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Acoustic Modeling of Granular Material and its Combination with a Flexible Perforated Membrane

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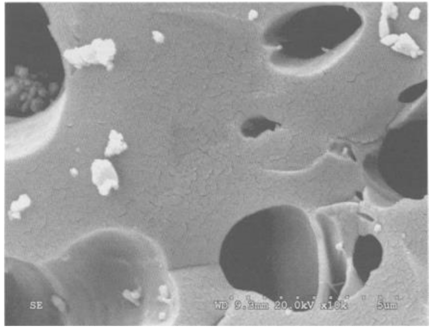
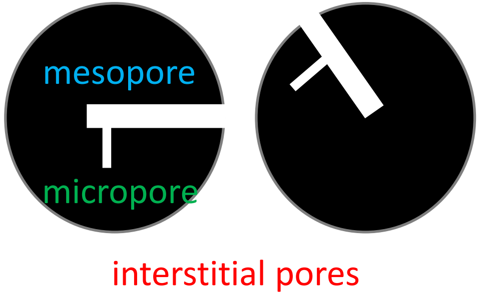
Introduction

Hierarchical Porous Particles

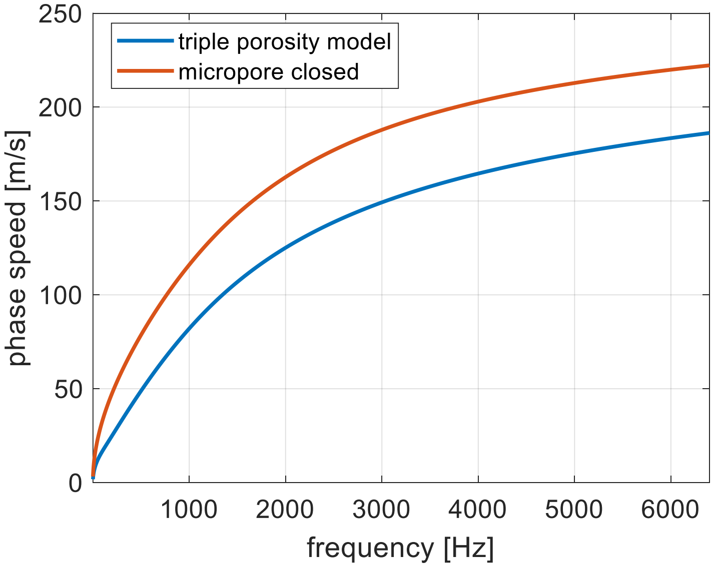
- SEM image of activated carbon (Marsh and Rodríguez-Reinoso, *Activated Carbon*, 2006)





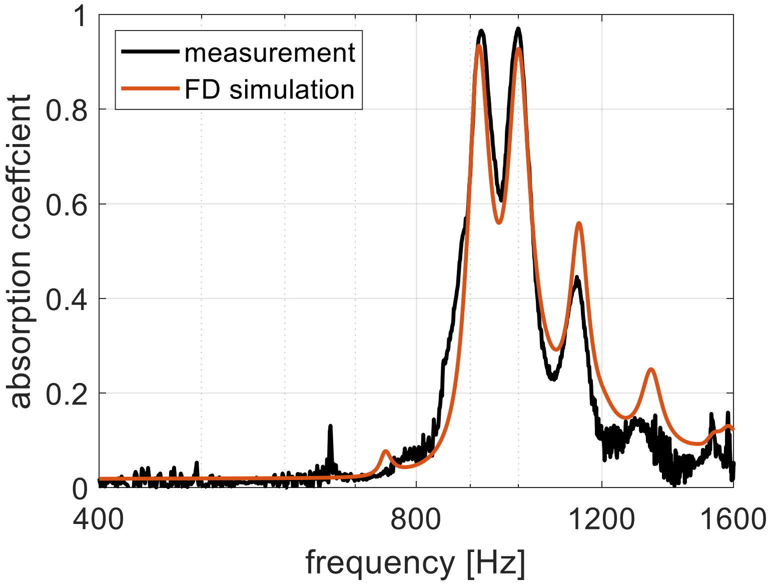
Triple porosity model for granular activated carbon (GAC)
(Venegas and Umnova, 2016)

- The micropores inside the granules can lower the speed of sound in the material, provides larger apparent volume:

