taken for laboratory testing, or when characterisation in actual environmental conditions is necessary.

Two standardised methods are frequently and conjointly used for the measurement of the sound absorption coefficient of ground surfaces. The ISO standard ISO 10534-2 [2] provides guidelines for sound absorption measurements using two microphones in an impedance tube and ISO 13472-2 [3] discusses the application to in-situ road measurements. The setup consists of a tube placed upon the ground surface, comprising two flush-mounted microphones and a source on top. As such, it provides the minimum necessary requirements to differentiate the incident and reflected waves on the ground at a particular frequency. Such system is sensitive to uncertainties, thus yielding errors in the estimation which are particularly common for low sound-absorbing surfaces and at low frequencies. This implies a reduced stability and repeatability of the measurements. Additionally, ISO standards define the frequency limits induced by both the tube diameter and the spacing between the microphones.

In the present paper, two data processing methods are proposed as extensions to the ISO standard by using more than two microphones in order to cope with the aforementioned limitations [4]. A major requirement is that both methods are identical to the ISO standard when using exactly two microphones, in order to ensure compliance with existing industrial solutions. The new methods are validated through a parametric study and using different spatial distributions of the microphones along the setup.

As a second step, a methodology is proposed for characterising the intrinsic properties of porous ground surfaces using these more robust results.

The methodology consists in an inverse estimation by fitting a phenomenological model by Hamet and Bérengier [5] onto the measured sound absorption coefficient [6].

2. Sound absorption measurement methods

Figure 1 represents a one-dimensional waveguide with an incident negative-going plane wave on the surface of the material to be characterised and M microphone positions.

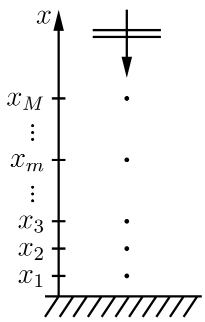

Figure 1. Plane wave incident on a reflecting surface and microphone positions inside an impedance tube or microphone array.

Using convention $e^{i\omega t}$ and denoting $k(\omega) = \omega/c$ the acoustic wavenumber, with ω the circular frequency and c the sound velocity, the sound pressure at microphone m can be written as

$$p_m(\omega) = a(\omega)e^{ik(\omega)x_m} + R(\omega)a(\omega)e^{-ik(\omega)x_m}, \quad (1)$$

where $a(\omega)$ is the amplitude of the incident wave, $R(\omega)$ is the reflection coefficient of the material and $m = 1, \ldots, M$, with $M \geq 2$. The sound absorption coefficient is defined by

$$\alpha(\omega) = 1 - |R(\omega)|^2. \quad (2)$$

The ISO standard method [2] uses 2 microphones to solve for the 2 unknowns, a and R for each frequency. When using more than 2 microphones, the sound absorption coefficient is obtained as the arithmetic mean over the estimations for the different pairs of microphones.

2.1. Coherence average

For a number of microphones larger than 2, the different microphone pairs present varying degrees of coherence. Thus, as a manner to give more importance to those microphone pairs with a larger coherence, a natural extension of the standard method may consist of a coherence-weighted average, as

$$\hat{\alpha}(\omega) = \frac{\sum_{mn} \gamma^2_{mn}(\omega)\hat{\alpha}_{mn}(\omega)}{\sum_{mn} \gamma^2_{mn}(\omega)}. \quad (3)$$

where $\hat{\alpha}_{mn}$ is the estimate of α from microphone pair (m, n) and γ^2_{mn} is the corresponding coherence function.

This operation automatically and smoothly discards microphone pairs which present a low coherence at particular frequencies. In the case where the setup comprises 2 microphones, Eq. (3) falls back to the ISO standard estimation [2].

