Recent developments in the acoustical properties of perforated and porous materials containing dead-end pores

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RECENT DEVELOPMENTS IN THE ACOUSTICAL PROPERTIES OF PERFORATED AND POROUS MATERIALS CONTAINING DEAD-END PORES – APPLICATIONS TO LOW FREQUENCY SOUND ABSORPTION

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It was shown recently in Nevers, France, Sherbrooke, Canada and Salford, UK, that porous materials with semi-opened pores or materials with open pores bearing lateral cavities or resonators at the microscopic scale of the pores can result in peculiar sound absorption properties. Various examples of these materials can be found in engineering and in everyday life including bio-based materials. The cavities and resonators can be assimilated to dead-end pores, which are opened at one end and closed at the other. The dead-end pores are known to geophysicists. We studied them more recently in the field of engineering acoustics where the saturating fluid is air. The closed ends prevent the fluid to flow in the dead-end pores so that a crucial assumption usually made in the classical models of the acoustics of porous media based on Biot's theory is not fulfilled for these materials. In some dead-end pore materials, it was observed that the frequency of the absorption peak was lowered and that the absorption was increased. This has led to the development of new materials with controlled microstructure for low frequency sound absorption applications. Perforated materials with dead-ends were designed and built and their low frequency performances were confirmed experimentally. Absorption peaks around 0.9 were measured at a few hundred Hz for materials of a few centimeters thickness. Future developments of dead-end pore materials are concerned with the optimization of the microstructure, new designs of the microstructure, the use of dead-end pore materials in muffler applications, the interaction with the black hole effect, the behavior under high sound level and the use of vibroacoustic properties of perforated plates for low frequency sound absorption.

Keywords: acoustical properties, perforated materials, dead-end porosity, sound absorption, low frequency)

1. Introduction

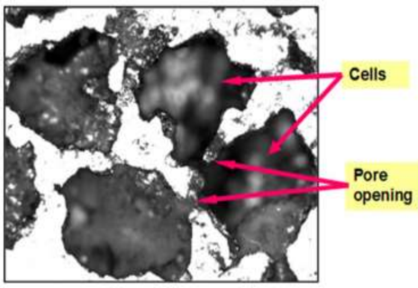
Perforated and porous materials are widely used in engineering acoustics for their interesting absorption properties. The acoustical properties of porous materials can be described with the help of models that have now become classical and based on Biot's phenomenological theory of the acoustics of porous media [1]. An overview of these models can be found in the book by Allard and Atalla [2]. Perforated materials can also be described by a model for porous materials in which the physical parameters involved take particular values [3].

In Biot's theory, the fluid flow in viscous boundary layers inside the pores are responsible for sound attenuation by viscous frictions between the different layers of the fluid in the vicinity of the pore walls. Thermal boundary layers can also be defined in which thermal exchanges between the different fluid layers occur and contribute to the sound attenuation. At the very beginning of his article published in 1956 in J. Acoust. Soc. Am., Biot made the assumption that "the fluid is incompressible and may flow relative to the solid causing friction to arise." Subsequent developments in sections 3 and 6 of Biot's article show that the additional assumption that the fluid flows in *all* the pores of the medium was made, implicitly.

The present article proposes to show how from this observation new thin materials displaying dead-end porosity features were designed for sound absorption at low frequency. It is shown in section 2 that the additional implicit assumption is not fulfilled in porous materials containing dead-end pores. Materials with dead-end porosity can be found in engineering and in everyday life. Two examples are presented. In section 3, it is shown that a simple approach can be used to account for the dead-end porosity in porous materials, regardless of which classical model is used. Perforated materials can also display dead-end porosity features. An example of material with surface dead-end pores obtained from perforations is also proposed. It was noticed that this material displayed peculiar acoustic properties at low frequencies. These properties have led to the design of new perforated materials with periodically distributed dead-end pores and more generally, of materials with controlled properties at the microscopic scale of the pores or perforations. New designs of thin materials capable of sound absorption at low frequencies are presented in Section 4. Future developments are proposed in section 5.