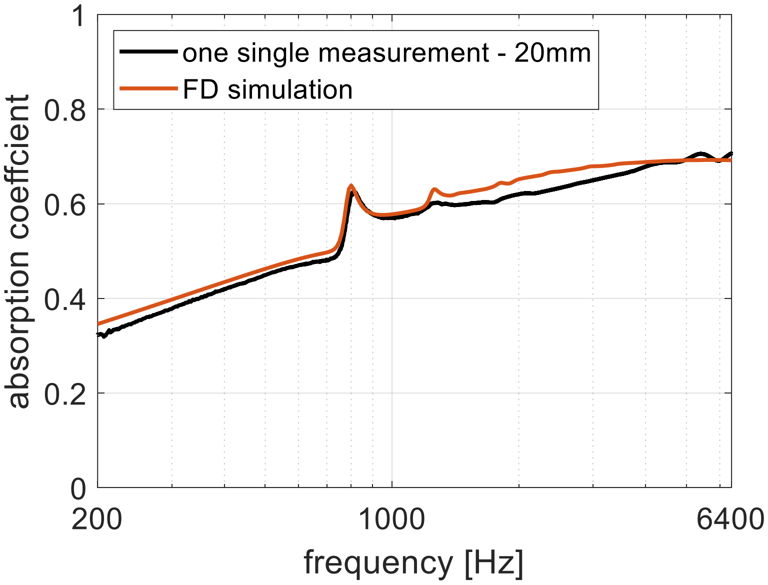


Particle 2-D Finite Difference Modeling

- In our previous study, with the 2-D Finite Difference method, acoustics response of different particles in impedance tube was successfully reconstructed



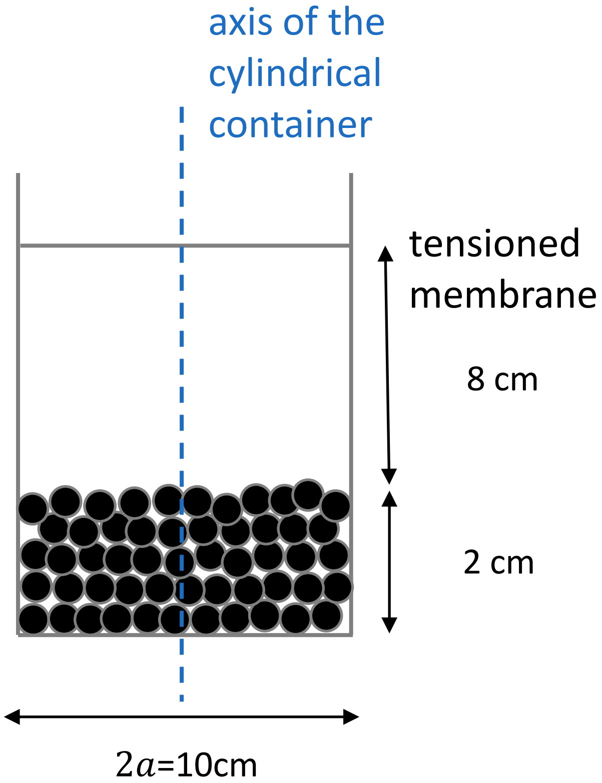
20-mm-thick glass bubble



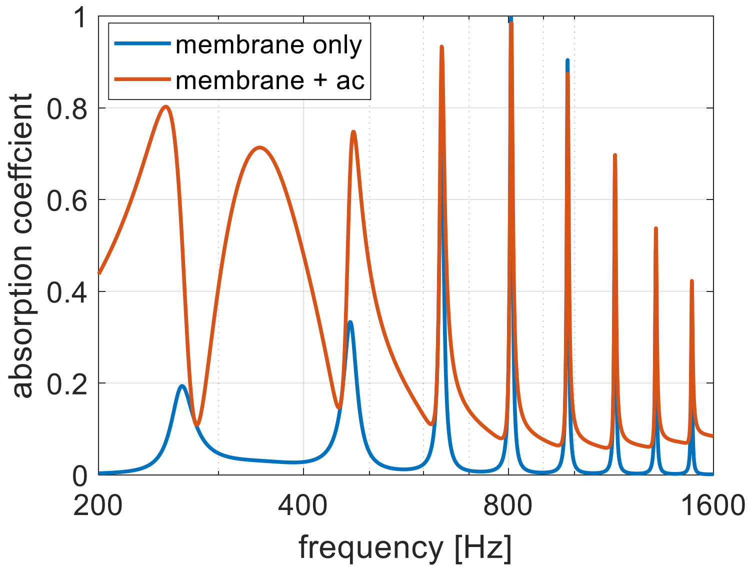
20-mm-thick GAC

GAC Infilled Membrane Sound Absorber

A set of parameters was chosen so that the surface impedance predicted by the triple porosity model matches closely to that reported in (Arenas et al., 2023):



- GAC helps improve the low frequency performance.



Model predictions that closely match those in figure 2(a) and 3(b) from Arenas et al., 2023.

