Sorrento SAPEM'23 常熟

Symposium on the Acoustics of Poro-Elastic Materials

Acoustical Properties of Anisotropic Spinodoid Structures

Yutong (Tony) Xue[1], Brittany Wojciechowski[2], Bhisham Sharma[3] and J. Stuart Bolton[4]

[1]WanDong Medical, Midea Group, Beijing, China

[2]Department of Aerospace Engineering, Wichita State University, Wichita, KS, U.S.A

[3]Department of Mechanical Engineering-Engineering Mechanics, Michigan Technological University, Houghton, MI, U.S.A

[4]Ray W. Herrick Laboratories, Purdue University, West Lafayette, IN, U.S.A

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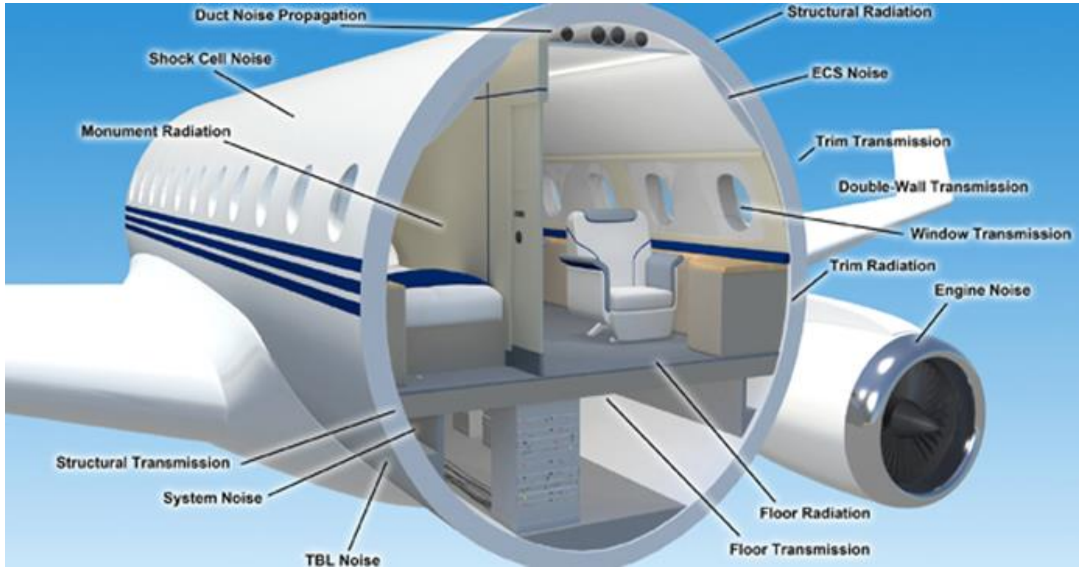
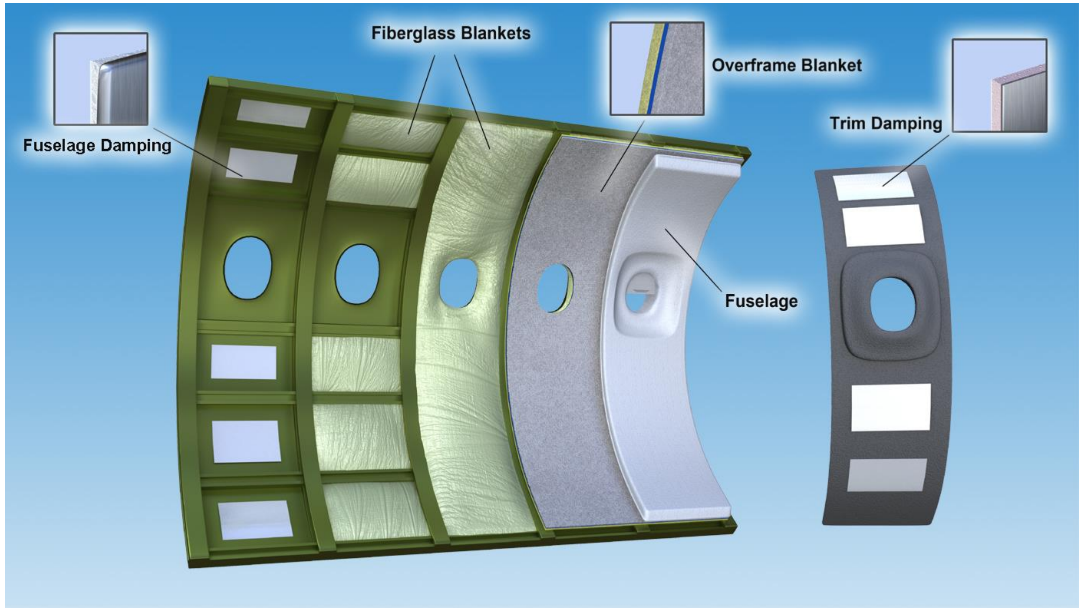
Challenge: Noise Control = “Constrained” Acoustics

