Acoustic metamaterials and their potential in the built environment

MEETING MATERIALS 5 APRIL 2022

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Building Acoustics, TU/e

Building Acoustics Group
http://building-acoustics.net

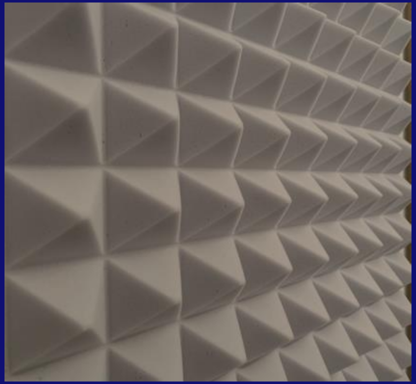
Department of the Built Environment
Eindhoven University of Technology (TU/e)

Group head: prof.dr.ir. Maarten Hornikx

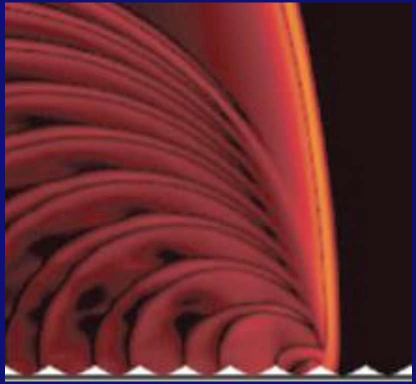
- 1 Full professor
- 2 Assistant professors
- 3 Postdocs
- 8 PhD students
- 2 University researchers

Building Acoustics, TU/e

Virtual acoustics



Acoustic materials



Environmental acoustics

Effects of the sound environment on humans

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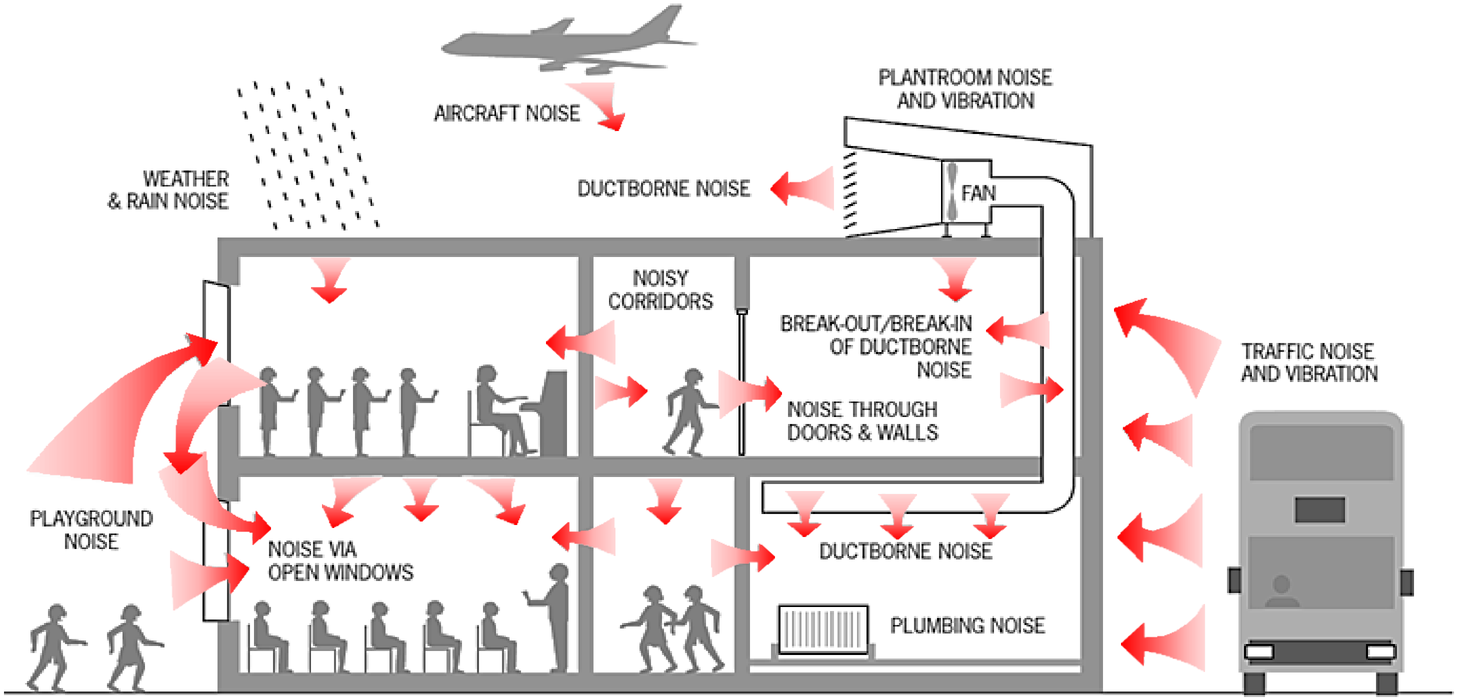
Noise around us



http://www.steelconstruction.info/Acoustics_regulations

Noise pollution, a silent killer

140 million Europeans
(60% of Europeans living in urban areas)
are exposed to harmful level of noise

Impact on health

6.5 million severe sleep disorders, 48,000 new cases of heart disease, and 12,000 premature deaths per year

Living with high sleep disturbance due to noise for 57 years
= equivalent in terms of DALYs to dying 1 year earlier than expected.

European Environmental Agency, 2020, Environmental noise in Europe — 2020, EEA Report No 22/2019.
World Health Organization, Burden of disease from environmental noise. Quantification of healthy life years lost in Europe, Bonn, 2011.