PART 02

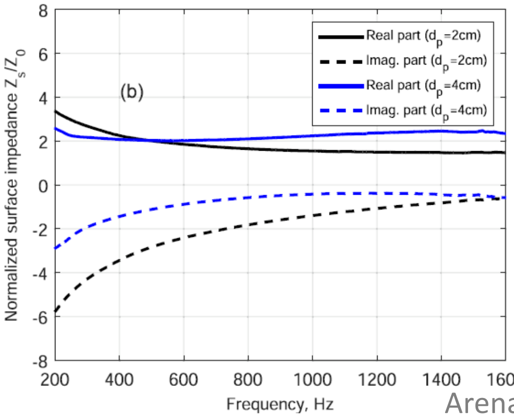
Modeling Method

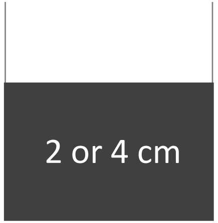
Porous Granules

- A recent study (Arenas et al., 2023) looked into the performance of an absorber consisting of GAC and a membrane using a 1D model

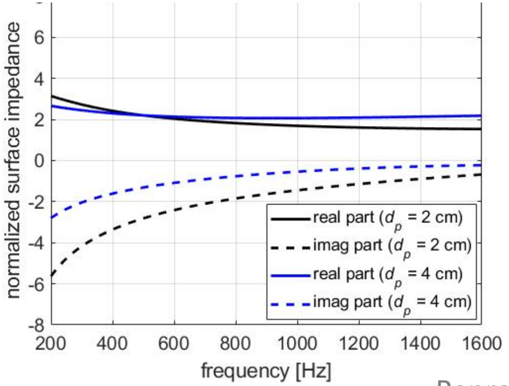
r_p [mm]	granule radius	0.29
r_m [μm]	mesopore radius	0.1973
r_n [nm]	micropore radius	1
ϕ_p	macroporosity	0.4059
ϕ_m	mesoporosity	0.3878
ϕ_n	microporosity	0.4285
b [Pa^{-1}]	Langmuir constant	4.919×10^{-7}
D_c [m^2/s]	configurational diffusivity	5×10^{-9}

Total porosity: 0.7922
Bulk density: 457 $\mathrm{kg/m^3}$





Arenas et al., 2023



Reproduction

Porous Granules

Further, the stiffness of the "frame" consisting of the unconsolidated granules was accounted for by applying Biot theory (poroelastic model).

The governing equations can be found in (Biot, 1956):

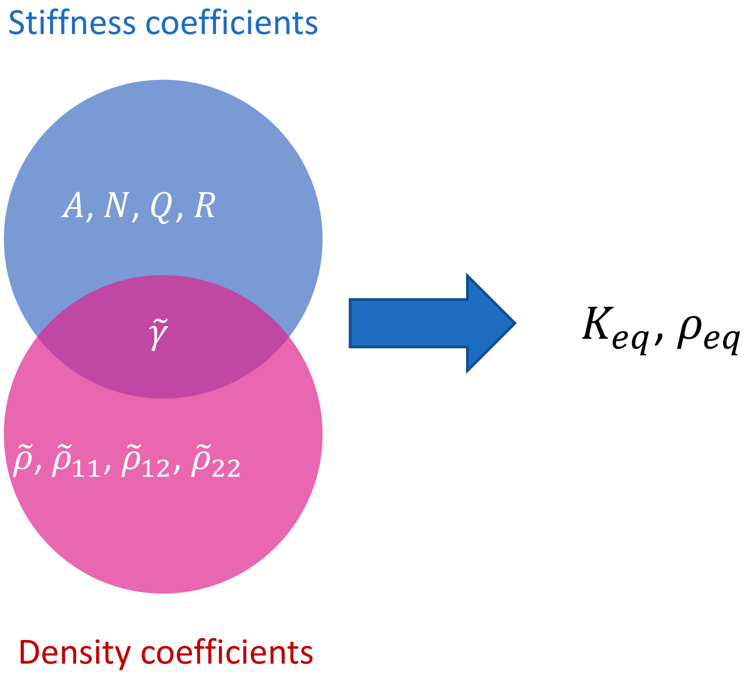
$$N\nabla^2\mathbf{u} + \nabla[(A+N)e + Q\varepsilon] = \frac{\partial^2}{\partial t^2}(\rho_{11}\mathbf{u} + \rho_{12}\mathbf{U})$$

$$\nabla(Qe + R\varepsilon) = \frac{\partial^2}{\partial t^2}(\rho_{12}\mathbf{u} + \rho_{22}\mathbf{U})$$

For the purpose of implementing the FD scheme, the $\mathbf{u} - \boldsymbol{p}$ formulation (Atalla et al., 1998) is applied:

$$\nabla \cdot \widehat{\boldsymbol{\sigma}}^s + \omega^2\tilde{\rho}\mathbf{u} + \tilde{\gamma}\nabla p = 0$$

$$\nabla^2 p + \omega^2\frac{\tilde{\rho}_{22}}{R}p - \omega^2\frac{\tilde{\rho}_{22}}{\phi^2}\tilde{\gamma}\,\nabla\cdot\mathbf{u} = 0$$