2.2. Least-squares estimation

An alternative method for the estimation of the sound absorption coefficient is a direct estimation using the data from all microphones in a single operation. Equation (1) may be written in the matrix form

$$\begin{bmatrix} p_1(\omega) \\ p_2(\omega) \\ \vdots \\ p_m(\omega) \\ \vdots \\ p_M(\omega) \end{bmatrix} = \begin{bmatrix} e^{ik(\omega)x_1} & e^{-ik(\omega)x_1} \\ e^{ik(\omega)x_2} & e^{-ik(\omega)x_2} \\ \vdots & \vdots \\ e^{ik(\omega)x_m} & e^{-ik(\omega)x_m} \\ \vdots & \vdots \\ e^{ik(\omega)x_M} & e^{-ik(\omega)x_M} \end{bmatrix} \begin{bmatrix} a(\omega) \\ R(\omega)a(\omega) \end{bmatrix}, \quad (4)$$

or equivalently as

$$\mathbf{p}(\omega) = \mathbf{W}(\omega)\mathbf{a}(\omega). \quad (5)$$

The number of microphones is larger or equal than the number of waves in the setup and therefore matrix $\mathbf{W}$ is rectangular. Matrix $\mathbf{a}$ is then obtained by inverting Eq. (5) in a least squares sense, yielding

$$\mathbf{a}(\omega) = \mathbf{W}^\dagger(\omega)\mathbf{p}(\omega), \quad (6)$$

where $\mathbf{W}^\dagger$ is the Moore-Penrose pseudo-inverse of $\mathbf{W}$. The reflection coefficient at circular frequency ω then arises as the ratio between the components of $\mathbf{a}$ and the absorption coefficient of the material is obtained from Eq. (2). In the case of a minimum number of microphones of $N = 2$, $\mathbf{W}$ is square such that the pseudo-inverse simplifies to a classical matrix inverse, the result being that of the standard impedance tube setup.

3. Parametric study and validation

In this section the robustness of the methods is evaluated in the presence of geometrical uncertainty and measurement noise using a Monte Carlo scheme [4].

For such purposes, the acoustic field at the microphone positions is simulated using a fictitious absorption coefficient and the ability of the different methods to retrieve it is evaluated.

The setup consists of 5 microphones located between 9 cm and 40 cm from the ground surface. A linear microphone spacing is first used for the comparative study of the different methods in secs. 3.1 and 3.2, and the benefits of a logarithmic spacing are discussed in sec. 3.3. The microphone spatial distributions are depicted in Fig. 2.

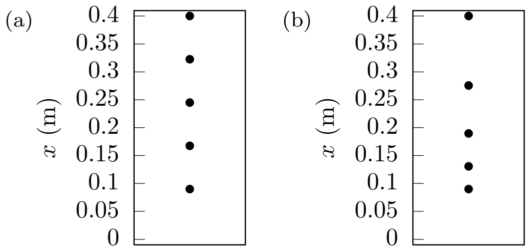

Figure 2. Microphone positions with (a) linear spacing or (b) logarithmic spacing.

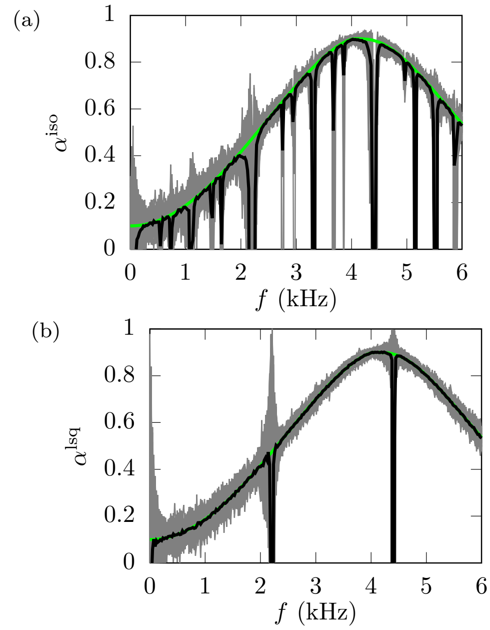

Figure 3. Estimated sound absorption coefficient in the presence of noise. target, Monte Carlo ensemble, mean. (a) ISO average, (b) least-squares.