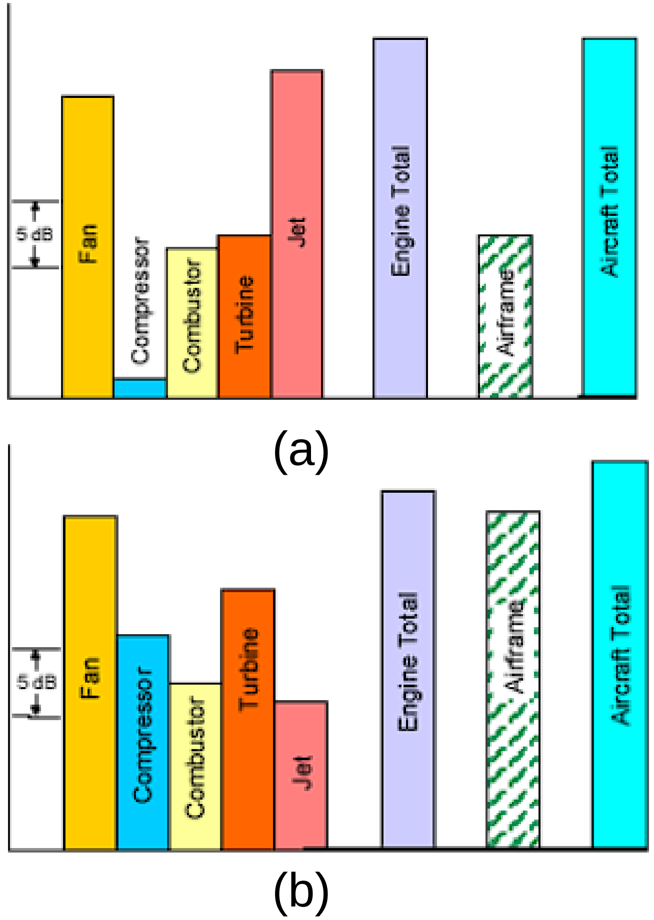
What’s important about noise control materials?

- Cost
- Safety
- Weight
- Volume
- Recyclability
- Structural Performance
- Thermal Performance
- …
- Acoustical Performance

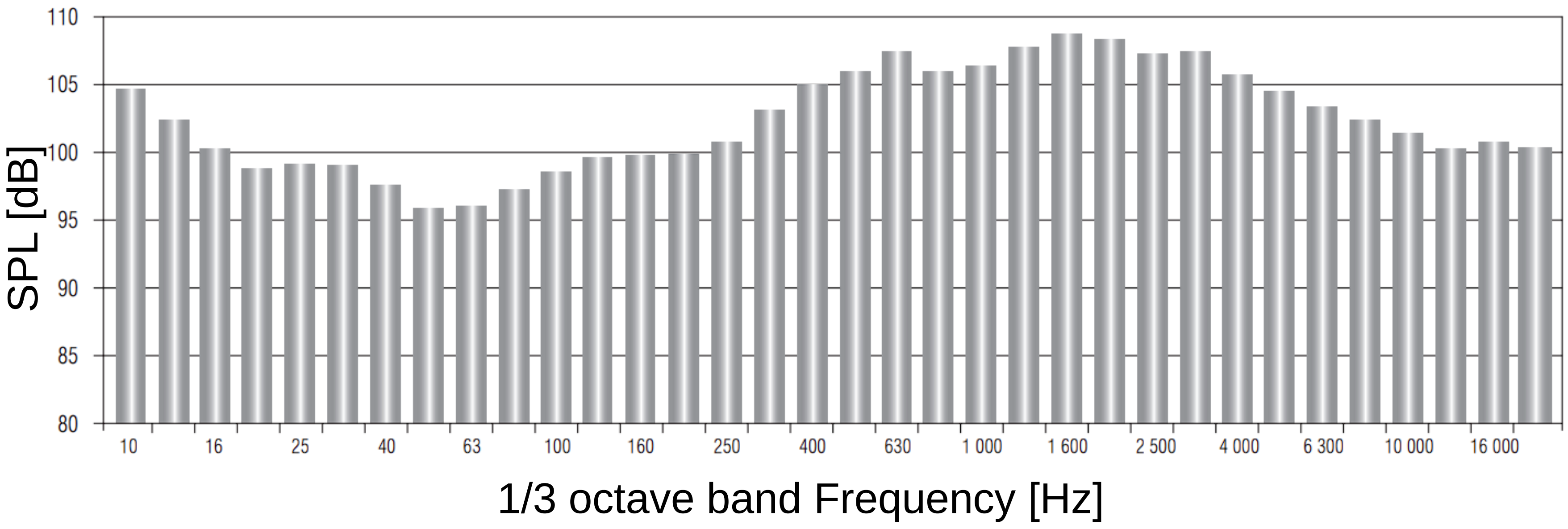




Jet Noise: Broadband Dominant

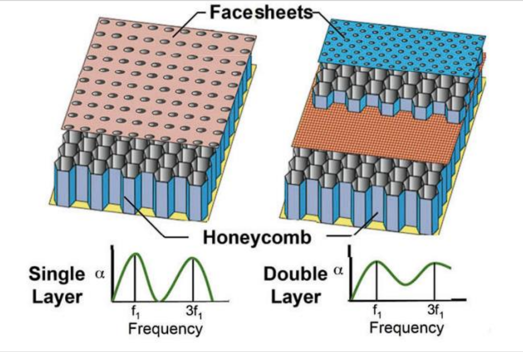
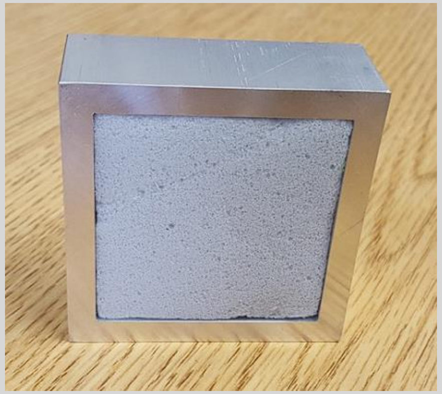
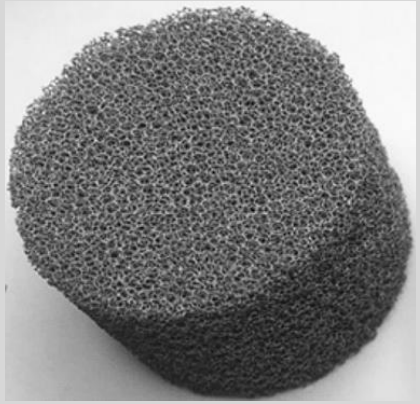
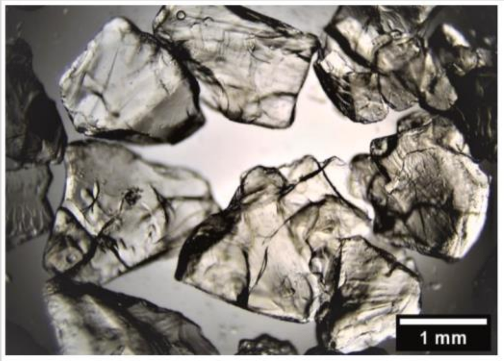