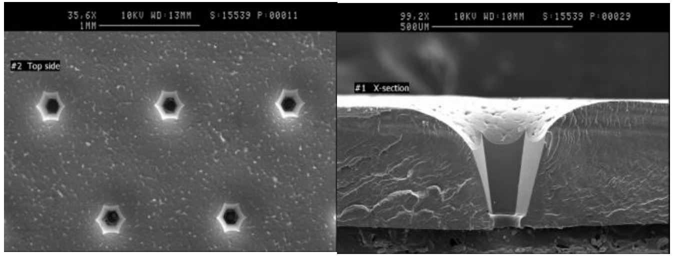
Membranes

- Tensioned Membrane (Arenas et al., 2023):

$$T\nabla^2 w + \Delta p = \rho_s \frac{\partial^2 w}{\partial t^2} \xrightarrow{\text{Spatial average 1D impedance}} Z_m = j\omega\rho_s\left[1 - \frac{2}{k_m a}\frac{J_1(k_m a)}{J_0(k_m a)}\right]^{-1}$$

$$k_m = \omega\sqrt{\rho_s/T}$$

- Micro-Perforated Membrane (Yoo et al., 2008)



Front side and cross-section of a micro-perforated membrane (Yoo et al., 2008)

$$\Delta p - R_t\Omega\frac{\partial\left(d_f - d_s\right)}{\partial t} = \rho_f h\frac{\partial^2 d_f}{\partial t^2}$$

$$\Delta p + R_t\frac{\Omega}{1-\Omega}\frac{\partial\left(d_f - d_s\right)}{\partial t} = D\nabla^4 d_s - T\nabla^2 d_s + \rho_s\frac{\partial^2 d_s}{\partial t^2}$$

Flexural stiffness **Tension** **Surface density**

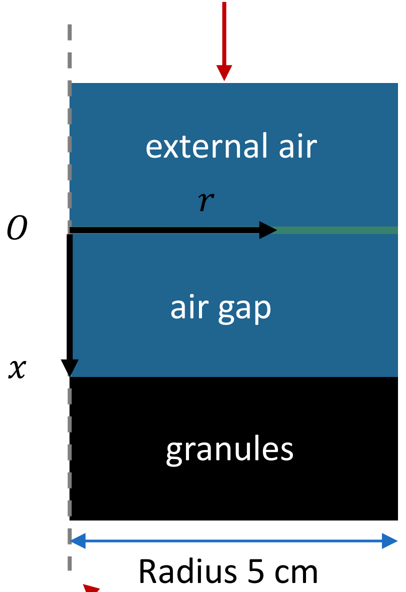
(Maa, 1998):

$$Z = j\omega\rho_0 h\left[1 - \frac{2}{g\sqrt{-j}}\frac{J_1\left(g\sqrt{-j}\right)}{J_0\left(g\sqrt{-j}\right)}\right]^{-1}, g = r\sqrt{\frac{\rho_0\omega}{\eta}}$$

The displacement of a perforated membrane can be described as follows (Yoo et al., 2008): $w = \Omega d_f + (1-\Omega)d_s$

2-D Finite Difference Simulation

Uniform sound pressure input



membrane

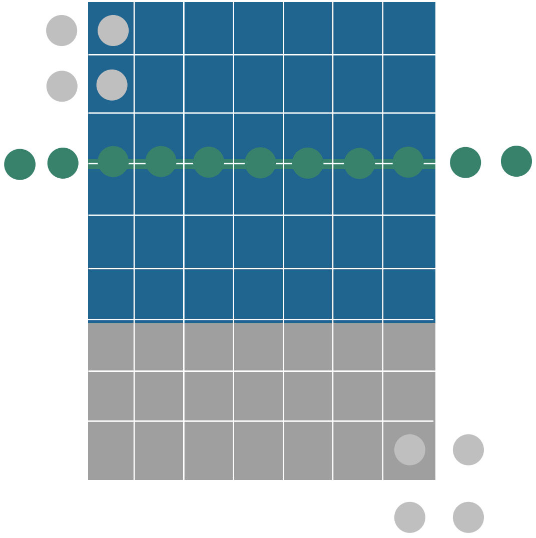
Simply supported for membrane with flexural stiffness and tension

