Effect of uncertainty of Biot parameter measurements on transmission loss and surface absorption

D. Blanchet

dBVibroAcoustics, Czech Republic, Email: denis.blanchet@dbvibroacoustics.com

Abstract

To build accurate NVH predictive simulation models of cars, airplanes, train cabins and the like, one has to properly represent the geometry of the structure, the acoustic fluid and the sound package. Furthermore, the model must contain accurate physical properties of the material used. Those physical properties are readily available for the structural elements but it is not the case for the sound package. When Biot parameters of various foams and fibers are not available, NVH engineers must "guestimate" the values and this can cause the predictiveness quality of the models to go down significantly. But how much of a risk are we taking by not knowing the physical properties of these NVH materials. This paper studies the effect of uncertainties of the Biot parameters on transmission loss and surface absorption. The method used in this paper rank the main sources of uncertainties of the response and can therefore identify the material properties that a NVH simulation engineer must know with precision to ensure his models are accurate and predictive in nature.

Introduction

Porous media (foams and fibers) are widely used in various industries to keep interior or exterior noise levels within regulation limits or at a pleasant level depending on the target audience the vehicle is designed for. Certain industries such as the automotive, aeronautic and space, have integrated porous media in their simulation models for quite some time and have accumulated a vast experience in building predictive simulation models using Biot parameters. Others are only starting and their knowledge will build up over time.

Several laboratories can measure Biot parameters using various equipment which differ from lab to lab. Several round-robin studies have been conducted to assess repeatability (in-lab) uncertainties and reproducibility (lab-to-lab) uncertainties. This study looks at the effect of Biot parameters measurements uncertainties from laboratory to laboratory (reproducibility) and the effect these uncertainties have on sound transmission loss and diffuse field surface absorption.

Biot parameters

Key to model porous media

Twenty years ago, very few engineers had the chance to use Biot parameters to model acoustic trim inside a vehicle. Existing analytical formulations were implemented in SEA software and work was done to create new FEM elements to represent porous material in a FEM environment.

Furthermore, only a handful of acoustic laboratories were able to measure all the Biot parameters and had to use expensive sophisticated measurements. Fortunately, today's situation has drastically changed. Biot parameters can be identified accurately and standards/best practices are being developed to help get uniform results from the numerous laboratories having the capability to measure Biot parameters although a lot remain to be done to improve correlation between labs.

Today, with a classical impedance tube and airflow resistivity meter measurements, the acoustic porosity and airflow resistivity can be determined experimentally with reasonable accuracy. The remaining acoustic Biot parameters can be calculated using indirect methods [1, 2]. These identified Biot parameters are the intrinsic properties of the poro-elastic material. This means Biot parameters can be used in simulation to model various thicknesses of the same acoustic materials without the need to repeat any measurements.

To fully characterize foam type materials, extra properties such as Young's modulus, Poisson's ratio and structural damping of the skeleton are needed. These are usually obtained from a quasi-static mechanical analyzer (QMA) test [3]. Table 1 shows the full list of acoustic and elastic parameters needed to fully represent a porous media in a simulation model. Figure 1 shows which Biot parameters are driving the absorption coefficient response over various frequency ranges [from 2].

σ	Flow resistivity
Φ	Open Porosity
α	Tortuosity
Λ	Viscous Characteristic Length
Λ'	Thermal Characteristic Length
E	Young's Modulus
ν	Poisson's Ratio
η	Damping Loss Factor (DLF)

Table 1: List of Biot parameters

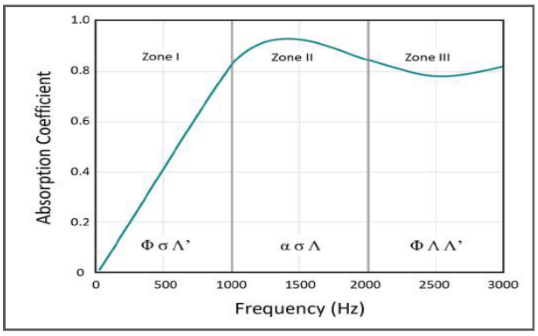

Figure 1: Effect of various Biot parameters on Absorption coefficient

Today's Accuracy of Biot parameter measurements

Several round-robin studies have been performed to shed light on the accuracies of porous media material property measurements. Usually, one is not so concerned with the "in-lab" repeatability since when a test procedure is followed scrupulously, samples tested with the same equipment and often by the same person, the repeatability is quite high.