Aircraft noise source on (a) take-off and (b) approach [1]



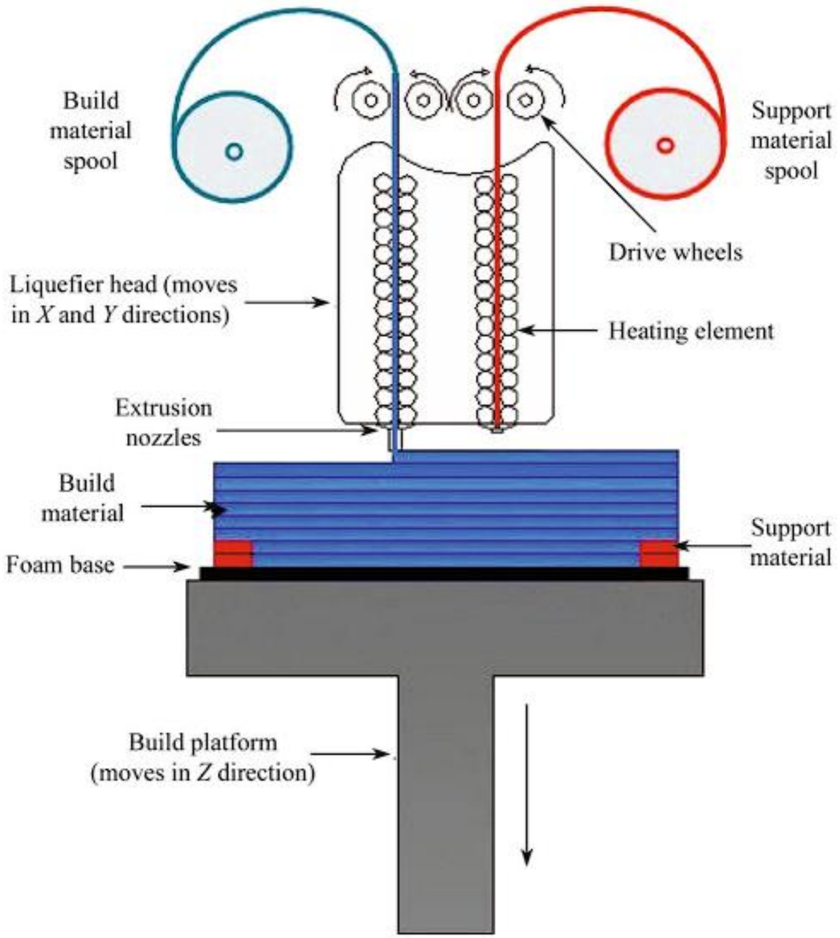
Noise generated by a modern jet engine [2]

Acoustic Treatments: A Comparison

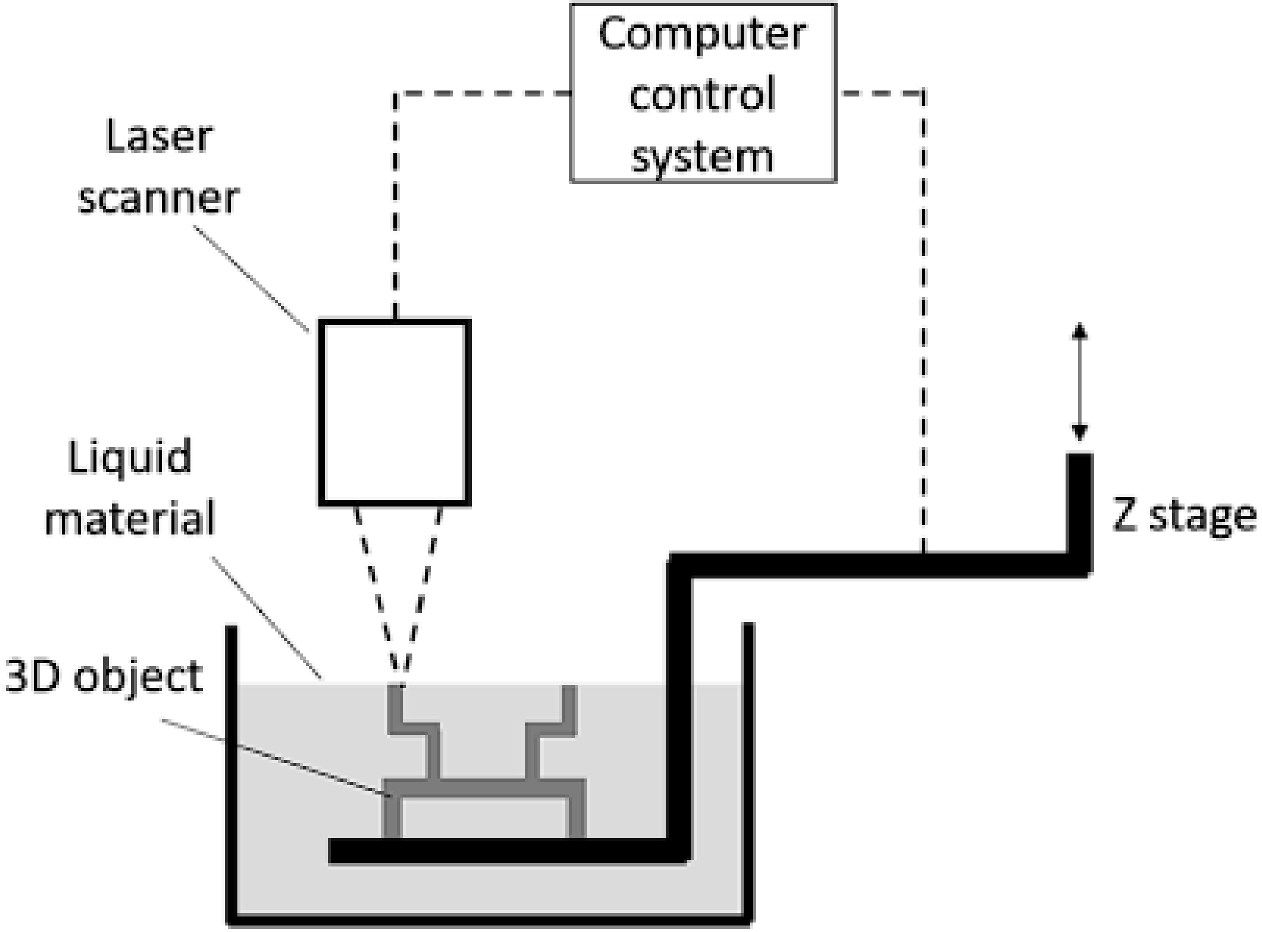
Material	Honeycomb acoustic liners [3]	Insulation foams [4-5] (melamine, polyimide)	Metal foams [6] (Aluminum)	Granular materials (aerogel [7], beads [8])
Demonstration				
Advantages	Structural Tunable	Lightweight; Broadband absorption	Stiffer than normal foams; Lightweight; Broadband absorption	Low frequency noise control; Lightweight
Disadvantages	Tonal over broadband noise control feature	Structural Limited tunability	Limited tunability	Difficult to contain