3.1. Robustness to noise in the pressure signals

A normally distributed random noise is here added to the pressure signals at the microphones. The standard deviation of the noise is 10% of the maximum nominal pressure amplitude. Figure 3 shows the estimated sound absorption coefficient using the ISO average and the least-squares method. The benefit of the coherence-weighted average over the ISO method is not substantial and therefore it is not represented in the figure. On the other hand, the least-squares method performs significantly better.

The drops in the sound absorption coefficient are induced by the spacing between two microphones, when this coincides with half the wavelength, or an integer fraction of the latter. Therefore, by considering individual microphone pairs, the errors associated with each microphone pair are carried onto the global estimation.

Conversely, the least-squares method consists of a single operation, which avoids the coincidence phenomenon, except for the frequencies corresponding to the smallest spacing.

An additional observation can be made on the standard deviation of the Monte Carlo ensemble, which increases for low sound absorption values.

3.2. Robustness to uncertainty in the microphone positions

The uncertainty in the microphone positions is here modelled as a normal distribution with a standard deviation of 2 mm. Note that in the absence of noise in the pressure signals, the coherence is equal to 1 for all microphone pairs. Thus, the coherence-weighted average yields the same result as the ISO average. Figure 4 represents the estimated sound absorption coefficient.

The least-squares estimator outperforms the pair-averaged methods in this case as well. Note that the comparative importance of the effect of noise and geometrical uncertainty on the accuracy of the

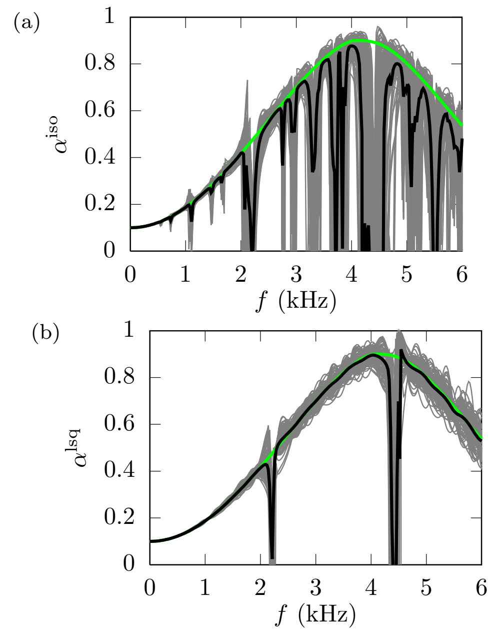

Figure 4. Estimated sound absorption coefficient in the presence of uncertainty in the microphone positions. target, Monte Carlo ensemble, mean. (a) ISO average or coherence weighted, (b) least-squares.

estimation cannot be established due to their different nature. However, it is possible to observe that in this case the spread of the Monte Carlo ensemble increases with frequency, which is due to the increasing position uncertainty as compared to the wavelength.

3.3. Influence of the microphone positions

Using more than two microphones allows to cover a larger distance along the setup, thus increasing the reliability at low frequencies. As observed above, a regular spacing of the microphones renders the observation impossible at frequencies such that the shortest microphone spacing is a multiple of the wavelength. In order to suppress these frequency cuts, an irregular spacing can be used.

Figure 2(b) shows the microphone positions according to a logarithmic law and Fig. 5 shows the sound absorption coefficient estimated using the least-squares method.

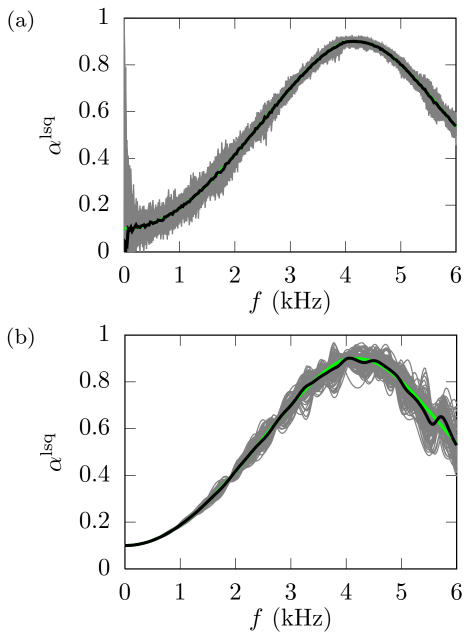

Figure 5. Estimated sound absorption coefficient using the least-squares method for a logarithmic microphone spacial distribution. — target, — Monte Carlo ensemble, — mean. (a) In the presence of noise, (b) with uncertain microphone positions. The noise and uncertainty in the positions are the same as in the previous examples.