On the other hand, an individual lab might get very repeatable results but still yield the wrong results. The next section looks at reproducibility accuracies ie. the "lab to lab" accuracy to get a sense of what to expect when asking different labs to measure samples.

Reproducibity analysis

Acoustic biot properties

From the analysis from Pompoli and al. [4], it is shown that the repeatability of measurements of flow resistivity is high with a relative standard deviation of 1%. On the other hand, reproducibility drops significantly to 10% for a common reticulated foam.

Other Biot parameters typical relative reproducibility standard deviation can be computed from the experimental results plotted in the article from the same authors (see Table 2).

Property	Relative reproducibility standard deviation
Flow resistivity	10%
Open Porosity	1%
Tortuosity	5%
Viscous Characteristic Length	20%
Thermal Characteristic Length	27%

Table 2: Typical relative reproducibility (lab to lab) standard deviation

These values are used in a Monte Carlo analysis based on a normal distribution of each of the biot parameters.

Viscoelastic properties

Choice of material

From the analysis from Bonfiglio and al. [5] discussing the measurement of density of 5 porous materials, it was demonstrated that the material with best (in-laboratory) repeatability and (inter- laboratory) reproducibility is material A with a relative reproducibility standard deviation of 7%. The other materials in the same paper show very large reproducibility coming from variability in the material sample themselves, the measuring methods and manipulation errors.

To avoid any of these adverse effects, a 25mm thick reticulated foam similar to material A in Bonfiglio paper is used as a reference in this study. This foam (see figure 2) is taken from the NVH material database dbporous [6].

Figure 2: Reticulated foam (light grey) used in this study (left), close-up view (center) and microscopic view (right)

The Biot parameters used to represent this reticulated foam are shown in table 3. You can find in [7] a full description of the measurements and detailed experimental data along with the corresponding repeatability standard deviations related to each Biot parameters measurement.

Property	Symbol	Units	Value
Density	ρ	(kg/m3)	28
Flow resistivity	σ	(N.s.m-4)	7800
Open Porosity	Φ	(-)	0.98
Tortuosity	α	(-)	1.54
Viscous Characteristic Length	Λ	(μm)	61
Thermal Characteristic Length	Λ'	(μm)	368
Young's Modulus	E	kPa	121.2
Poisson's Ratio	ν	(-)	0.49
Damping Loss Factor (DLF)	η	(-)	0.12

Table 3: Measured Biot parameters used in this study for the selected reticulated foam

Reproducibility selection

Again, in Bonfiglio and al. [5], the relative reproducibility standard deviation when considering all labs for Young's modulus of material A is 71%. As concluded by the authors, the levels of discrepancy between the labs for all materials suggest that there is an obvious need for harmonization of the procedures to measure Young's modulus and Poisson's ratio in porous media. Table 4 – Case A shows the relative reproducibility standard deviation of viscoelastic properties for material A and all labs.

These levels of relative reproducibility are of course unusable and untrustworthy but they do paint an accurate picture of today's viscoelastic biot parameter measurements state. In order to use more realistic relative reproducibility values, let's use only the labs which have :

- Actually measured the Poisson's ratio instead of assuming a fixed value or not measuring it at all (see table II in [5])
- Used the proven QMA method (see table III in [5])
- Not shown any possible outlier results (table VI in [5])

The relative reproducibility standard deviation for young's modulus decreases to 30% compared to 71% for all labs. These labs are labs 2, 8 and 9 (see table 4 – Case B).

Note that if only lab 8 and 9 were chosen, relative reproducibility standard deviation would fall down to 7.5%, 3.7% and 14.3%, for Young's modulus, Poisson's ratio and Loss factor respectively. This is true for Material A and many other materials, although not for all of them in that study.

One can only hope that in the future, reproducibility improves to these levels when several labs are compared again. Table 4 shows the relative reproducibility standard deviation for these three sets of data called case A, B and C.