→ Motivation: development of tunable and broadband acoustical treatments

Additive Manufacturing

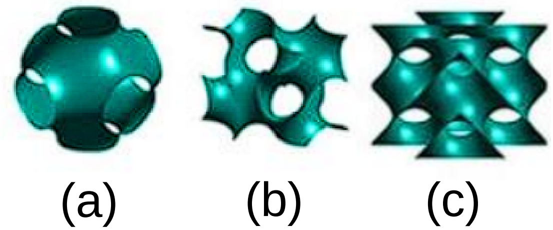


Schematic of fused deposition modeling (FDM) printer [9]

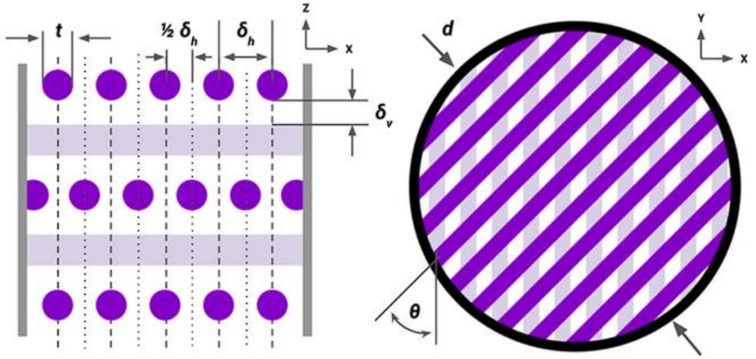


Schematic of stereolithographic (SLA) printer [10]

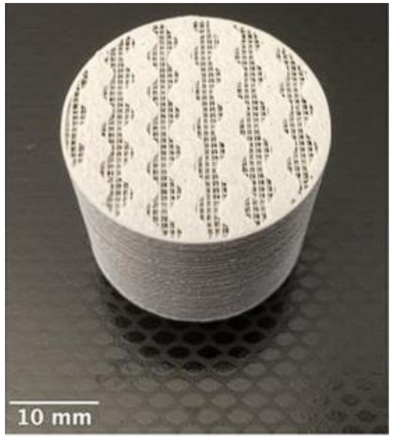
3D Printed Acoustic Treatments with Periodic Microstructure



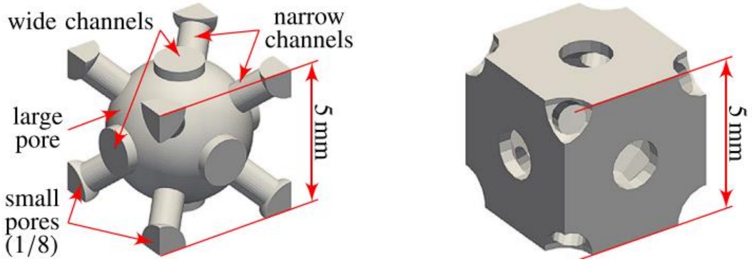
Triply periodic minimal surfaces (TPMS) with (a) primitive, (b) gyroid, and (c) diamond unit cells [11]



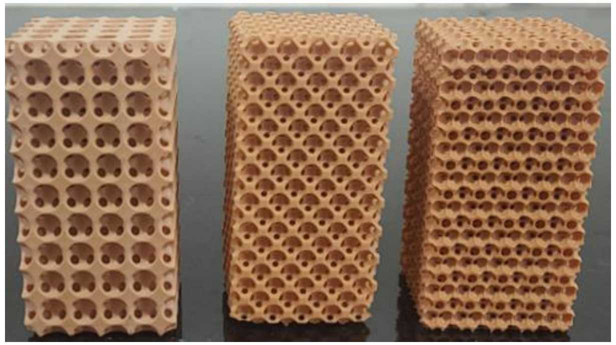
Schematic of fiber sample [12]



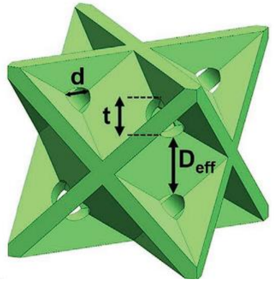
Gyroid with overlaid fibers [13]



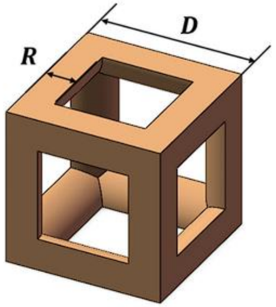
'Sphere subtracting' sample (a) pore network and (b) unit cell [15]