The frequency cuts are observed to disappear under logarithmic microphone spacing. Indeed, such an irregular spatial sampling avoids the situation of having the microphones at the same wavefront.

In practice, any other irregular spatial distribution may be used as well, such as power-law spacing or random microphone positions. The crucial point is that the microphone-to-microphone distances should not follow a regular or harmonic series.

The least-squares method in combination with an irregular microphone spatial distribution therefore removes the limitation of the setup to a maximum total distance covered by the microphones.

4. Characterisation of porous ground surfaces

4.1. Hamet-Bérengier model

For the purposes of the characterisation of porous ground surfaces, it is convenient to consider a simplified model based on the assumption of a rigid material. A model by Hamet and Bérengier [5] is here used, consisting of three material parameters: the porosity ϕ, a pore shape factor or tortuosity K and the flow resistivity σ. The specific impedance and wavenumber of the material are respectively modelled as

$$Z_0(\omega) = \frac{\rho c}{\phi} \frac{\sqrt{K\left(1 - i\dfrac{\omega_\mu}{\omega}\right)}}{\sqrt{\gamma\left(1 - \dfrac{1-1/\gamma}{1-i\omega_\theta/\omega}\right)}} \tag{7}$$

and

$$k(\omega) = \frac{\omega}{c}\sqrt{K\left(1 - i\frac{\omega_\mu}{\omega}\right)}\sqrt{\gamma\left(1 - \frac{1-1/\gamma}{1-i\omega_\theta/\omega}\right)}, \tag{8}$$

where $\omega_\mu = \dfrac{\sigma\phi}{\rho K}$ and $\omega_\theta = \dfrac{\sigma}{\rho \mathrm{Pr}}$ respectively denote viscous and thermal characteristic frequencies. The above equations involve the properties of air: the density $\rho = 1.2\,\mathrm{kg{\cdot}m^{-3}}$, the speed of sound $c = 344\,\mathrm{m{\cdot}s^{-1}}$, the ratio of specific heats $\gamma = 1.4$ and the Prandtl number Pr$= 0.71$.

In practice, due to the low porosity and high flow resistivity of road surfaces in general, the material to be characterised may be considered infinite in depth, in which case the impedance of the ground is equal to the specific impedance,

$$Z(\omega) = Z_0(\omega). \tag{9}$$

However, in particular cases the thickness may play an important role, such as for example in the case of gravel or grass over a rigid surface. For a material backed by a rigid wall, the impedance is given by

$$Z(\omega) = -iZ_0(\omega)\cot(k(\omega)h). \tag{10}$$

Conversely, for a material backed by a soft wall,

$$Z(\omega) = iZ_0(\omega)\tan(k(\omega)h). \tag{11}$$

In such cases, the thickness h of the material layer must be included among the material properties to be estimated.

The reflection coefficient observed above the ground is given by

$$R(\omega) = \frac{Z(\omega) - \rho c}{Z(\omega) + \rho c}. \tag{12}$$

4.2. Characterisation method

In order to estimate the set of unknown properties according to the above model, an inverse methodology [7, 6] is used, consisting in fitting the model onto experimental data. The underlying set of properties yielding the best fit are then considered as the corresponding material properties.

The measurement methods developed in sec. 2 provide the reflection coefficient or the sound absorption coefficient of the ground. These depend in a non-linear fashion on the model parameters. Therefore, the model fitting is formulated as an optimisation algorithm where the objective function is chosen as the discrepancy between the simulated and measured sound absorption coefficient over the observed frequency range.