Acoustic materials

Acoustima®

Dekustik

Ecophon®

ReFocus

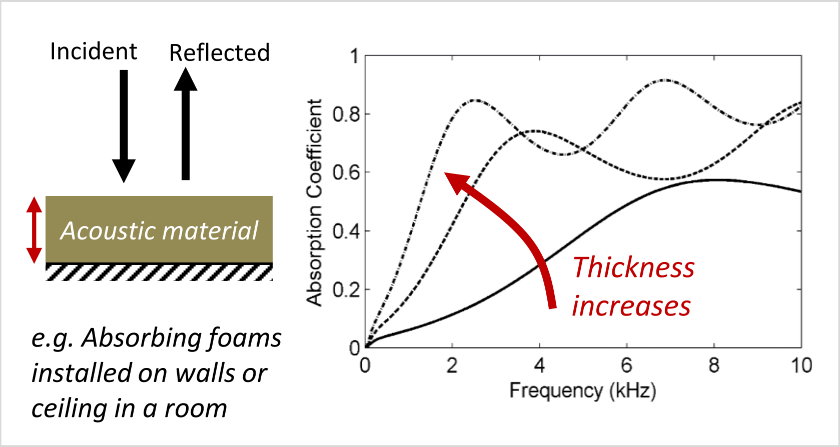
KOHLHAUER SCORSA®

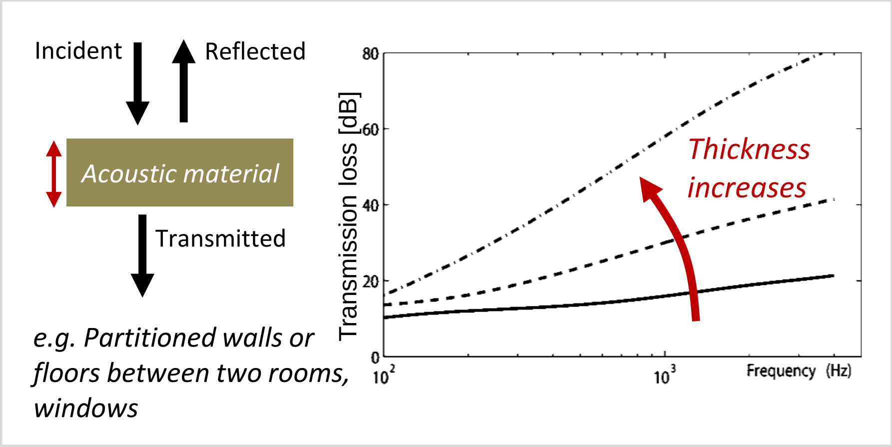
KINETICS®

Isolmat

IKEA (ODDLAUG)

Challenges in acoustic materials





- For effective noise reduction
  → Requires acoustic materials occupying large space
- Lack of low-frequency performance

→ Innovative acoustic material design

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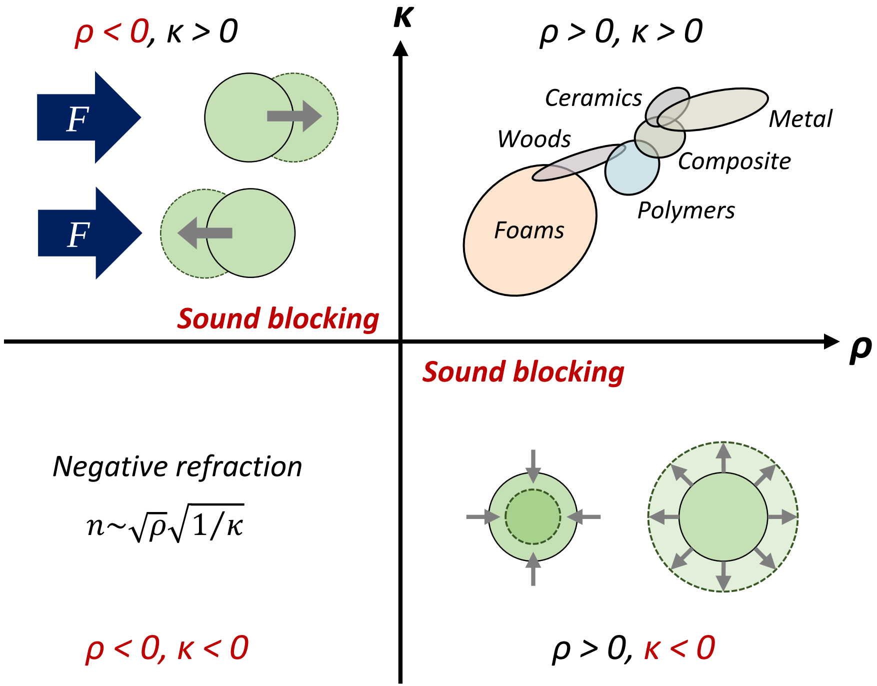
Acoustic metamaterials

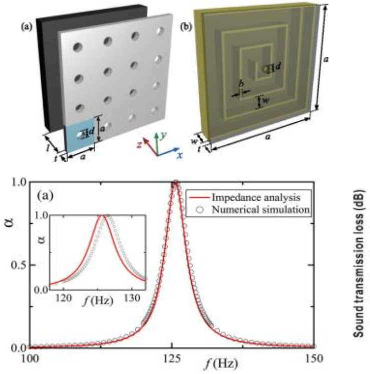


Modified from original figure in M. Haberman and M. Guild, *Phys. Today* 69(6), 2016