2. Acoustical properties of materials containing dead-end pores

Two examples of materials that were strongly suspected to contain dead-end pores or clusters are showed in Figure 1. For these materials, it was observed that the classical models of the acoustics of porous media based on Biot's theory (e.g. Refs. [4-8]) were not as accurate as initially expected. Phenomena that were not accounted for so far had to be involved. The microscope observation of the samples revealed that although the porosity was opened (both materials were permeable to airflow), some pores seemed to be opened at one end and closed at the other end.



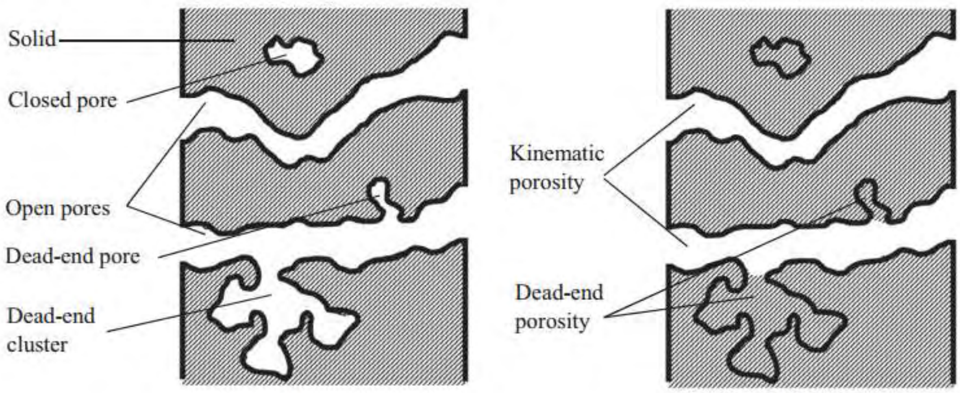
(a)

(b)

Figure 1: Examples of materials containing dead-end pores or clusters. (a): a porous aluminum foam (after Ref. [9,10]), (b) a sunflower composite obtained from crushed sunflower stalk particles (bark and pith [11,12]).

The complex microstructure of these materials and the potential existence of dead-end pores or cluster is illustrated in Figure 2 (a) and (b) where different types of porosities are represented. It is well known that the porosity that matters for the acoustic wave propagation is the open porosity (the open white areas) and so the closed porosity is considered as part of the solid acoustically (see Refs.

[1,2]). However, Figure 2b shows that semi-opened pores that are closed at one end cannot let the fluid flow as they offer an entry inside the pore but no exit route. Therefore there is a non negligible surface area of pore walls that cannot participate in the viscous boundary layers the same way as for the other pores. Since dead-end pores or clusters do not allow fluid flow as in the rest of the open pores, it can be considered that, as far as the viscous fluid/solid interactions are concerned, the porosity actually "seen" by the acoustic wave is the kinematic porosity (the white areas in Figure 2(b)).



(a) (b)

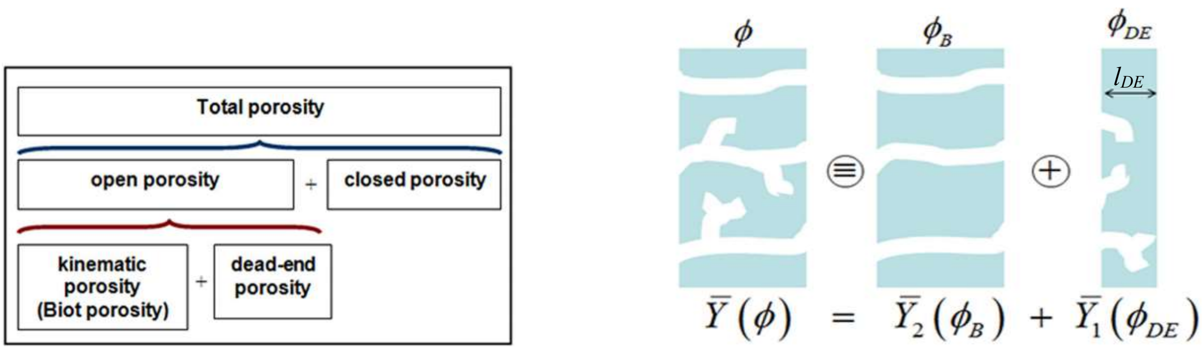
Figure **2**: (a): Different porosities in a porous medium. (b) Kinematic and dead-end porosities after. Ref. [12].