Radius 5 cm

Fixed solid phase

Axisymmetric axis

2D five point stencil

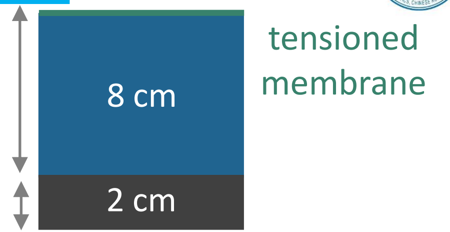


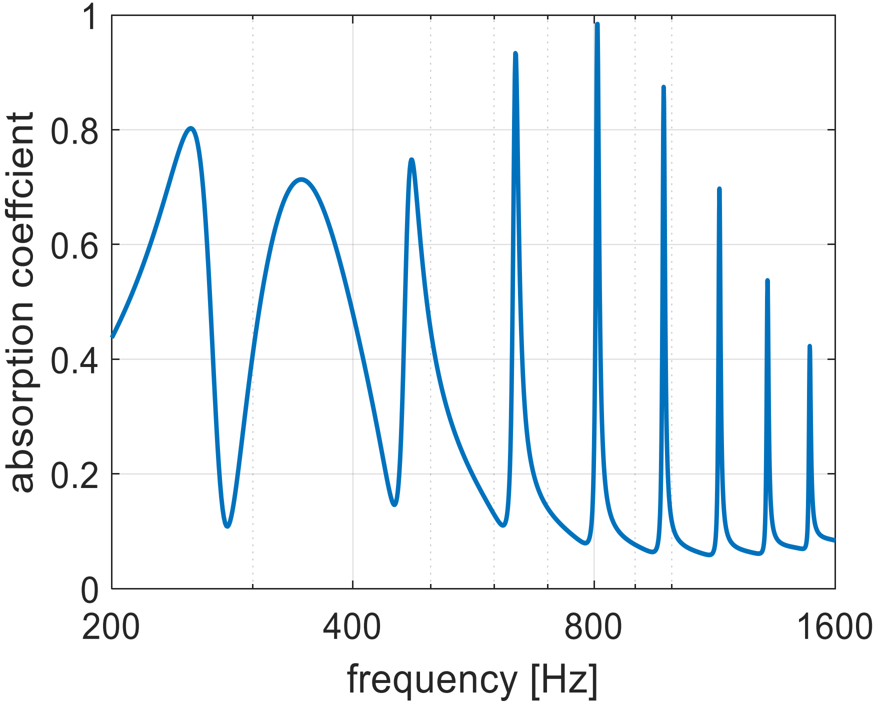
PART 03

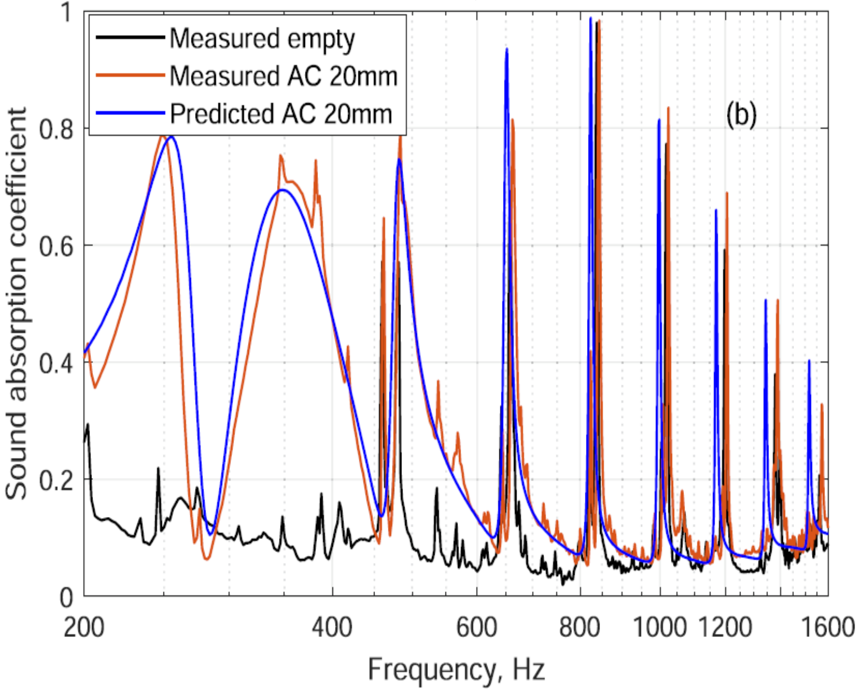
Simulation Result

Membrane + Particle 1-D Simulation

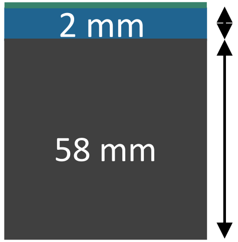
- **Good match between measurements and 1D predictions with large air gap**