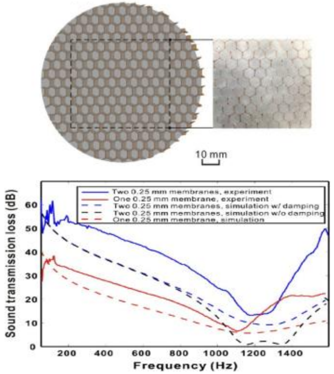
- ✓ Expanded the limits of the achievable acoustical properties of a material
  - *ρ = 0 and/or κ = 0*
  - *ρ = ∞ and/or κ = ∞*
  - Extreme anisotropy
  - Slow sound ($c_{material} < c_{air}$)
  - ***→ Control sound waves at will***
- ✓ A synthetic composite material with a structure such that it exhibits properties not usually found in natural materials
- ✓ ***Thin & high-functional acoustic materials***

Acoustic metamaterials

Noise reduction (Sound absorption & insulation)

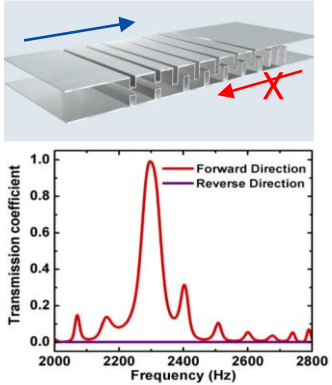


Y. Li *et al.*, *Appl. Phys. Lett.* 108, 063502, 2016



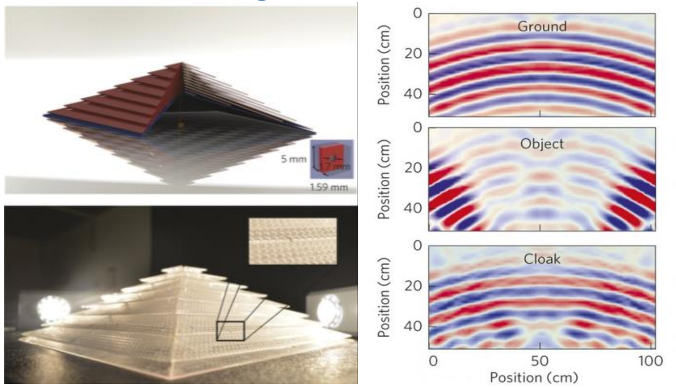
N. Sui *et al.*, *Appl. Phys. Lett.* 106, 171905, 2015

Acoustic diode



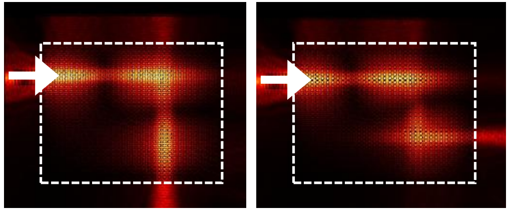
et al., *Phys. Rev. Appl.*, 13, 041001, 2020

Acoustic cloaking



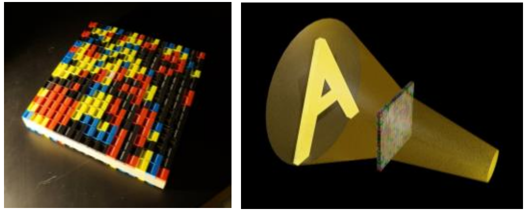
L. Zigoneanu *et al.*, *Nat. Mat.* 13, 351-355, 2014

Wave path guiding



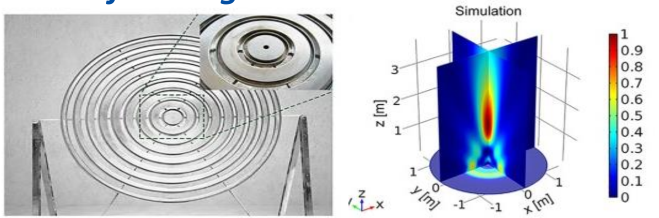
J. H. Oh *et al.*, *Appl. Phys. Lett.* 99, 083505, 2011

Acoustic holography



Y. Xie *et al.*, *Sci. Rep.* 6, 35437, 2016

Sound focusing



Y. Li *et al.*, *Sci. Rep.*, 4, 6830, 2014

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Remaining challenges

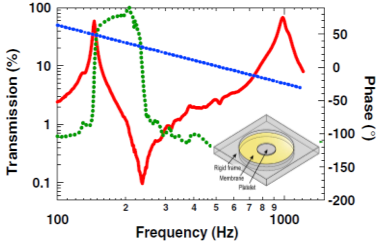
I Broadband performance

II Lack of consideration in finite dimension

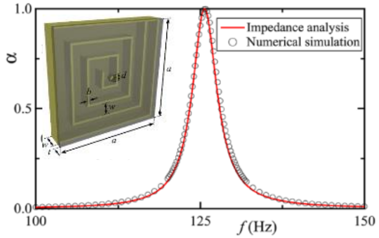
III Manufacturing

I. Broadband performance

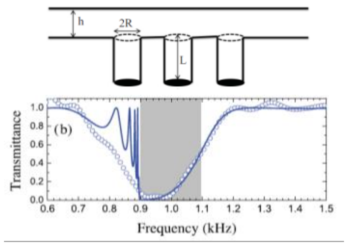
Low-frequency, narrow-band performance



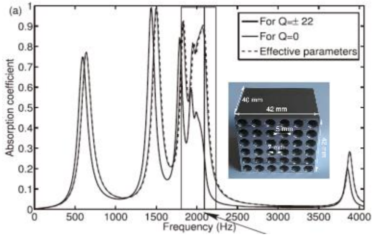
Z. Yang et al., *Phys. Rev. Lett.* (2008)



Li et al., *Appl. Phys. Lett.* (2016)



V. M. García-Chocano et al., *Phys. Rev. B* (2012)



Groby et al., *J. Appl. Phys.* (2015)