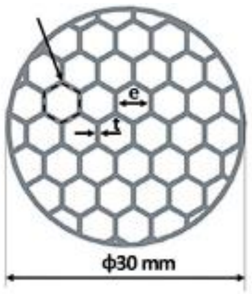
Truss Structures [14]



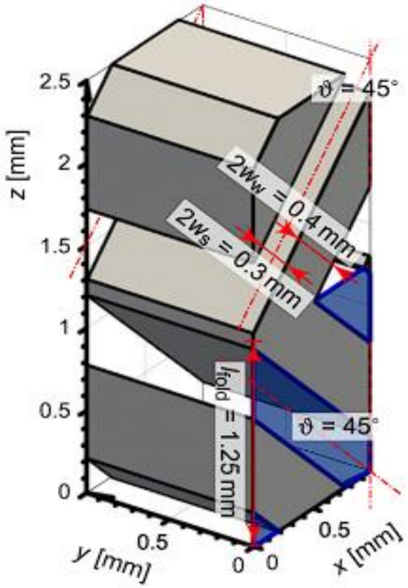
Fluorite-plate unit cell [16]



Body-centered cubic unit cell [17]



Narrow tube array with hexagonal unit cell [18]



Folded slit unit cell [19]

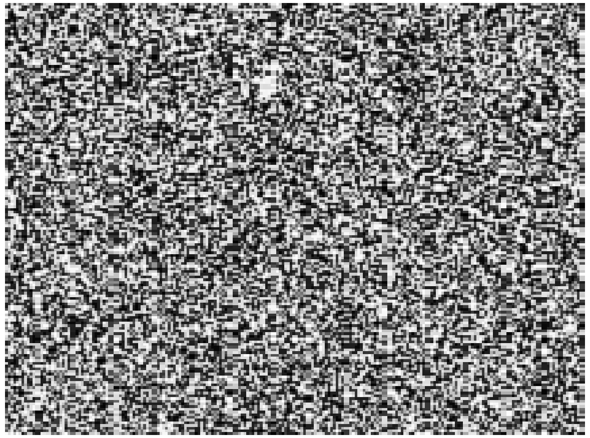
3D Printed Spinodoid with Non-Periodic Microstructure

Advantage of non-periodic microstructure

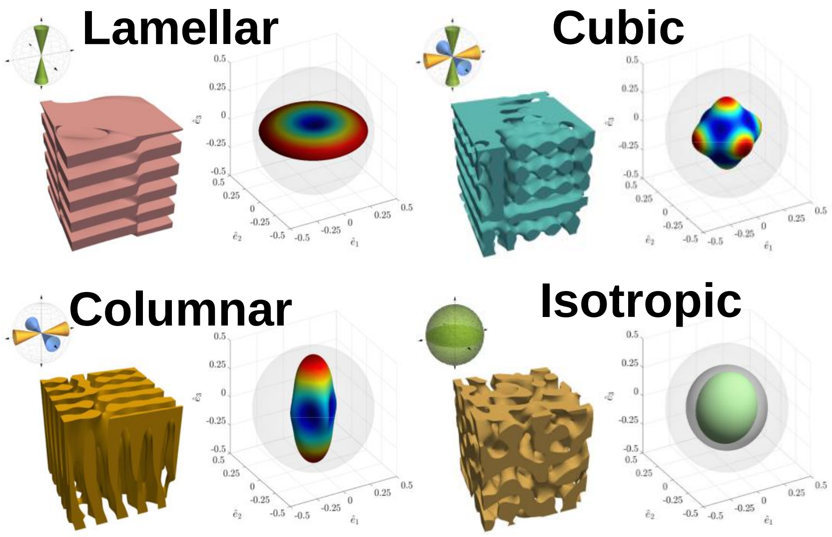
- Optimization options
- Easy to generate gradients and anisotropy

Introducing our target material

- **Spinodoid Structure, with potentials in acoustical plus structural applications**

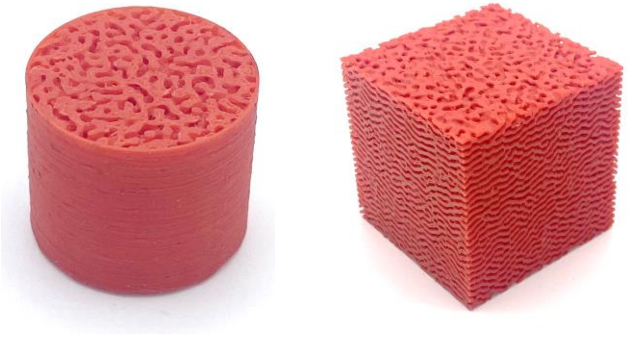


Physics: Spinodal Decomposition [20-21], e.g. oil & water separating out



Modeling: Gaussian Random Fields [22]