In order to account for the viscous interactions during the wave propagation, Figure 2(b) suggests that a simple porosity correction to the classical modelling [1,2,4-8] should be sufficient to account for the dead-ends. This was suggested by Zwikker and Kosten [13]. In fact, this correction can be applied and improves the theoretical description but is not sufficient to describe the material with accuracy. The dead end pores correspond to open/closed cavities or resonators in which standing wavefields can settle. These have an effect on the local impedances at the entries of the dead-end pores or clusters and therefore have an influence on the propagating sound waves. A simple modelling of the two effects (porosity correction and resonator effect) is proposed in the next section.

3. Acoustic model accounting for the dead-end porosity effect

Figure 3 (a) shows that simple relationships exist between the different porosities defined in Figure 2 (a) and (b). The principle of the model involves two independent actions:

1) Applying a porosity correction in one of the classical models [1,2,4-8]
2) Using a simple model of cavity or resonator to account for the standing wavefields in the dead-end pores or clusters.



(a) (b)

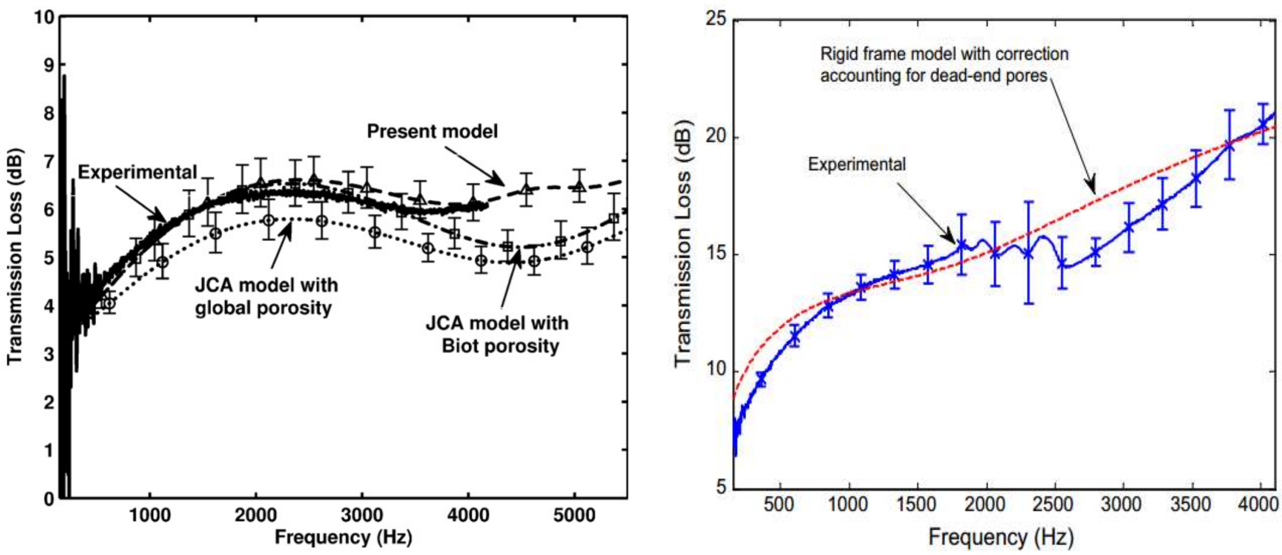
Figure **3**: (a) Relationships between the porosities. (b) Principle of the model for the acoustical properties of porous materials with dead-end pores (redrawn after [9]).

Assuming that the sound propagation in the material is linear, it was proposed that the two effects could be added up through a sum of admittances at the junctions between the main pores and the dead-ends [9]. After a homogenization process, a simple relationship was found between three admittances as illustrated in Figure 3 (b).