Case	Labs	Young's modulus	Poisson's ratio	Loss factor
A	All	71%	37%	85%
B	2,8,9	30%	14%	25%
C	8,9	7.5%	3.7%	14.3%

Table 4: Relative reproducibility standard deviation of viscoelastic properties for material A and various labs (see [5])

The current study uses the relative reproducibility shown in table 5- Case C to compute their effect on STL and absorption.

Sensitivity analysis

In this study, a Monte Carlo analysis is used to account for the reproducibility of biot parameters and their effect on the sound transmission loss and absorption. All computations are performed with the commercial software NOVA from Mecanum [8].

A normal distribution is used to generate the variations in the Biot parameters fed into the computation of STL and absorption. A similar study by Cousineau [9] suggested to use 500 iterations. Biot parameters generated for 500, 1000 and 5000 iterations are shown in figure 3. The gray lines represent a relative standard deviation of 74%, the red lines 30% and the blue 7.5%. It is clear that it is preferable to use the 5000 iterations case since the other 2 cases under-estimate the standard deviation of the young's modulus distribution. The same was observed for all other Biot parameters.

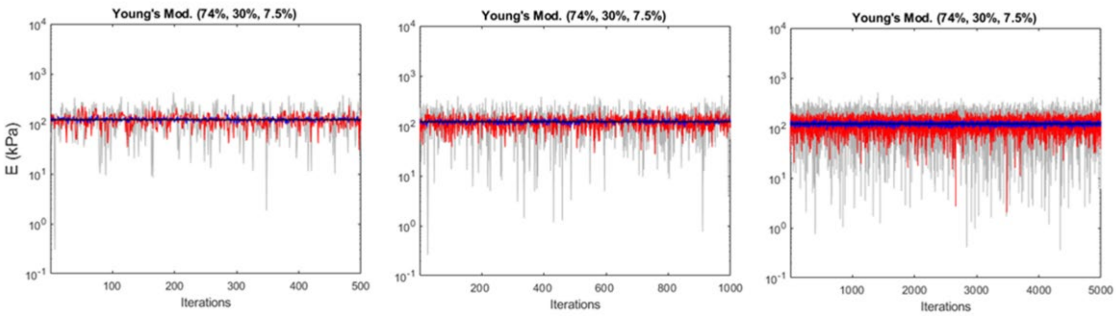

Figure 3: Values of young's modulus generated randomly with a normal distribution for 500 iterations (left), 1000 iterations (middle) and 5000 iterations (right)

Effect of uncertainties on STL and Absorption

The random values of all biot parameters used to compute the STL and the diffuse field surface absorption for each iteration are shown in figure 4.

Each parameter is displayed with its relative reproducibility standard deviation in parenthesis. Additionally, for the viscoelastic properties, the relative reproducibility is shown for case A, B and C. The scale of each graph corresponds to the commonly agreed range of manufacturability of porous materials. For example the y-scale of porosity is from 0 to 1 and tortuosity from 1 to 5. This provides insights as to where this material lies with respect to the domain of feasibility. Finally, case A is presented in light gray, case B in red and case C in blue for the viscoelastic properties of the frame structure. Note that some graphs have their y-axis in logarithmic scale to help see the data better, this is the case for flow resistivity, both characteristic lengths, the young's modulus and the loss factor. For these, the data seems skewed downward but is really normally distributed around the mean. It provide a visual sense of how much the data is spreading around the mean.