Bed Temperature: 60°C
Nozzle Diameter: 0.4 mm
Layer height: 0.1 mm

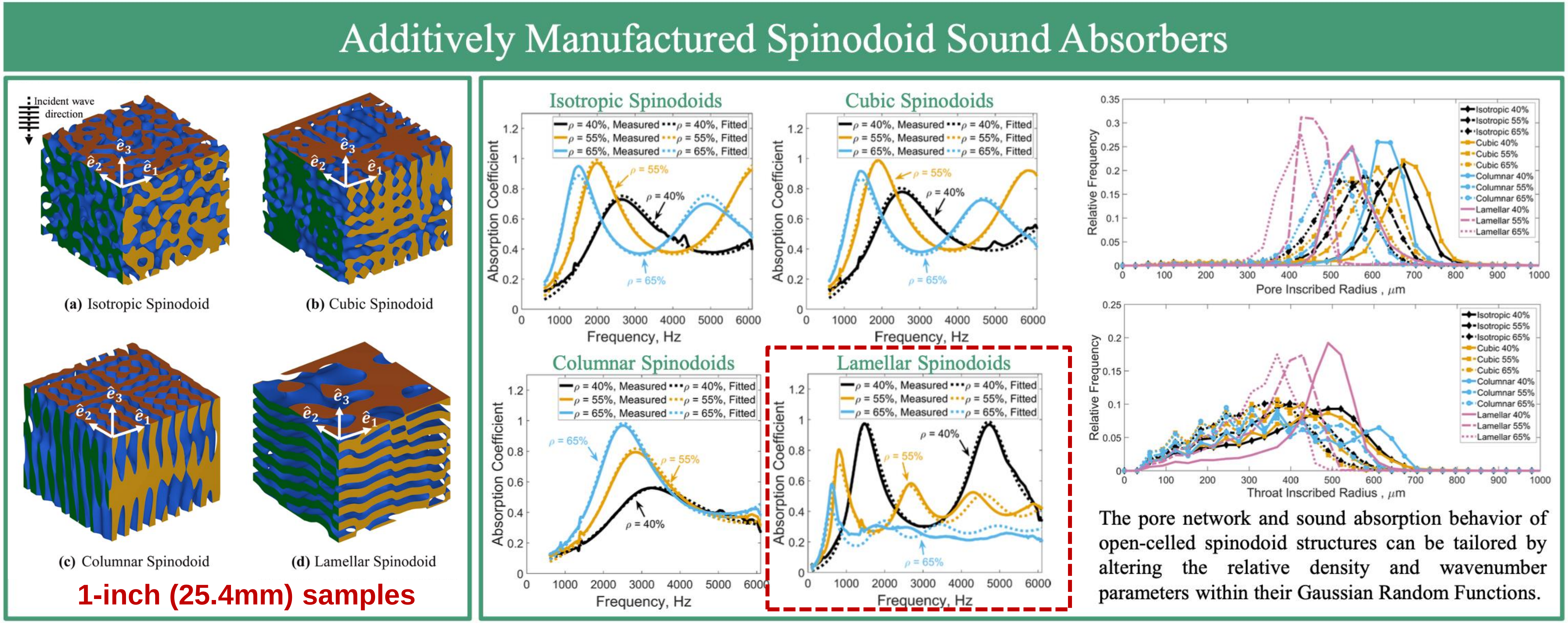


Fabrication: 3D Printing

Super-position of waves:

$$GRF = \sum_{i=1}^{N} \sqrt{\frac{2}{\boldsymbol{N}}} \cos\left[\left(\boldsymbol{x}_{\boldsymbol{w},\boldsymbol{i}} \cdot \boldsymbol{x}\right)\boldsymbol{\beta} + \varphi_{w,i}\right] \quad \varphi_b = \sqrt{2}erf^{-1}(2\boldsymbol{\rho} - 1)$$

Acoustics of 3D Printed Spinodoid [23]



Measured normal incidence sound absorption coefficient

Johnson-Champoux-Allard (JCA) Model [24-25]

Inversely-Characterized Bulk Properties

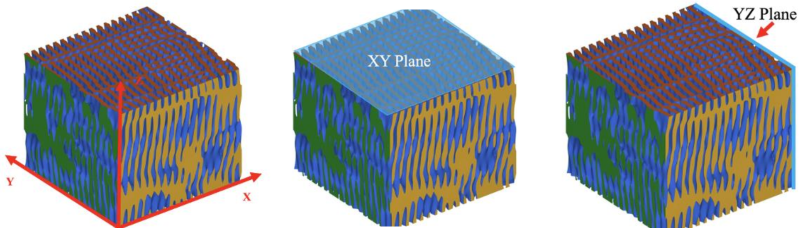
Johnson-Champoux-Allard (JCA) Model [24-25]