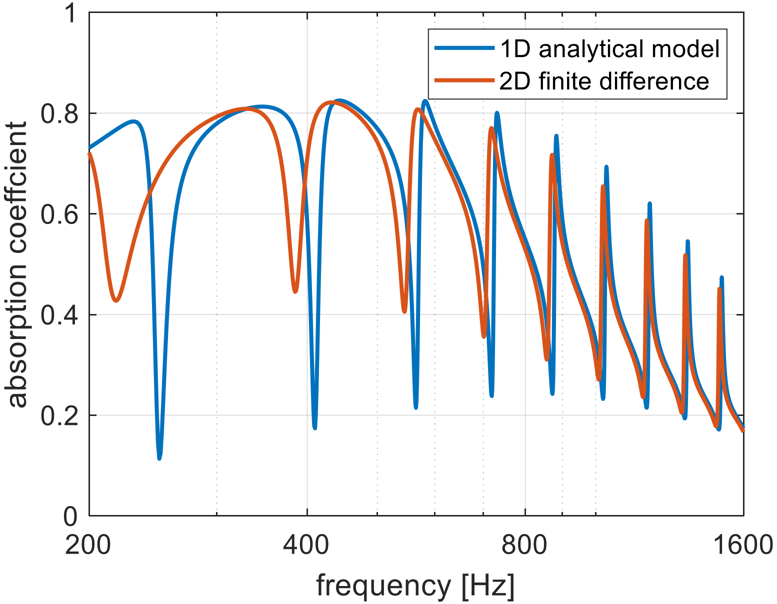


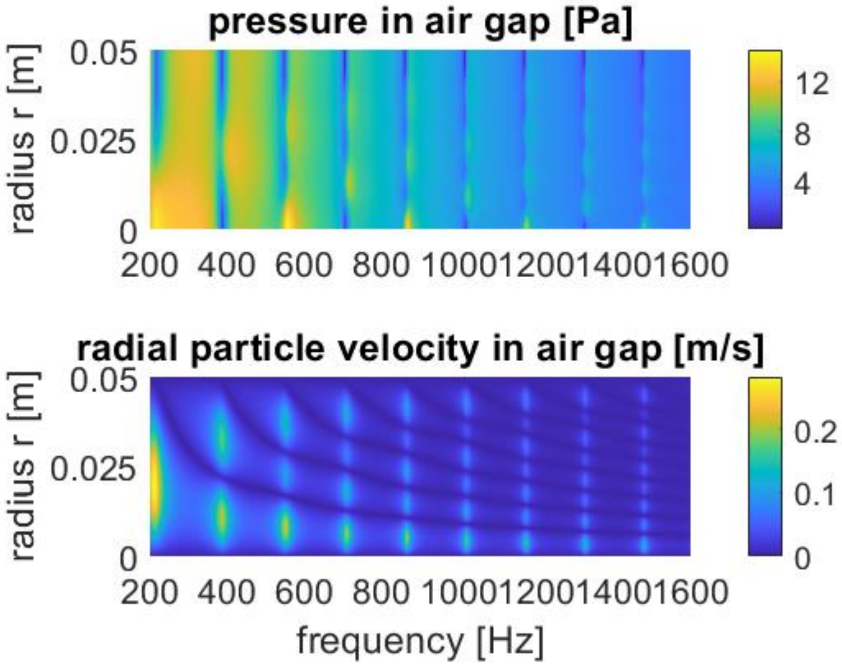


2-D Simulation Study



Tensioned membrane:
$\rho_s = 0.265\ \mathrm{kg/m^3}$
$T = 62 \times (1 + 0.005j)\ \mathrm{N/m}$
58 mm GAC + 2 mm air gap



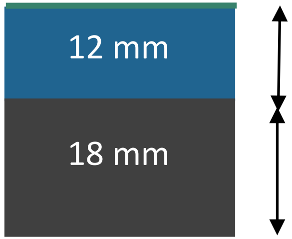


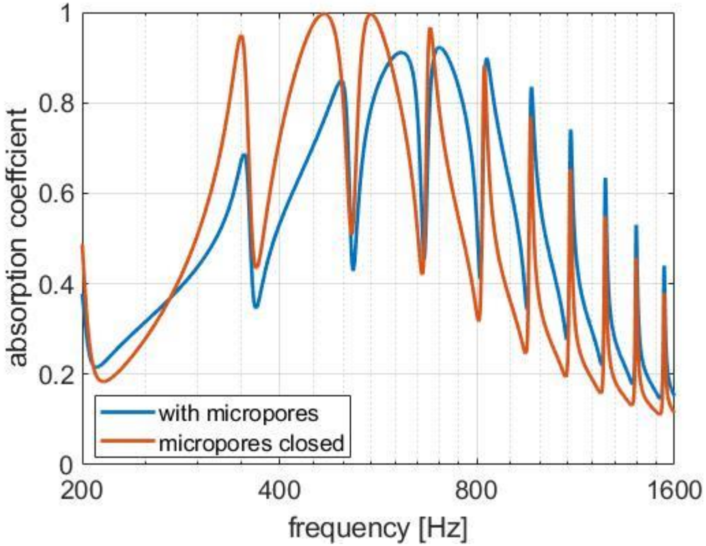
- **It is necessary to consider the radial modes**
- **Radial fluid motion in granule stack dissipates energy: i.e., "Nearfield damping"**