Broadband performance

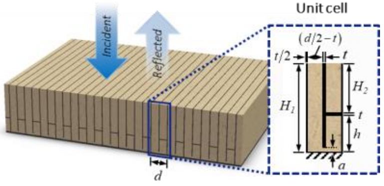
Low frequency

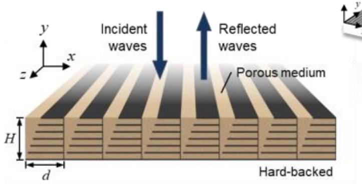
Wave-path elongation
Slow wave

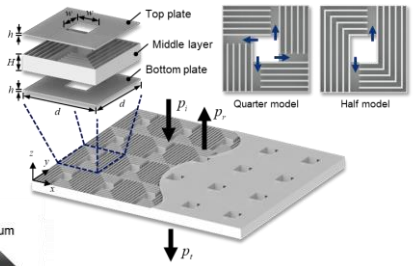
&

Mid-high frequency

Acoustic dissipation
Multiple resonances



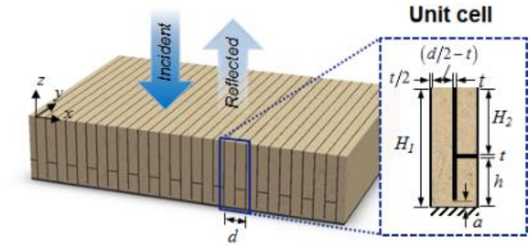


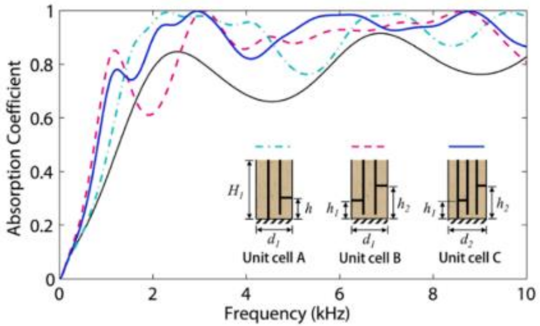


I. Broadband performance

Supported by SAMSUNG
Samsung Research Funding Center

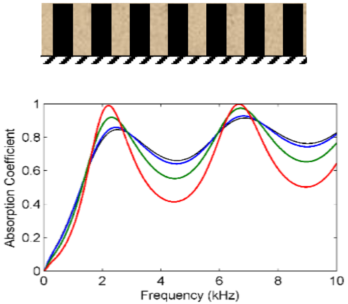
Metaporous layer with tuned thickness resonances





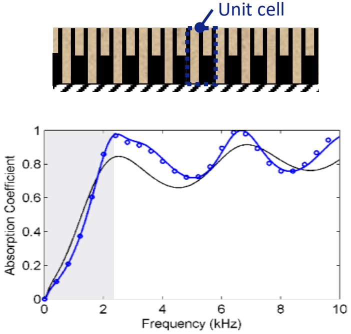
Broadband sound absorption is achieved by a combination of three different mechanisms

Periodic rigid partitioning of a porous layer



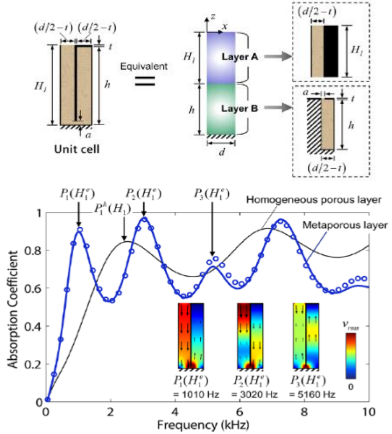
- Impedance matching at thickness resonance frequencies → High absorption peaks

Multiple thickness resonances



- Overall absorption enhancement by multiple thickness resonances
- Below the 1st resonance frequency?

Elongation of wave propagation path

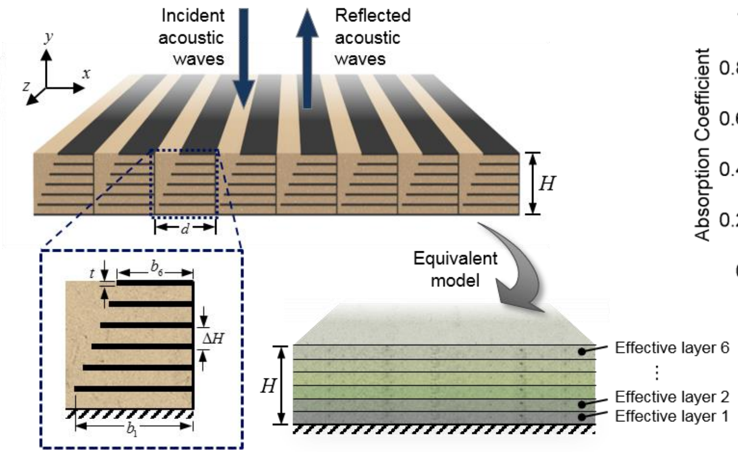


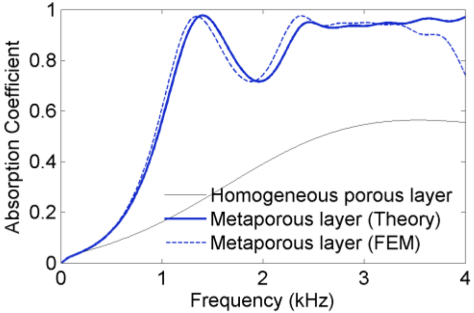
J. Yang, J.S. Lee, and Y.Y. Kim, *J. Appl. Phys.* **117**, 174903, 2015.