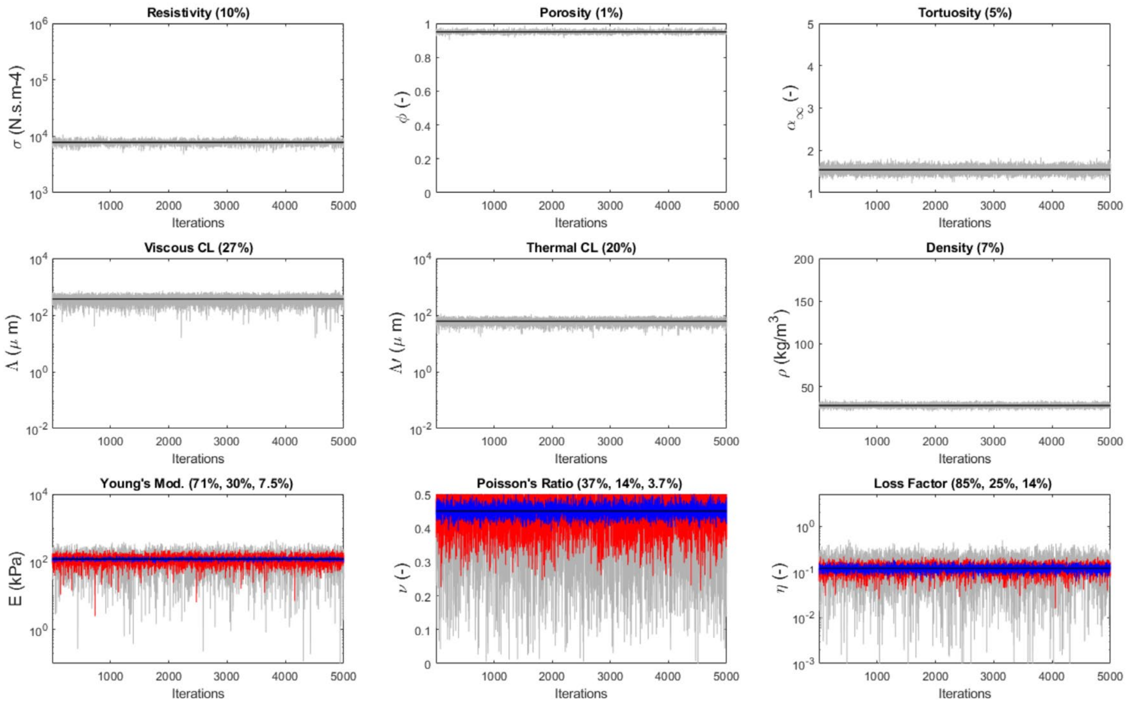

Figure 4: Values of all Biot parameters randomly generated with a normal distribution. Relative reproducibility standard deviation in parenthesis (Case A: gray, Case B: red, Case C: blue). The measured values used as the initial iteration are shown in a black bold horizontal line.

It is evident that the data for case A and B show too much spread around the mean and therefore in the subsequent computations, only the Case C will be considered.

The computation of STL and absorption for the 5000 iterations are presented in figure 5. The top graphs show the STL and absorption response. The bottom graphs show the variation from the initial iteration response for both the STL and absorption. The STL variation from the mean is a little over 1 dB with a few outliers at 2 and 3 dB. It seems low but considering that the maximum STL level is 3 dB, the variability is quite high. The bottom right graph shows that the maximum variation around the mean is approximately 10 to 15% for the majority of the population with outliers at 20 to 30%. This level of variation is quite high and it would be interesting to learn which Biot parameters are driving the absorption response.