The term $\overline{Y}(\phi)$ represents the homogenized surface admittance of the porous layer of material with dead-end pores as a function of the total open porosity ϕ, the term $\overline{Y}_2(\phi_B)$ represents the characteristic impedance of the layer as a function of the kinematic (or Biot) porosity ϕ_B, and $\overline{Y}_1(\phi_{DE})$ corresponds to a homogenized expression of the surface admittance at the dead-end pores entries. The dead ends have an average length l_{DE} corresponding to the thickness of the dead-end pores layer in Figure 3 (b). Action 1) is carried out through the use of $\overline{Y}_2(\phi_B)$ while action 2) is performed in the use of $\overline{Y}_1(\phi_{DE})$. The proposed model consist in using successively two times one of the classical models [1,2,4-8] to determine $\overline{Y}_2(\phi_B)$ and then $\overline{Y}_1(\phi_{DE})$. The global admittance is finally given by the sum of the two contributions.

3.1 Application of the model to a porous aluminium and a sunflower composite

Figure 4 (a) and (b) show that the proposed model can describe fairly well the experimental data obtained on the porous materials described in section 2: the porous aluminium and the sunflower composite. In the case of porous aluminium and for the Transmission Loss for which the effect was most visible, a comparison with one of the classical models, the Johnson-Champoux-Allard model (JCA) [5,6], shows that the present model provides a much better fit of the experimental data. Figure 4 (a) demonstrates the positive effect of porosity correction on the JCA model and validates the global model with the addition of the effect of resonators as well.



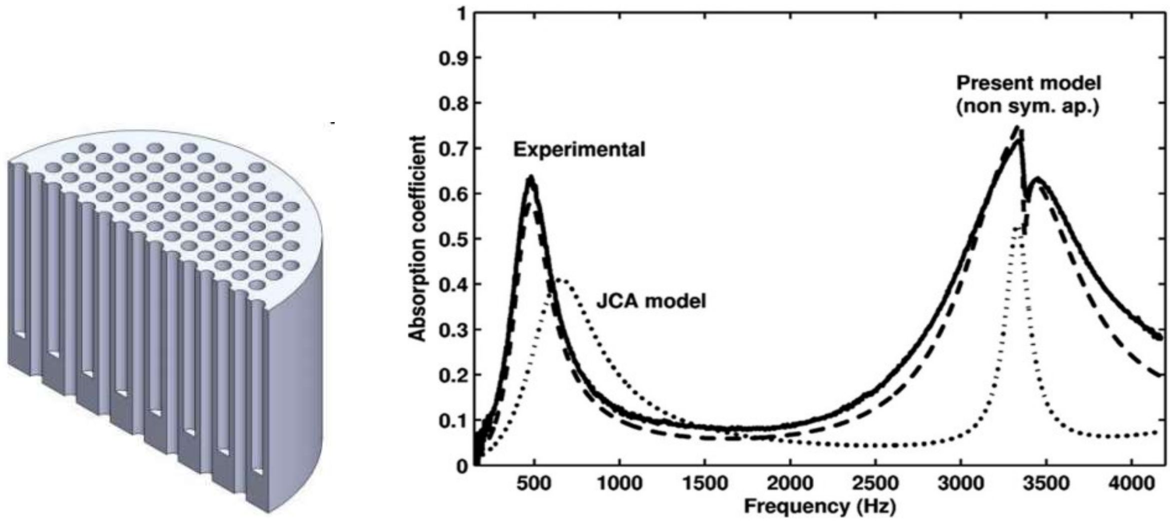
(a) (b)

Figure **4**: Theoretical and experimental Transmission Loss for the materials of section 2 (after [9] and [12]).

For the theoretical description of the sound propagation in the sunflower composite in Figure 4 (b), only a porosity correction of the classical JCA model was applied. This had the effect of improving considerably the match between theoretical and experimental data as shown in the figure. The initial use of the classical model without accounting for dead-end porosity provided rather inaccurate results (see detailed results in Ref. [12]). The results of Figure 4 tend to show that as expected dead-end pores or clusters can exist in engineering and everyday life materials.