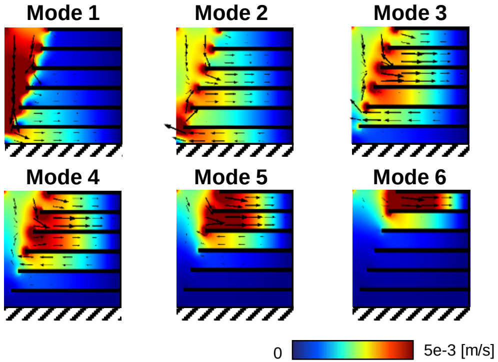
I. Broadband performance

Supported by SAMSUNG
Samsung Research Funding Center

Metaporous layer with multiple slow waves



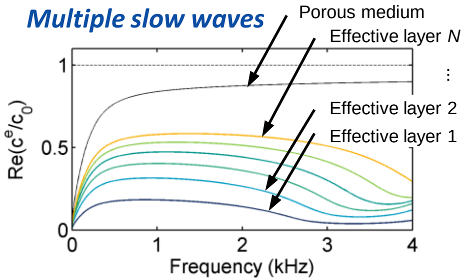


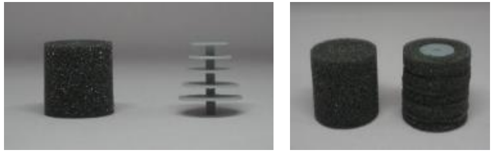


Effective parameters

$$\rho_i^{e} = \rho/(1-\phi_i),$$

$$\kappa_i^{e} = \frac{\kappa}{(1-\phi_i)\cdot[1+\eta\tan(kb_i^{t})/k(d-b_i^{t})]},$$





Samples for impedance-tube measurement

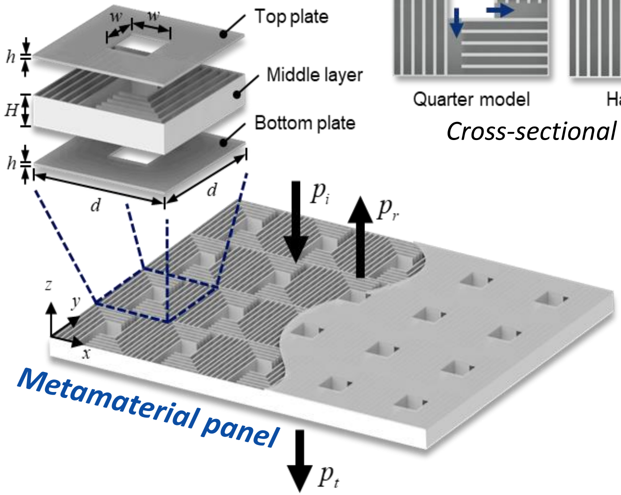
J. Yang, J.S. Lee, and Y.Y. Kim, *J. Phys. D: Appl. Phys.* **50**, 015301, 2017.

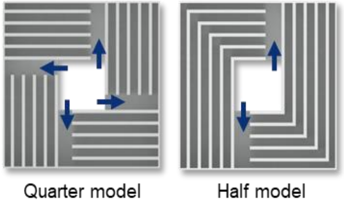
I. Broadband performance

Supported by SAMSUNG
Samsung Research Funding Center

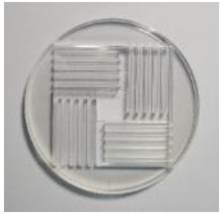
Ventilating but soundproof metamaterial panel