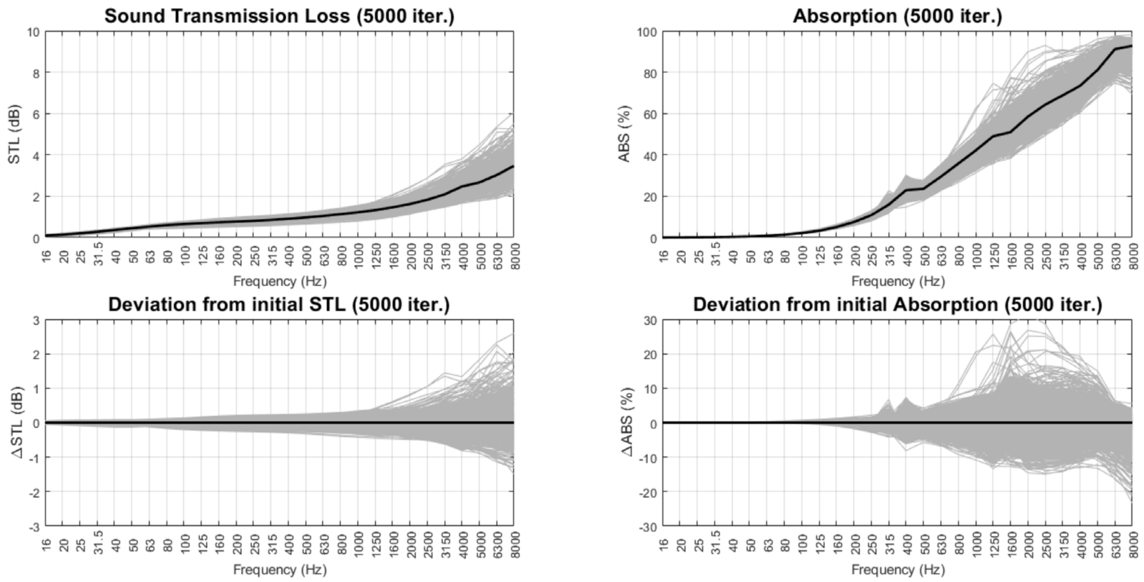

Figure 5: Top: STL and Absorption for all 5000 iterations (gray) and initial results from measured Biot parameters (black line). Bottom: Variation from initial results (gray).

Contribution analysis

To identify and rank which Biot parameter is causing the most uncertainties in the STL and absorption, separate Monte Carlo computations are performed on each individual Biot parameters. Figure 6 shows that flow resistivity is the dominant source of uncertainty for both the STL and absorption and by a large margin.