Fitted sound absorption coefficient given characterized bulk properties

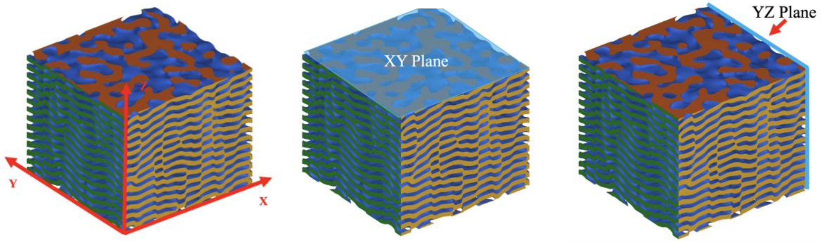
Anisotropic 3D Printed Spinodoid

- Sound absorption measured at both XY- and YZ-plane-incidence

Columnar

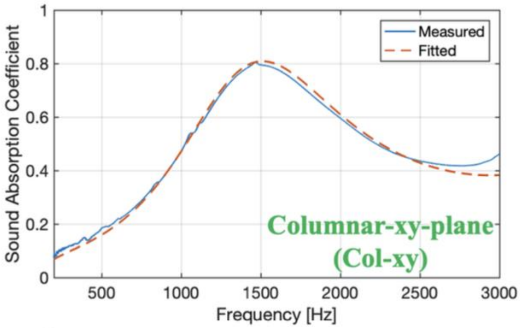


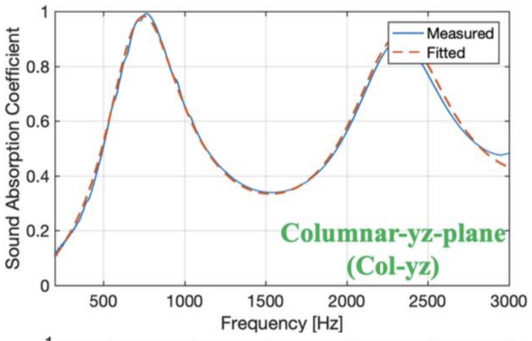
Lamellar

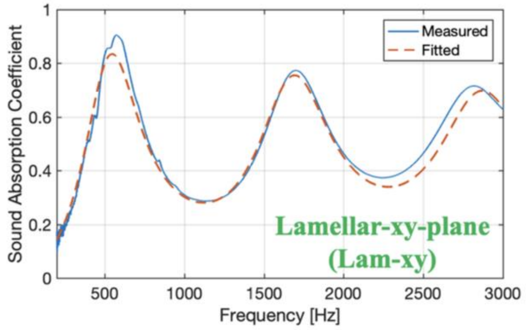


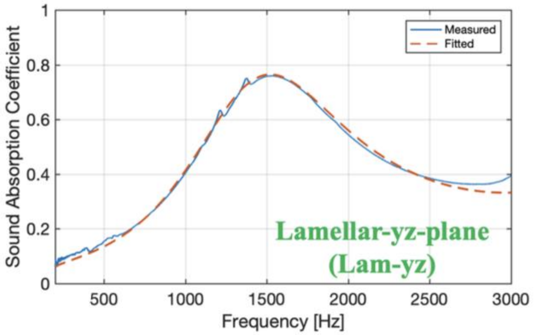
2-inch (50.8mm) samples

JCA Model [24-25] Fitted









Inversely-Characterized

- **Inversely-characterized properties are very different** in the XY-normal and YZ-normal directions, and are consistent with physical expectations:

	$\rho_b (\mathrm{kg/m})^3$	ϕ	σ (Rayls/m MKS)	α_∞	Λ	Λ'
Col-xy	592	0.53	2912	1.1	323	358
Col-yz	592	0.53	14312	3.9	279	311
Lam-xy	613	0.51	30450	7.3	281	402
Lam-yz	613	0.51	2419	1.1	379	421

Note

- Bulk density, ρ_b (calculated from sample weight and volume)
- Porosity, $\phi = 1 - \rho_b/\rho_s$, ρ_s = 1.25 g/cm^3 is the PLA density

Transversely-Isotropic Poro-elastic (TIP) Model

Bulk density, ρ_b
Porosity, ϕ

XY-normal direction
Flow resistivity, σ_{xy}
Tortuosity, $\alpha_{\infty xy}$
VCL, Λ_{xy}
TCL, Λ'_{xy}
Young's Modulus, E_{1xy}
Poisson's ratio, ν_{xy}
Loss factor, η_{mxy}

YZ-normal direction
Flow resistivity, σ_{yz}
Tortuosity, $\alpha_{\infty yz}$
VCL, Λ_{yz}
TCL, Λ'_{yz}
Young's Modulus, E_{1yz}
Poisson's ratio, ν_{yz}
Loss factor, η_{myz}

- **JCA Model [24-25] applied for both directions**
- **Biot Theory [26] adapted for transversely isotropic poro-elastic media [27]**

XY-normal direction
Bulk modulus, K_{fxy}
Mass coupling factors:
ρ_{111}, ρ_{121}, ρ_{221}

YZ-normal direction
Bulk modulus, K_{fyz}
Mass coupling factors:
ρ_{112}, ρ_{122}, ρ_{222}

Fluid coefficients:
M, Q, R
Elastic coefficients:
A, C, F, N, G

- **Solution of characteristic dispersion equation**
- **Solution of amplitude coefficients of field variables**

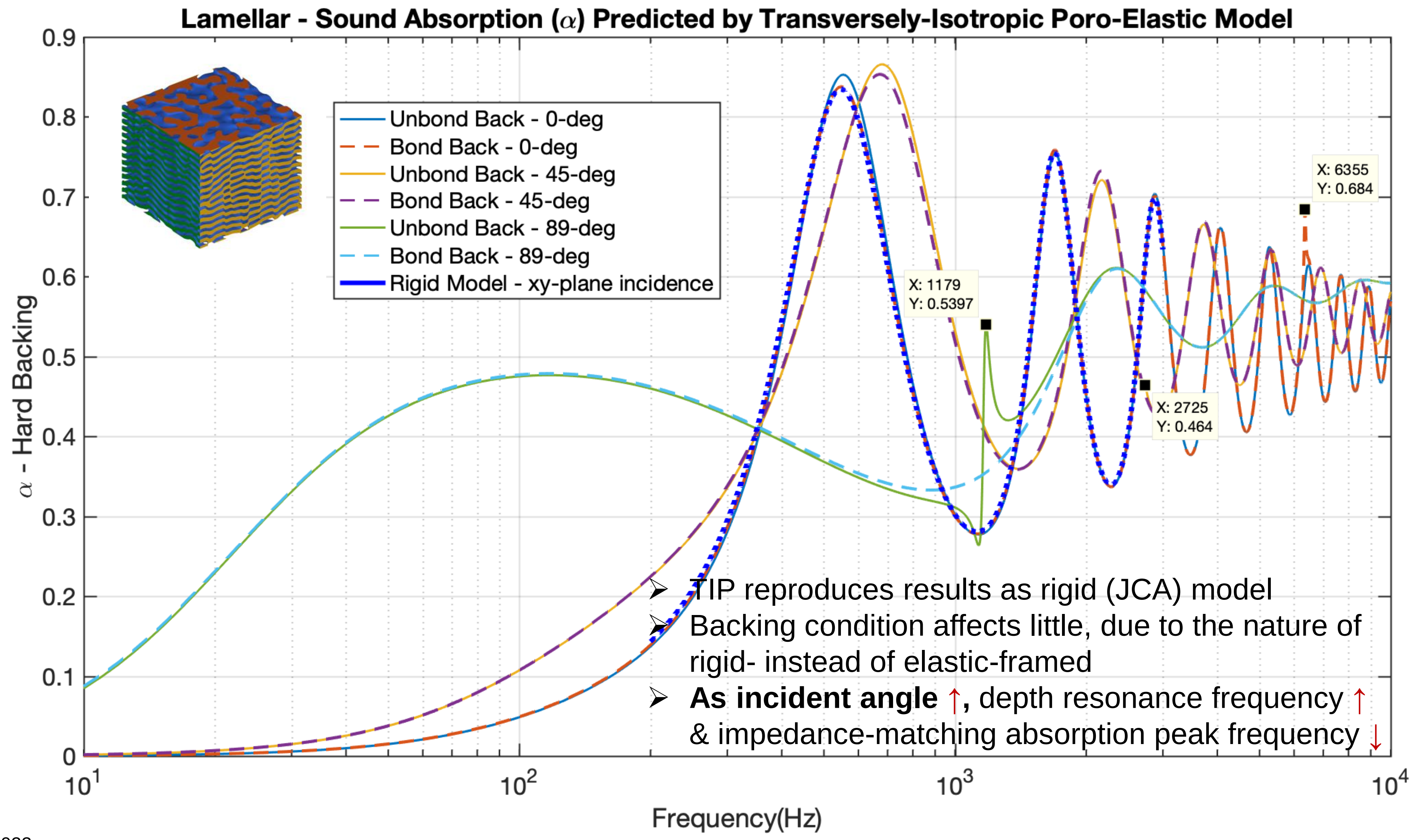
Wavenumbers:
k_1, $k_2 = -k_1$,
k_3, $k_4 = -k_3$,
k_5, $k_6 = -k_5$
Amplitude coefficients:
α_i, β_i, γ_i, i=1,2,3