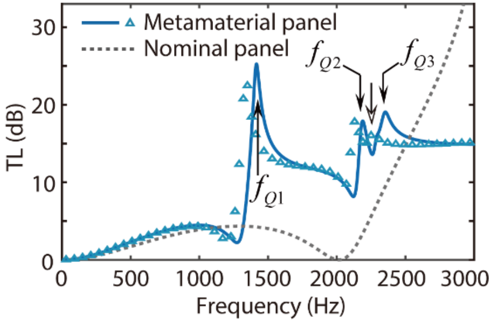
Designed unit cell

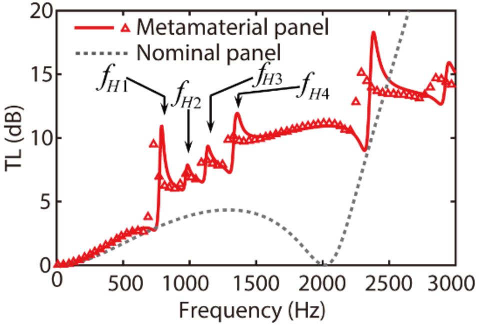




Cross-sectional view

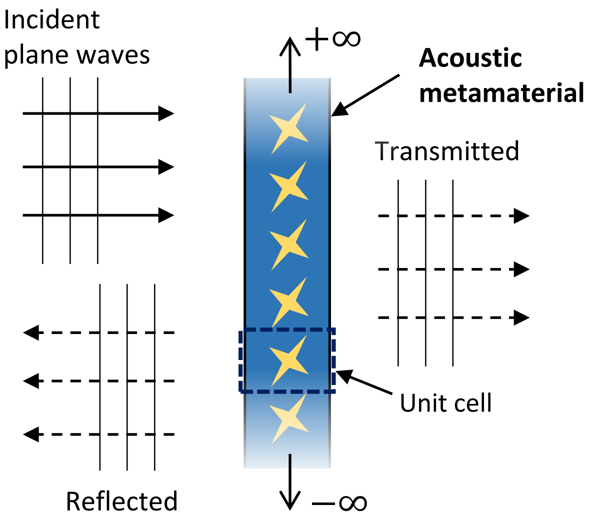




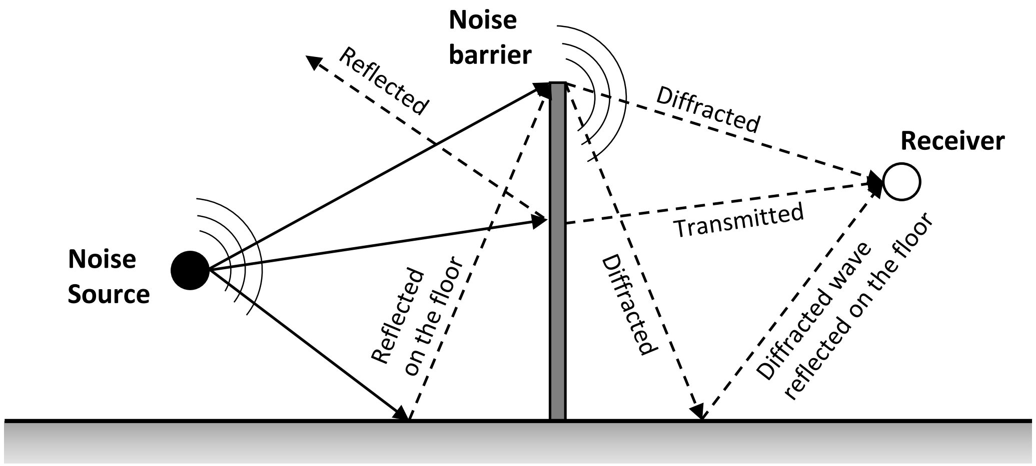


J. Yang, *et al.*, *Appl. Phys. Lett.*, **112**(9), 091901, 2018.

II. Finite dimension



Metamaterial analysis approach

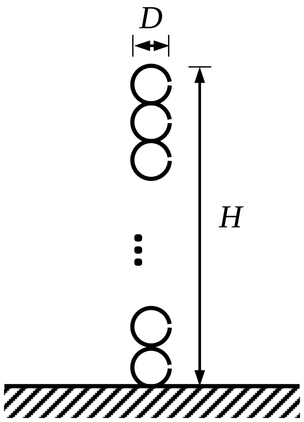


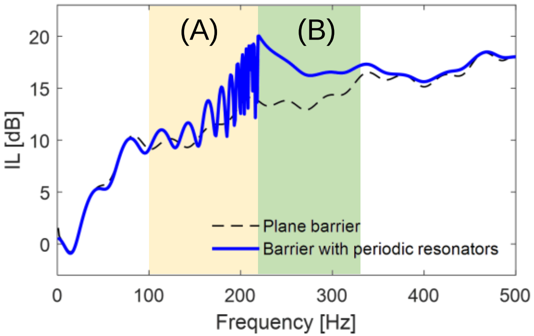
Real scenario

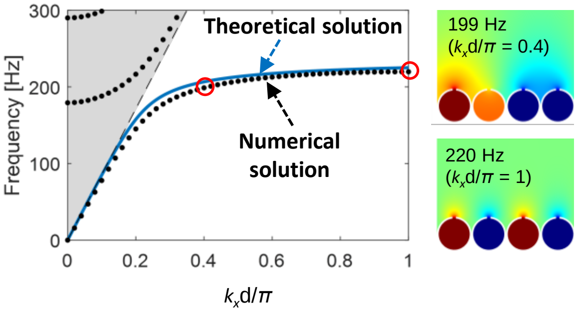
II. Finite dimension

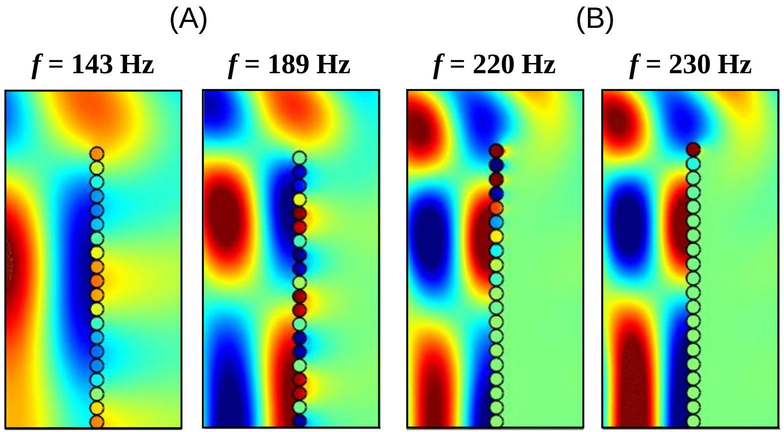
Supported by EuroTechPostdoc Programme
Excellence in Science and Technology

Periodicity-induced noise reduction effects by barriers







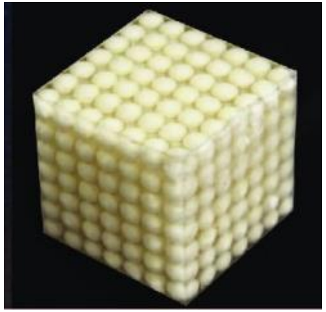


Propagating guided modes (surface waves) + Standing waves

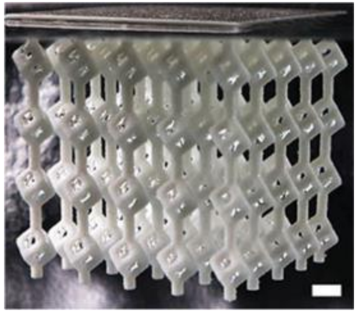
Evanescent waves around resonance frequency (resonance gap)