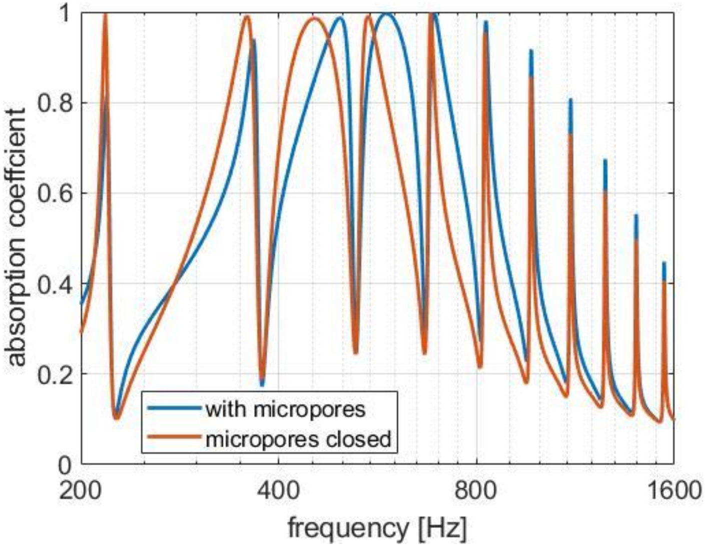
2-D Simulation Study

Tensioned membrane:
$\rho_s = 0.265\ \mathrm{kg/m^3}$
$T = 55.2 \times (1 + 0.005j)\ \mathrm{N/m}$
18 mm GAC + 2 mm air gap

Tensioned membrane:
$\rho_s = 0.265\ \mathrm{kg/m^3}$
$T = 55.2 \times (1 + 0.005j)\ \mathrm{N/m}$
18 mm GAC + 12 mm air gap







- **More significant impact of GAC pores with narrow gap**

2-D Simulation Study

Perforated membrane: tension + flexural stiffness + finite flow resistance

$\rho_s = 0.912\ \mathrm{kg/m^3}$

$h = 0.8\ \mathrm{mm}$

$T = 50.04 \times (1 + 0.005j)\ \mathrm{N/m}$

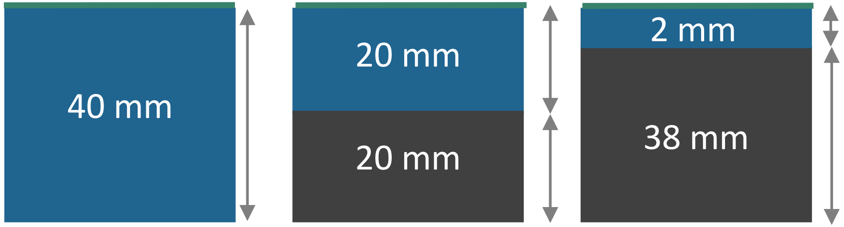
$\Omega = 0.02$

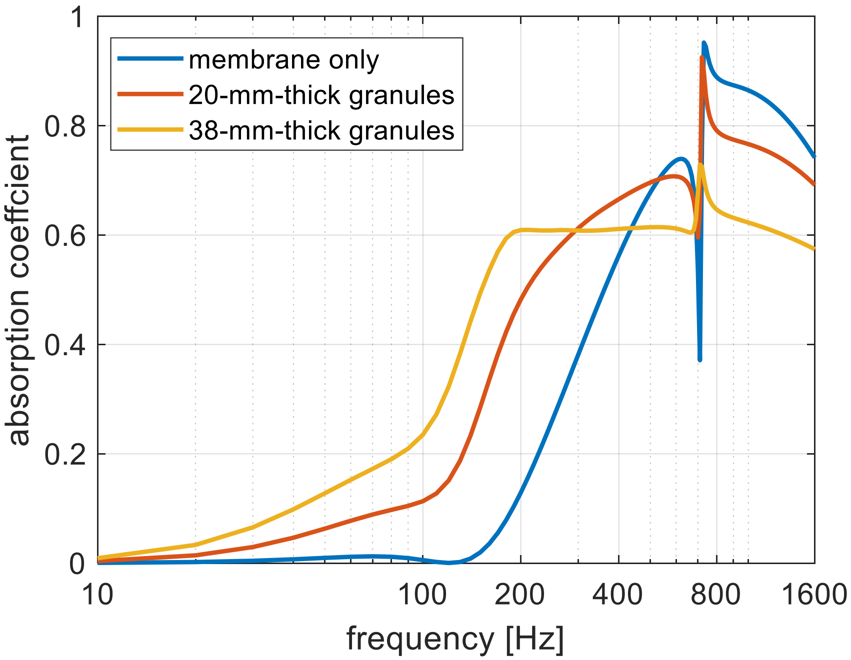
$r = 0.15\ \mathrm{mm}$

$D = 0.1313 + 0.0007j\ \mathrm{Pa \cdot m^3}$

$R_{t0} = 1.03 \times 10^3\ \mathrm{rayl}$

Total cavity depth: 40 mm





- **GAC contributes to higher low frequency absorption**
- **The simulation of narrow gap predicts obvious increase at low frequency**

