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A Computational Approach for Characterization of Rigid Frame Porous Materials

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Introduction

Flow resistivity of a porous material is normally experimentally derived using an airflow resistivity meter. This parameter provides a measure of pressure drop across the specimen as a function of the volume airflow. At low frequencies, it partially characterizes the viscous and inertial effects, when the viscous boundary layer is large enough to be comparable to the size of the pores [1]. For acoustical materials, the range of values for the static air flow resistivity is approximately $[10^3\ 10^6]\ Pa \cdot s \cdot m^{-2}$. In order to get this value computationally, the literature is rather limited according to the authors' knowledge. This study is providing study cases on two dimensional open pore geometries using finite element method, including thermal and viscous losses and analyses the flow resistivity calculation methods.

In general, the parameter is used widely in characterization models for rigid or elastic frame porous materials. For example: Delany-Bazely and Delany-Bazely-Miki models use only this parameter to outline the behavior of porous acoustic materials. Works of M. Saouki and Peter Göransson used semi-empirical methods to estimate the flow resistivity in low frequencies ranging from 40-100 Hz [2] [3].

Mathematically, Static flow resistivity σ, can be derived from the generalized Darcy's law [2] as Equation (1).

$$\sigma\phi\vec{v} = -\vec{\nabla}p \qquad Pa \cdot s \cdot m^{-2} \qquad (1)$$

Where, ϕ is the open porosity of the material, $\vec{v}$ the velocity of the fluid particles subjected to the pressure gradient $\vec{\nabla}p$ ($\phi\vec{v}$ is thus the fluid flow inside the porous material).The definition of σ assumes that $\vec{v}$ and $\vec{\nabla}p$ are constants i.e. they are not harmonic or time dependent.

The inspiration of the current work to build a computational model came from the uncertainties regarding inversion characterization models and obstacles in determining porous parameters such as porosity. To explore the high frequency regime [10000 40000] Hz with considering thermos-viscous loses, a complete numerical approach is described in this paper.

Approach

This study tries to create a computational model for conventional air flow resistivity measurement experiment using commercial finite element software. A previous model of impedance tube measurement for porous materials is taken and modified to calculate absorption coefficient of custom designed rigid frame porous material to check the compatibility of the newly proposed approach [4]. It can be seen from the convergence study that the new method with microscopic approach converges to the previously determined results at 10000 Hz.

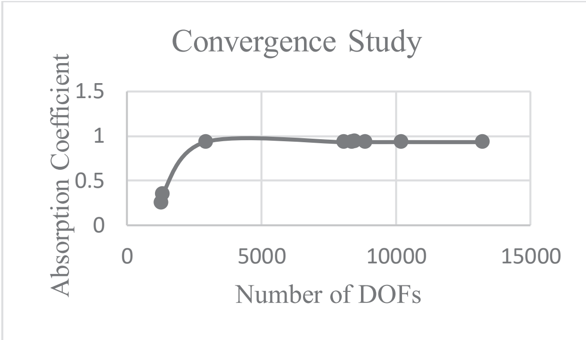

Figure 1: Convergence study using absorption coefficient versus the number of degrees of freedom at 10000 Hz.

Study Cases

The complexity of geometry increases gradually in the flowing test cases

- Rectangular pore
- Curvilinear pore
- Circular particle

As can be seen from Figure 2, all three samples are placed in the middle of flow resistivity measurement tube. On the left end of the tube a normal velocity is applied which is compared to the input air flow in the experiment. Two boundary probes are applied to determine the pressure at the left and right end of the sample. A domain point probe is mounted inside the sample to measure the velocity inside. A perfectly matched layer is placed at the right end of the tube to prevent reflected wave inside the sample. Thermo-viscous acoustics is used at the sample domain to calculate loses. A multi-physics interface is defined at the junction of acoustics domain and thermo-viscous acoustic domain to interface the different physics used.

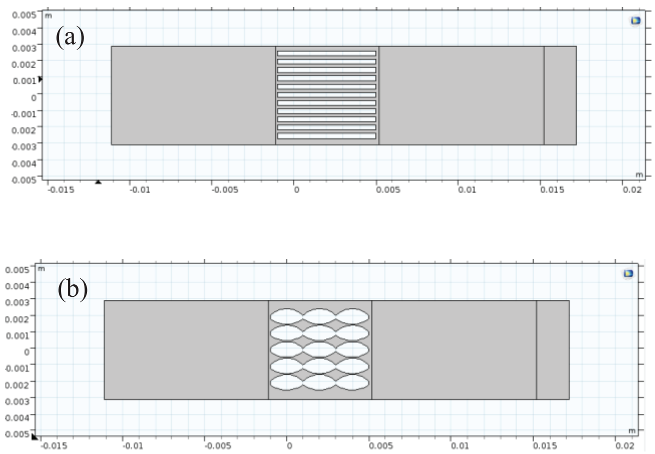

Figure 2: Geometry in 2-D for the test cases: (a) Rectangular pore shape and (b) Curvilinear pore shape.

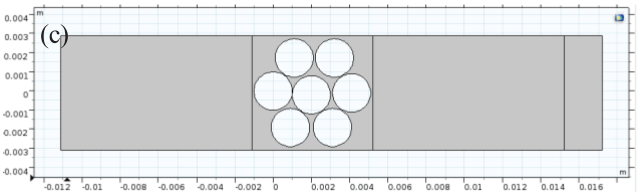

Figure 2: Geometry in 2-D for test cases (c) Circular Particle. Figures 2 is derived using commercial FE Software [5].