J. Yang and M. Hornikx, manuscript in preparation.

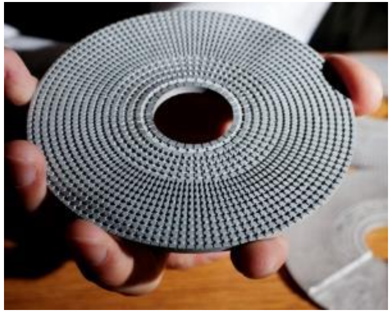
III. Manufacturing



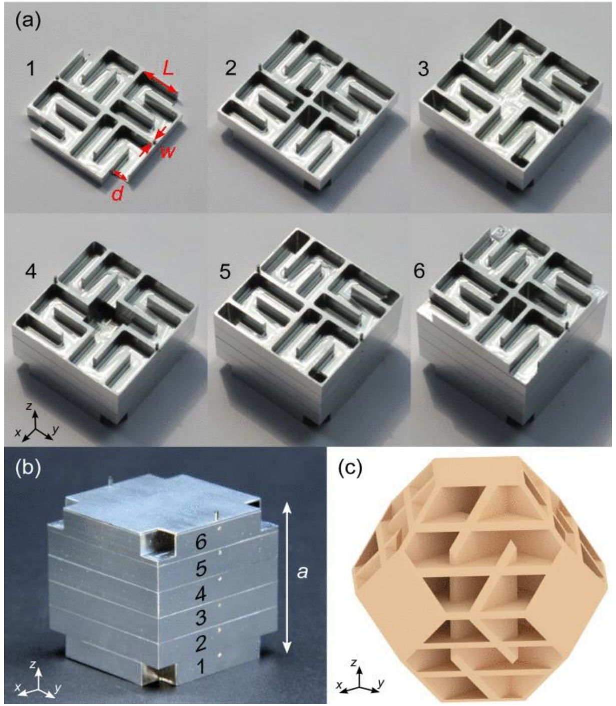
G. Ma and P. Sheng, *Sci. Adv.* 2(2), 2016



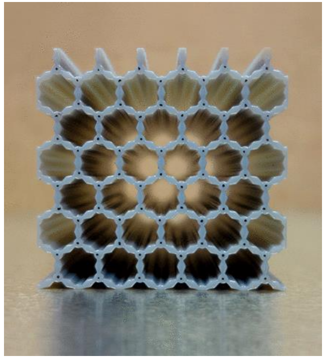
Z. Cai *et al.*, *Adv. Funct. Mater.* 29(51), 2019



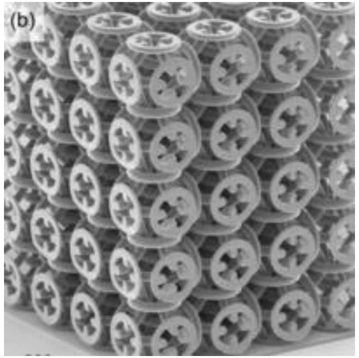
S. Zhang *et al.*, *Phys. Rev. Lett.* 106, 024301, 2011



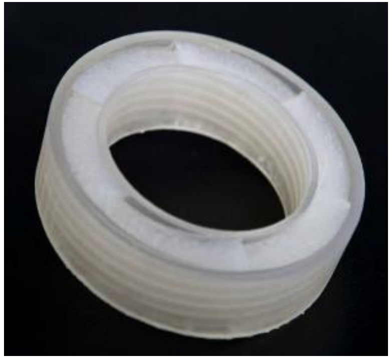
T. Frenzel *et al.*, *Appl. Phys. Lett.* 103, 061907, 2013



M. Haberman and M. Guild, *Phys. Today* 69(6), 2016



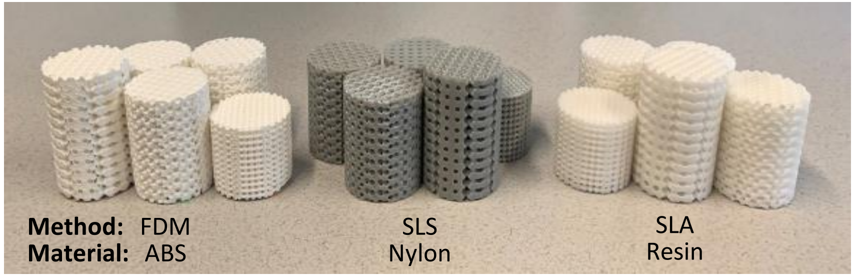
C. Kern *et al.*, *Phys. Rev. Lett.* 118, 016601, 2017



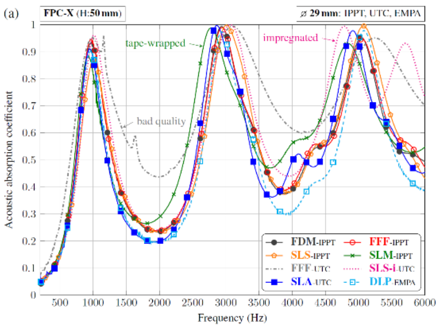
R. Ghaffrivardavagh *et al.*, *Phys. Rev. B.* 99, 024302, 2019

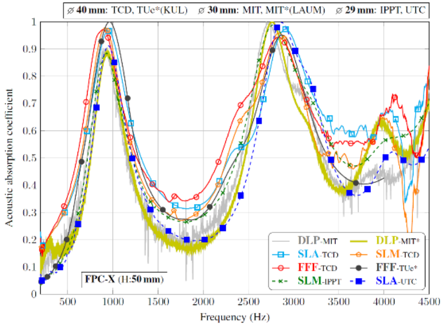
III. Manufacturing

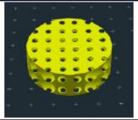
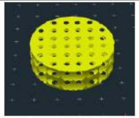
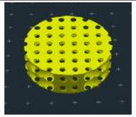
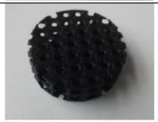
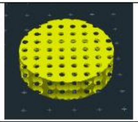
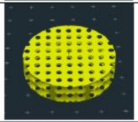
3D-printed acoustic materials (porous structures)