The inverse estimation problem is then formulated as

$$\min f_{\mathrm{obj}}(\mathbf{x}) = \sum_n |\alpha(\mathbf{x}, \omega_n) - \alpha_0(\omega_n)|^2, \qquad (13)$$

where

$$\mathbf{x} = \{\phi, K, \sigma, h\} \qquad (14)$$

is the space of unknown properties. The properties of a particular material characterised by a given sound absorption coefficient α_0 then arise as the minimum of the objective function in such space. The minimisation problem is solved using an optimisation algorithm [8].

5. Experimental application

This section discusses the experimental application of the proposed sound absorption measurement methods and of the inverse estimation technique.

5.1. In-situ sound absorption measurement of asphalt

The measurement techniques are applied to the on-site measurement of the sound absorption coefficient of the asphalt at the parking at Siemens Industry Software headquarters.

The setup consists of an open-ended impedance tube with three 1/2-inch microphones at positions 10.795 cm, 15.4 cm and 19.05 cm from the ground surface. The tube was designed such that the drops in the coherence function of the three possible microphone pairs are homogeneously distributed across the frequency range of interest, yielding an optimal configuration for the ISO average and for the coherence-average methods. The tube diameter is 10 cm, which imposes a high-frequency limit at 1.98 kHz [2]. The largest microphone spacing is 8.25 cm, such that the first frequency cut is at 2.06 kHz. Since the microphones are not regularly spaced, this limitation does not apply to the least-squares method. The acquisition is performed using an LMS SCADAS frontend together with LMS Test.Lab software.

A calibration in two steps is performed. First, a set of microphone phase correction functions is determined by performing wide-band measurements with an anechoic ground condition. Each microphone is placed sequentially at each of the three positions in the tube. Second, standing-wave amplitude correction functions are determined in the same manner by using a highly-reflecting surface. In order to avoid numerical errors in applying the correction functions, the required pressure spectra ratios are avoided by using a combination of auto-powers and cross-powers instead. It is worth noting that this does not alter the considerations of sec. 2. The measurements are performed with a 4 Hz resolution and using 200 averages in order to stabilise the estimations of the auto- and cross-powers.

Fig. 6 shows the estimation of the sound absorption coefficient using the ISO average, the coherence average and the least-squares estimator. It can be observed that the results are nearly indistinguishable for the three methods in the frequency band of interest. Indeed, in the present case the setup was specifically built for optimal results using the ISO average. The new methods are expected to outperform the ISO average in situations where noise and uncertainties are significant and using a larger number of microphones over a larger distance in the tube.

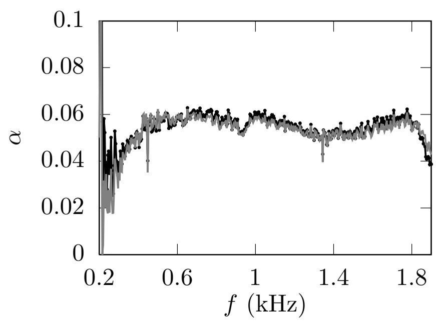

Figure 6. Sound absorption coefficient of a sample of asphalt. ▬ ISO average; ··· coherence average; ▬ least-squares method.

5.2. Characterisation of a controlled sample of gravel

In order to validate the characterisation methodology, an application to a material sample of known boundary conditions and thickness is performed. The sample consists of a 40 mm-thick layer of gravel placed on top of a rigid surface. The gravel used has a grain size of about 5 mm. The sound absorption coefficient is measured using the least-squares method with the setup described above and used as a target for the inverse estimation methodology. As the parameters

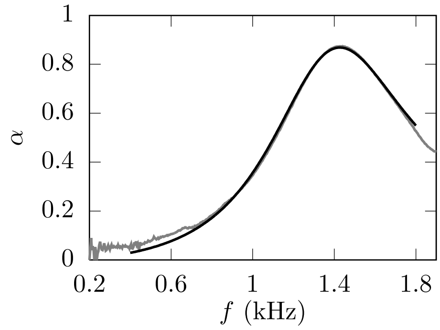

Figure 7. Sound absorption coefficient of a controlled sample of gravel. —— Measurement using the least-squares method; —— fitted Hamet-Bérengier model.