To start the calculation, the porosity ϕ of the simulated sample is computed using the formula

$$\emptyset = \frac{area\ of\ the\ voids}{total\ area\ of\ the\ sample} \times 100\% \qquad (2)$$

Then, $\vec{\nabla}p$ is calculated from the difference of pressure P_1 and P_2 in the boundary probe 1 and 2. Afterwards, $\vec{v}$ is determined from the results given by the domain point probe inside the sample. Finally, the flow resistivity is computed from Equation (1).

Results and Discussion

Frequency is varied from 100 to 40000 Hz to observe the thermos-viscous effects. It can be seen from the study that the samples used here showed no flow resistivity until 4000±200 Hz.

The simplest frame i.e. rectangular frame responds with a 7152.93 $Pa \cdot s \cdot m^{-2}$ at 3800 Hz. The highest value 44736$Pa \cdot s \cdot m^{-2}$ for this structure occurs at 22700 Hz. It exhibits another peak 8867.3 $Pa \cdot s \cdot m^{-2}$ at 35200 Hz. During the rest of the frequencies it shows a value less than 103 $Pa \cdot s \cdot m^{-2}$.

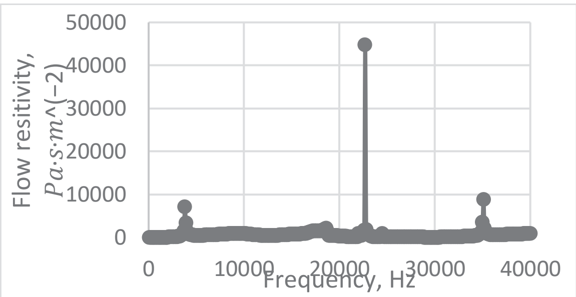

Figure 3: Results for the first case

The medium complex geometry of curvilinear pore shows a bit different response compared to the first one. The first peak occurs at 4000 Hz with a value of 1000 $Pa \cdot s \cdot m^{-2}$. The highest value for this one is 54600 Pa.s.m^{-2} which is observed at 8600 Hz. Starting from 10500 Hz until 40000 Hz, it shows a steady value of 1540 $Pa \cdot s \cdot m^{-2}$ with a peak 21900 $Pa \cdot s \cdot m^{-2}$ at 11600 Hz.

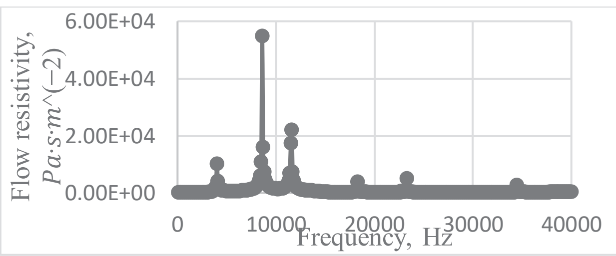

Figure 4: Results for the second case

The most complex geometry with circular beads exhibits a different picture. The first value of 12041 $Pa \cdot s \cdot m^{-2}$occurs at 2300 Hz. It has an average flow resistivity of 17409 $Pa \cdot s \cdot m^{-2}$ within 10200 Hz to 40000 Hz with a peak of 52139 $Pa \cdot s \cdot m^{-2}$ at 27400 Hz.

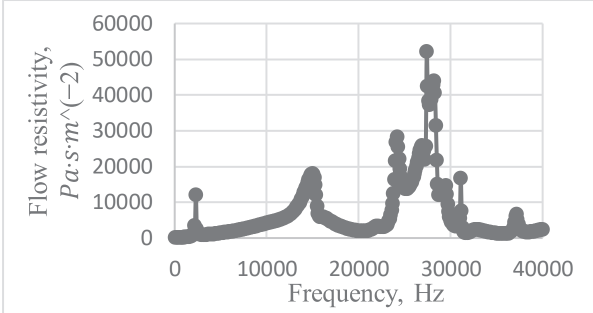

Figure 5: Results for the third case

The complexity degrees are chosen as preliminary samples to see how the flow resistivity behavior changes according to such variations and if the calculation method proposed is functioning. The complex frequency dependent results we achieve for the flow resistivity does not match with the single positive absolute value that is usually reported in literature. Upon the authors' knowledge, in order to fix this problem, the frequency range is limited to that of the most interest to the study at hand. Absolute values are then regarded as the final reportable parameter.

Conclusions

All three geometries proposed showed a strong frequency dependent behavior, the dependency increasing as the complexity level goes higher. The peak of flow resistivity is around $4 - 5 \times 10^4\ Pa \cdot s \cdot m^{-2}$. The first sample had only three main peaks, each happening over a narrow frequency range. The second geometry had six peaks and the frequency range widened. The third case had even more variations over the frequency. It has an average of 23344 $Pa \cdot s \cdot m^{-2}$ over the frequency range 25000 to 30000 Hz where the peak is as large as 52139 $Pa \cdot s \cdot m^{-2}$ at 27400 Hz. As found in the literature, some authors averaged the flow resistivity over a narrow frequency range of interest [2]. The goal is to develop a more complicated geometry which yields smoother flow resistivity behaviour over a wider range of frequency where averaging is more sensible and can be deemed as independent of frequency.

References

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