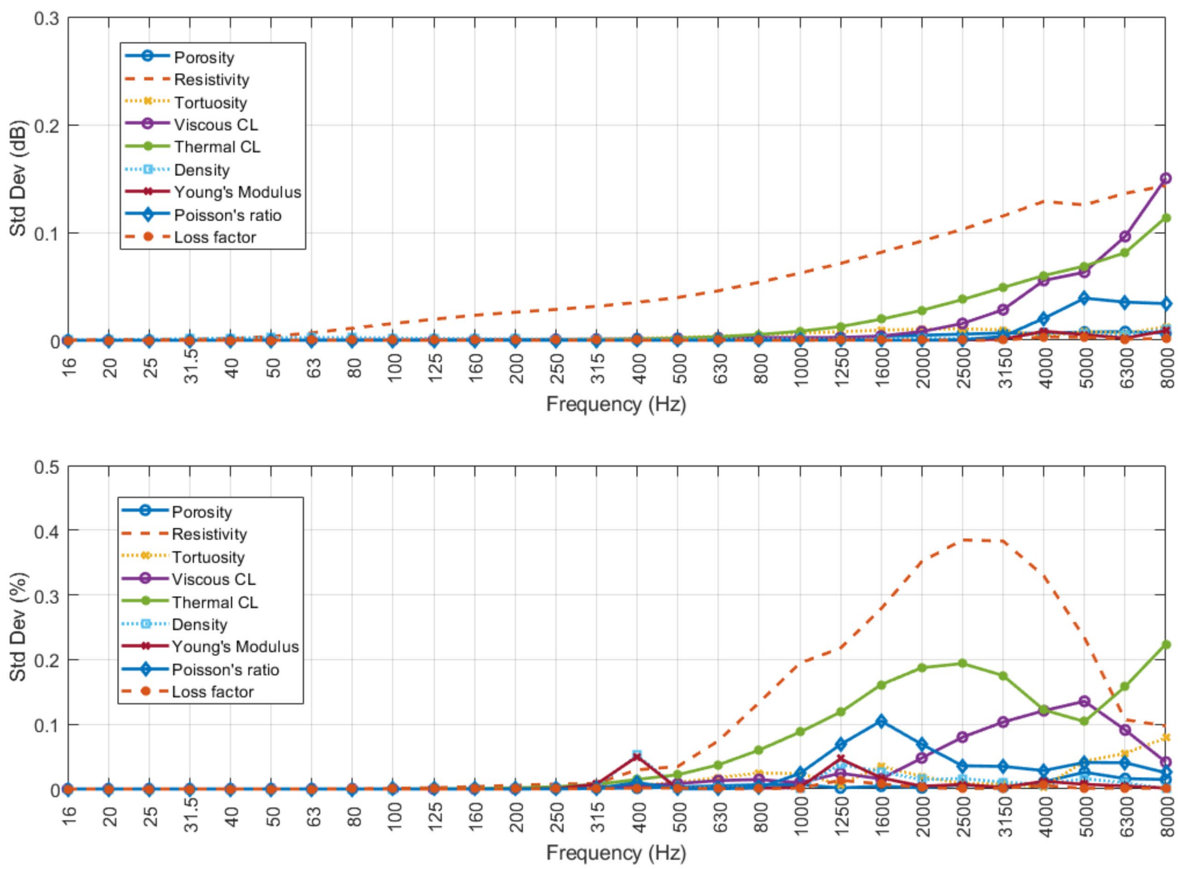

Figure 6: Standard deviation from the mean, for multiple Monte Carlo analysis where each use a single distinct Biot parameter as source of uncertainty for STL (Top) and absorption (Bottom)

Therefore, for similar foams, the accuracy of the flow resistivity measurement is crucial to obtain low variability of the resulting predictions. Then comes the viscous and thermal characteristic lengths and finally the Poisson's ratio. This ranking applies only to materials similar to the one chosen for this study.

Conclusion

Good in-lab repeatability of Biot parameter measurements is in general easier to obtain that the lab-to-lab reproducibility. The various round robin exercises related to porous media measurement have clearly shown that there is a lot of potential for improvement and that the industry would benefit from a harmonization of measurement methods and best practices. As shown in this paper, variation of the response due to Biot parameters uncertainties are significant and we should aim at reducing these uncertainties to generate more consistent predictive simulation models.

Acknowledgment

The author would like to thank Mecanum for having graciously provided NOVA to compute the STL and absorption curves and support for the use of NOVA in batch mode.

Reference

[1] Y. Atalla and R. Panneton : "Inverse Acoustic Characterization of Open Cell Porous Media Using Impedance Tube Measurements," Canadian Acoustics 33(1), 2005

[2] R. Panneton, Y. Atalla, D. Blanchet and M. Bloor: "Validation of the Inverse Method of Acoustic Material Characterization," SAE Technical Paper 2003-01-1584, 2003

[3] C. Langlois, R. Panneton and N. Atalla : "Polynomial Relations for Quasi-Static Mechanical Characterization of Isotropic Poroelastic Materials," J. Acoust. Soc. Am. 110:3032–3040, 2001.

[4] F. Pompoli, P. Bonfiglio, K. V. Horoshenkov, A. Khan, L. Jaouen, F-X. Becot, F. Sgard, F. Asdrubali, F. D'Alessandro, J. Huebelt, N. Atalla, C. K. Amedin, W. Lauriks and L. Boeckx: "How reproducible is the acoustical characterization of porous media?", J. Acoust. Soc. Am. 141 (2), February 2017, pages:945-955

[5] P. Bonfiglio, F. Pompoli, K.V. Horoshenkov, M.I.B.S.A. Rahim, L. Jaouen, J. Rodenas, F.-X. Bécot, E. Gourdon, D. Jaeger, V. Kursch, M. Tarello, N.B. Roozen, C. Glorieux, F. Ferrian, P. Leroy, F.B. Vangosa, N. Dauchez, F. Foucart, L. Lei, K. Carillo, O. Doutres, F. Sgard, R. Panneton, K. Verdiere, C. Bertolini, R. Bär, J-P. Groby, A. Geslain, N. Poulain, L. Rouleau, A. Guinault, H. Ahmadi, C. Forge: "How reproducible are methods to measure the dynamic viscoelastic properties of poroelastic media?", Journal of Sound and Vibration, Volume 428, 2018, pages:26-43

[6] dBPorous from dBVibroAcoustics. URL:https://dbporous.com/

[7] D. Blanchet and M. Feist-Muench "InNOVAtive Acoustic Material Concept Integration into Vehicle Design Process", SAE Technical Paper 2020-01-1527, 2020

[8] NOVA from Mecanum. URL: https://www.mecanum.com/en

[9] G. Cousineau-Bouffard: "Analysis of Uncertainties in Gross Properties of SEA Model Subsystems", Internoise proceedings, Honolulu, Hawaii, USA, 2006