Parameter	Symbol	Estimated value
Porosity	ϕ	0.155
Shape factor	K	1.54
Flow resistivity	σ	$36824\,\mathrm{N{\cdot}s{\cdot}m^{-4}}$
Thickness	h	$0.0414\,\mathrm{m}$

Table I. Estimated parameters for a controlled sample of gravel.

of the Hamet-Bérengier model are independent from frequency, the frequency band chosen for the estimation is limited to $0.4 - 1.8\,\mathrm{kHz}$, where the impact of uncertainties is lower.

Figure 7 shows the sound absorption coefficient measured using the least-squares method and resulting from the inverse estimation method. Table I summarises the corresponding estimated parameters for the gravel sample. It can be observed that the estimated thickness is close to the real thickness by only 1 mm, which is below the grain size of the gravel. Furthermore, the main parameters of the model are estimated within realistic ranges and are reasonably close to those encountered in the literature [5].

6. Conclusion

Two methods for the estimation of the sound absorption coefficient using an arbitrary number of microphones have been proposed. The first generalises the ISO standard method by computing a coherence-weighted average of the sound absorption coefficient by microphone pairs. The second method consists of a single operation taking advantage of the overdetermination of the problem, thus guaranteeing a least-squares solution using all microphone signals simultaneously.

Simulations in the presence of a high noise level or large uncertainties in the microphone positions predict the least-squares method to be substantially more accurate and stable than the coherence-weighted method, the latter only providing localised and small improvements over the ISO standard. Furthermore, irregular spatial distributions of the microphones allow for a wide frequency range of application by avoiding the coincidence phenomenon between the microphone spacings and a multiple of half the wavelength. The main conclusion is that the least-squares method with irregular microphone spacings is not limited to a maximum spatial spread of the microphones, which allows to increase the reliability at low frequencies.

The experimental application of the three methods show little differences in a setup that has been optimised for the ISO average within the working frequency range of the tube. It is concluded that three microphones are not enough to clearly observe the benefits of the new methods, which are expected to come to light in a highly noisy environment.

A characterisation method has been presented, allowing to estimate four intrinsic properties of the ground material by using an inverse methodology. The latter consists of a model fitting using an optimisation algorithm. This has been successfully applied to the estimation of the properties of a controlled sample of rigid-backed gravel, whose thickness is retrieved with an accuracy below the grain size.

The present methods are developed in view of applications to wider frequency ranges, both using impedance tubes and free-field microphone arrays.

Acknowledgement

The authors would like to thank Kevin Menino, Danilo Sabbatini, Patrick Van de Ponseele and Karl Janssens for their contributions to the present work.

References

[1] ISO 10844. *Acoustics – Specification of test tracks for measuring noise emitted by road vehicles and their tyres.*, 2014.

[2] ISO 10534-2. *Acoustics – Determination of the sound absorption coefficient and impedance in impedance tubes – Part 2: Transfer-function method.*, 1998.

[3] ISO 13472-2. *Acoustics – measurement of sound absorption properties of road surfaces in situ – Part 2: Spot method for reflective surfaces.*, 2010.

[4] L. De Ryck, J. Cuenca, and K. Menino. Innovative estimation methods of in-situ sound absorption : Beyond the iso standards. In *SAPEM 2014*, Stockholm, 2014.

[5] J.F. Hamet and M. Bérengier. Acoustical characteristics of porous pavements: A new phenomenological model. In *Internoise 93*, pages 641–646, Leuven, 1993.

[6] J. Cuenca, L. De Ryck, and K. Menino. Inverse estimation of the properties of porous ground surfaces from in-situ sound absorption measurements. In *SAPEM 2014*, Stockholm, 2014.

[7] J. Cuenca, C. Van der Kelen, and P. Göransson. A general methodology for inverse estimation of the elastic and anelastic properties of anisotropic open-cell porous materials—with application to a melamine foam. *J. Appl. Phys.*, 115(8):–, 2014.

[8] K. Svanberg. A class of globally convergent optimization methods based on conservative convex separable approximations. *SIAM Journal on Optimization*, 12(2):555, 2002.