3.2 Application of the model to a perforated material with surface dead-end perforations

Materials with well controlled microstructure containing dead-end pores were also investigated theoretically and experimentally. Surface dead-end pores were created artificially by partial perforations ending in the bulk of the material (See Figure 5 (a)) and mixed with full perforations going in-through the thickness of the material.



(a) (b)

Figure **5**: (a) Perforated material with surface dead-end pores. (b) Theoretical and experimental results.

The results on the absorption coefficient (sample backed by a 50 mm air cavity and a rigid wall) clearly show that the classical JCA model cannot predict very well the acoustic behaviour. The present model allowed a porosity correction (corresponding to the dead-end porosity of the partial perforations) and also to account for the resonance effect created by the presence of the quarter wavelength cavities created by the partial perforations. In the example presented in Figure 5, the main and dead-end perforations had a diameter of 2 mm and a depth in the material of 25 mm for the dead-ends while the sample thickness was 30 mm. The dead-end, the kinematic and the total open porosities were easily determined. Their values were respectively of 13.5%, 14% and 27.5%. These results confirmed the validity and power of the proposed approach based on dead-end porosity.

Observing Figure 5 (b), it is very interesting to notice that the first absorption peak is shifted to a lower frequency while its value is increased. These effects are attributed to the combined effects of the resonators and the periodicity of the dead-end pore distribution on the surface. These observations led to new designs of materials described in the next section.

4. New designs of thin materials for low frequency sound absorption

Based on the previous results, Leclaire et al. [14] proposed new designs of materials containing periodically spaced dead end pores for low frequency applications. The underlying idea was to create a periodicity in the distribution of dead-ends in the thickness of the sample contrary to the previous case where the dead-ends were distributed on the surface. A typical example of design is shown in Figure 6. Typically, all dimensions including main pore diameters, dead-end lateral sizes, distance between two consecutive dead-ends (or period) are millimetric or submillimetric. The overall sample thickness can therefore be of the order of a few cm for a number of consecutive dead-ends between 10 and 20. The dead-ends are located at nodes regularly spaced along the main pore and several dead-ends can be designed at each node. There are 4 dead-ends per node in the example of Figure 6.

It was demonstrated that this arrangement results in an increase of the effective compressibility of the effective fluid in the main pore. This behaviour is thought to be due to thermal exchanges between the fluid in the dead-ends and the fluid in the main pore. In turn, the increase in compressibility in the main pore is responsible for a decrease of the wave velocity that can be drastic. Wave slowing was also observed by Huang et al. [15] in other systems.

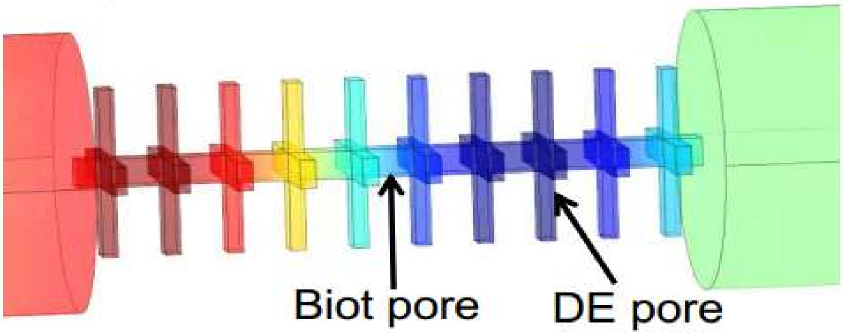


Figure **6**: Sound absorbing materials with periodically spaced dead-end pores. FEM Virtual measurement tube representation of the sample. The void correspond to the solid space.

The drastic slowing of the effective celerity of the wave in the main pore will results in a very interesting acoustical behaviour of the system as resonances responsible for absorption peaks have frequencies that depend on the celerity. This results in absorption peaks that can be unusually low considering the sample overall thickness (a few cm).

Leclaire et al. [14] presented first experimental results with a material fabricated using 3D printing technology and several suggestions of design improvement. They also propose a low frequency asymptotic expansion of the effective density and compressibility of the fluid in the main pore. Using these expansions, it was inferred qualitatively that the low frequency performance should be improved by increasing the dead-end pore to main pore volume ratio. The number of dead-ends per node should also be increased.