PART 04

Conclusion

Conclusion

A 2DFD model was built to simulate the performance of absorbers consisting of membrane and porous granules:

1. **The comparison between the 2DFD simulation and 1D analytical model prediction shows that it is necessary to consider the modal response in the radial direction when separation between membrane and granules is small**

2. **The simulation shows potential advantages of bringing the granules close to the membrane, where the interaction of the membrane nearfield and the granule stack may be exploited to increase energy dissipation and to reduce reflection**

3. **The simulation of the absorber with a perforated membrane shows more dramatic improvement at low frequencies when GAC is added to the absorber**

In the future, it is of interest to experimentally validate the predictions of the 2DFD model, and find theoretical explanation of the difference with the 1D model prediction, especially when the air gap is narrow

References

1. Yuan-Wu Jiang, Dan-Ping Xu, Joong-Hak Kwon, Zhi-Xiong Jiang, Jun-Hyung Kim, and Sang-Moon Hwang. Analysis and application of zeolite in microspeaker box. *Journal of Mechanical Science and Technology*, 33(8):3679–3683, 2019.
2. Yutong Xue, Esmeralda Sanchez-Torres, Bhisham Sharma, and J. Stuart Bolton. Tunable sound packages consisting of granular aerogels and fibrous media. *Noise Control Engineering Journal*, 70(5):406–415, 2022.
3. Rodolfo Venegas and Olga Umnova. Influence of sorption on sound propagation in granular activated carbon. *The Journal of the Acoustical Society of America*, 140(2):755–766, 2016.
4. Julian R Wright. The virtual loudspeaker cabinet. *Journal of the Audio Engineering Society*, 51(4):244–247, 2003.
5. R Venegas. Microstructure influence on acoustical properties of multiscale porous materials. *PhD thesis, Ph. D. dissertation*, University of Salford, UK, 2011.
6. Fouad Bechwati. Acoustics of activated carbon. *PhD thesis, Ph. D. dissertation*, University of Salford, 2008.
7. Jorge P Arenas, Veronica Marin, and Rodolfo Venegas. Membrane sound absorber with a granular activated carbon infill. *Applied Acoustics*, 202:109180, 2023.
8. Zhuang Mo, Guochenhao Song, J. Stuart Bolton, Seungkyu Lee, Tongyang Shi, and Yongbeom Seo. Predicting acoustic performance of high surface area particle stacks with a poro-elastic model. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, volume 263, pages 3523–3529. Institute of Noise Control Engineering, 2021.
9. Zhuang Mo, Guochenhao Song, and J. Stuart Bolton. A finite difference approach for predicting acoustic behavior of the poro-elastic particle stacks. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, volume 264, pages 350–361. Institute of Noise Control Engineering, 2022.
10. Andrew J. Matchett and Takeshi Yanagida. Elastic modulus of powder beds—the effects of wall friction: a model compared to experimental data. *Powder Technology*, 137(3):148–158, 2003.
11. T. Tsuruha, Y. Yamada, M. Otani, and Y. Takano. Effect of casing on sound absorption characteristics of fine spherical granular material. *The Journal of the Acoustical Society of America*, 147(5):3418–3428, 2020.
12. Jacques Duran. *Sands, Powders, and Grains: An Introduction to the Physics of Granular Materials*. Springer, 2000.
13. AC Fischer-Cripps. The Hertzian contact surface. *Journal of Materials Science*, 34(1):129–137, 1999.
14. Maurice A Biot. Theory of propagation of elastic waves in a fluid-saturated porous solid. i. low-frequency range. ii. higher frequency range. *The Journal of the Acoustical Society of America*, 28(2):168–191, 1956.
15. Noureddine Atalla, Raymond Panneton, and Patricia Debergue. A mixed displacement-pressure formulation for poroelastic materials. *The Journal of the Acoustical Society of America*, 104(3):1444–1452, 1998.
16. F.-X Bécot and L. Jaouen. An alternative Biot's formulation for dissipative porous media with skeleton deformation. *The Journal of the Acoustical Society of America*, 134(6):4801–4807, 2013.
17. Jean-François Allard and Noureddine Atalla. *Propagation of Sound in Porous Media: Modelling Sound Absorbing Materials, second edition*. John Wiley & Sons, 2009.
18. Taewook Yoo, J. Stuart Bolton, Jonathan Alexander, and David Slama. Absorption from finite-size microperforated panels at arbitrary incidence angles. In *Proceedings of the 15th International Congress on Sound and Vibration (ICSV15)*, pages 2879–2886. International Institute of Acoustics & Vibration, 2008.
19. Dah-You Maa. Potential of microperforated panel absorber. *The Journal of the Acoustical Society of America*, 104(5):2861–2866, 1998.
20. Marsh, H., & Reinoso, F. R. (2006). *Activated carbon*. Elsevier, 2006.

Thanks for your attention!