FDM: Fused Deposition Modeling, SLS: Selective Laser Sintering, SLA: Stereo-lithography



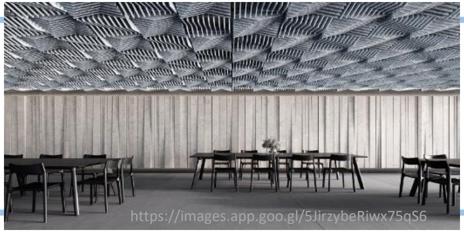


Name	Geometry	3D modelling	Printed sample
Layer 1	Pore size: 7 mm Height: 13 mm Diameter model: 39.5 mm Porosity: 15.55%		
Layer 2	Pore size: 6.5 mm Height: 12 mm Diameter model: 39.5 mm Porosity: 17.43%		
Layer 3	Pore size: 6 mm Height: 11 mm Diameter model: 39.5 mm Porosity: 18.33%		
Layer 4	Pore size: 5.5 mm Height: 10 mm Diameter model: 39.5 mm Porosity: 19.65%		
Layer 5	Pore size: 5 mm Height: 9 mm Diameter model: 39.5 mm Porosity: 21.15%		

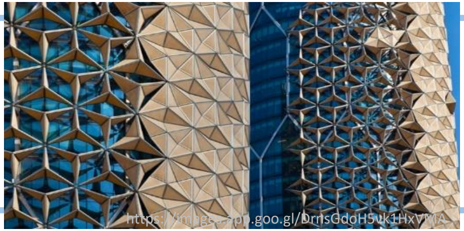
T. Zielinski *et al.*, *Additive Manufacturing* **36**, 101564, 2020.

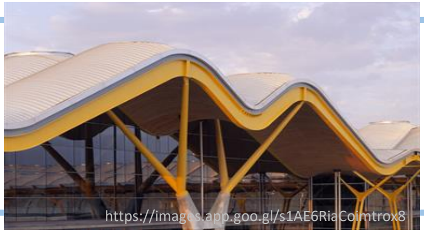
Applications

INDOOR SPACES

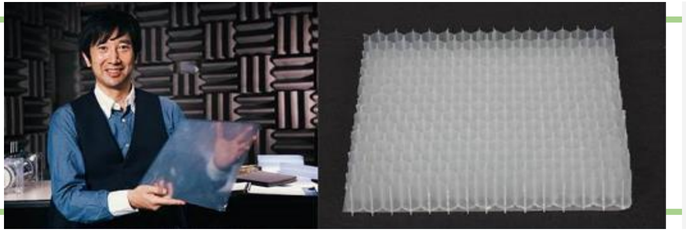


OUTDOOR SPACES





BESIDES BUILDING APPLICATIONS



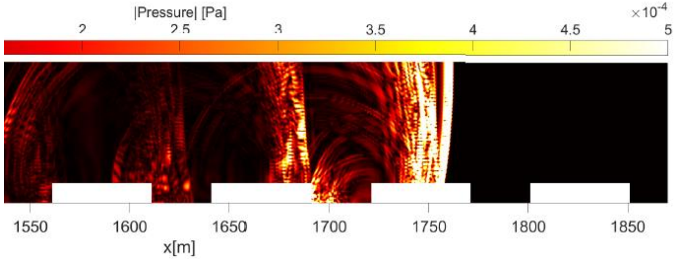
Acoustic metamaterial by Nissan, CES 2020

Acoustic metamaterial by KEF, 2020

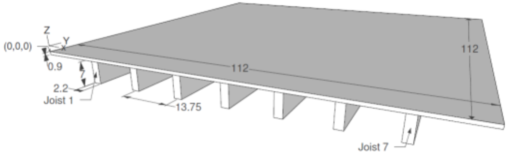
TU/e

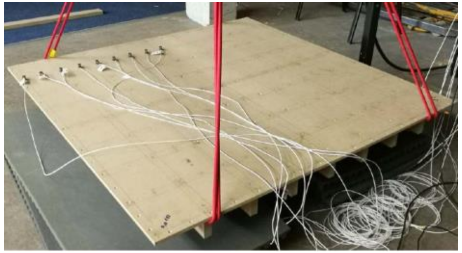
Applications

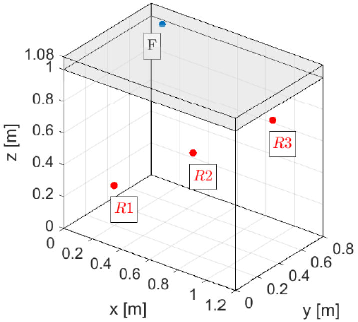
Time-domain modelling of noise intervention scenarios in an airport environment

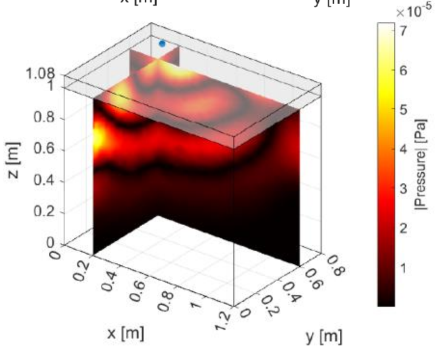


Time-domain modeling of structural vibration & acoustic-structure interactions









I. Sihar, R. Pagan Munoz, G. Fernandes, J. Yang, and M. Hornikx, manuscript in preparation.
I. Sihar, J. Yang, and M. Hornikx, manuscript in preparation.

Thank you for your attention!