This last remark led to a new design of materials reported in Ref. [16] that allows to increase considerably the frequency shift towards low frequencies for a given overall thickness (see Ref. [16] for full details). With this new design, first experimental results were obtained and compared to the theoretical prediction involving a lump model and the use of the transfer matrix method. Figure 7 shows an example of experimental and theoretical results on the absorption coefficient for this new material of external diameter of 29 mm.

The first absorption peak was located at 550 Hz for a material of overall thickness of 31 mm. A low frequency of 392 was obtained in another sample design for the same overall thickness and an external diameter of 44 mm. Optimization of the design is currently being studied. The first results on optimisation are promising as the frequency of the first peak is expected to be reduced by a factor 2 or more in new designs.

5. Future works

Future developments will investigate the optimization and new designs of the microstructure, the use of dead-end pore materials in muffler applications, interactions with the black hole effect, the behaviour under high sound level and the use of vibroacoustic properties of perforated plates for low frequency sound absorption. The interactions between successive dead-ends at two different nodes of between two dead-ends at one node are currently also investigated.

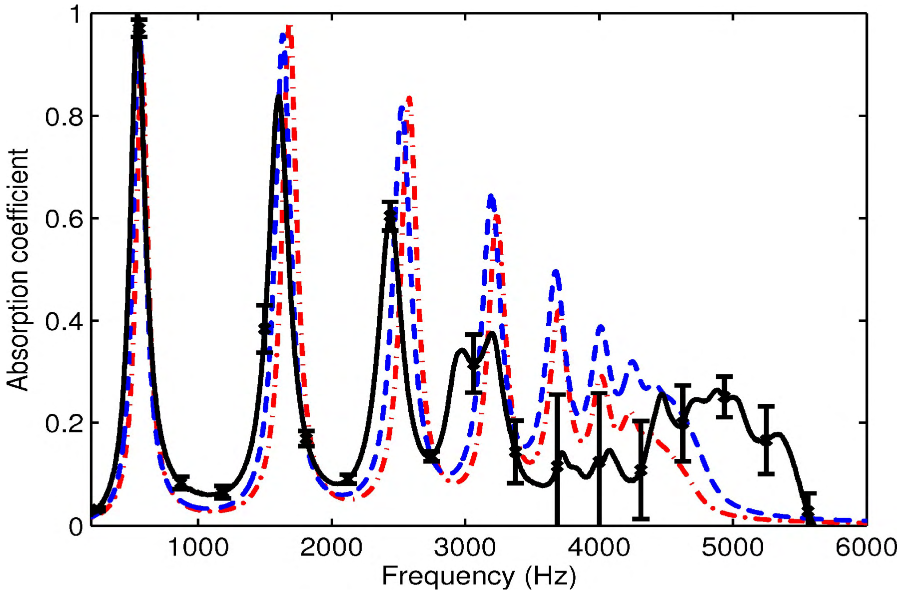


Figure **7**: Normal sound absorption coefficient (sample backed by a rigid wall) in a newly designed sound absorbing material with controlled microstructure (Ref. [16]). (---): measurements in acoustic tube, (- - -): simulation by the analytical model, (-.-.-): simulation by Finite Element approach (rigid frame assumption). The overall material diameter is 44.4 mm and thickness is 31 mm.

6. Conclusions

The study of peculiar materials that could not be described accurately with the help of the classical models based on Biot's theory has revealed the possible existence of dead-end pores or clusters in these materials.

Investigation of perforated materials with surface dead-end pores obtained by partial perforation showed that the periodicity of the dead-end arrangement and the resonator effect seemed to produce a shift of the absorption peak to lower frequencies.

This observation has led to the design of new materials with controlled microstructure involving periodically spaced dead-end pores and quarter wavelength or Helmholtz resonators.

First measurements on these materials allowed to produce absorption peaks at low frequencies of a few hundred Hz for sample thicknesses of a few cm. Optimization of the microstructure is currently underway and should results in significant improvements of the low frequency performances of these new materials for small thicknesses.

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