Note: **In this study,** Large but finite stiffness (**E_1=10^{9}Pa, ν=0.1, η_m=0.01**) was given at anisotropic spinodoid's both directions to make it "rigid-framed"

- **Boundary condition coupling by the transfer matrix method (TMM) [28] or the arbitrary coefficient method (ACM) [29]**

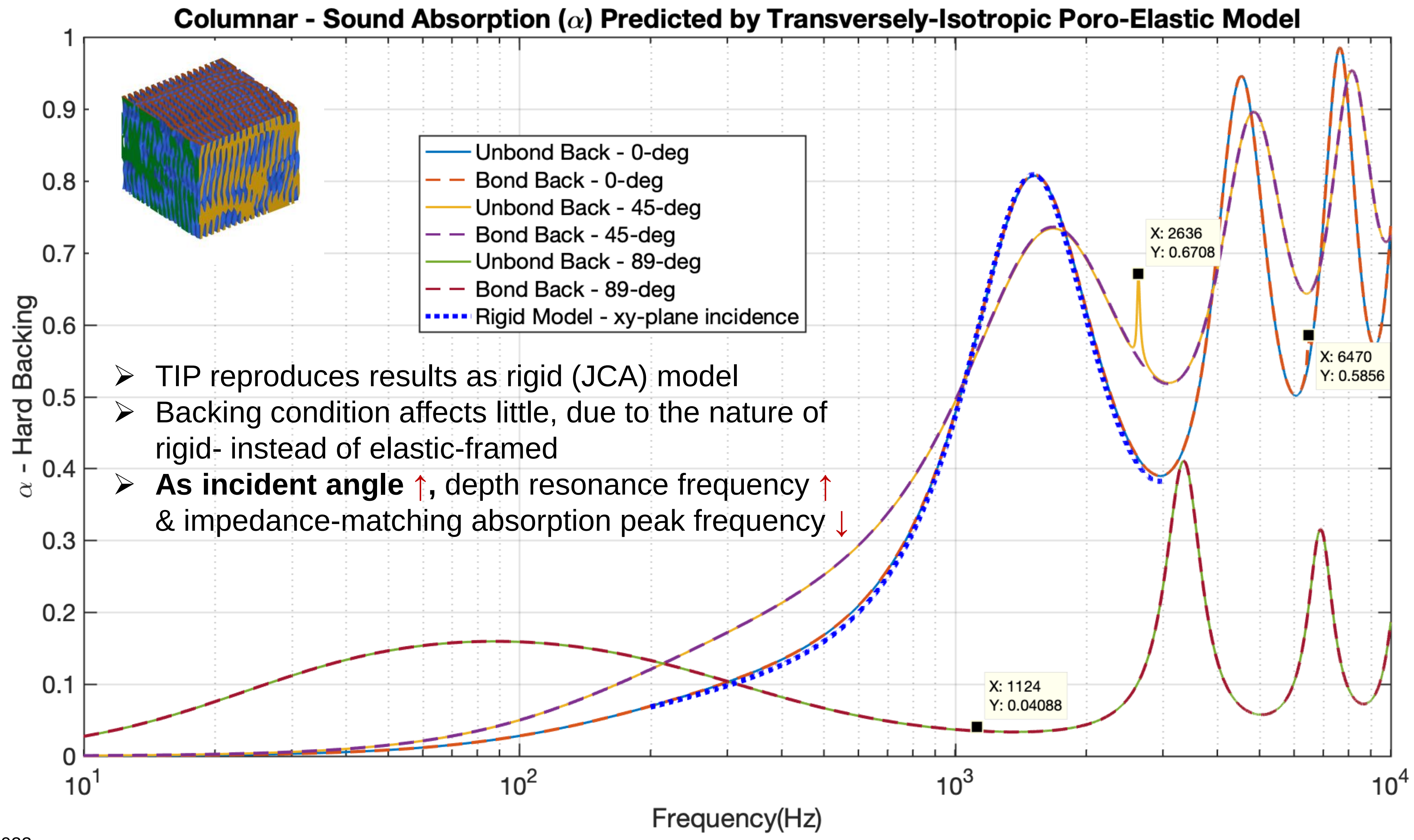
→ Sound absorption coefficients

Sound Absorption Prediction by TIP



- ➢ TIP reproduces results as rigid (JCA) model
- ➢ Backing condition affects little, due to the nature of rigid- instead of elastic-framed
- ➢ **As incident angle ↑,** depth resonance frequency ↑ & impedance-matching absorption peak frequency ↓

Sound Absorption Prediction by TIP



- TIP reproduces results as rigid (JCA) model
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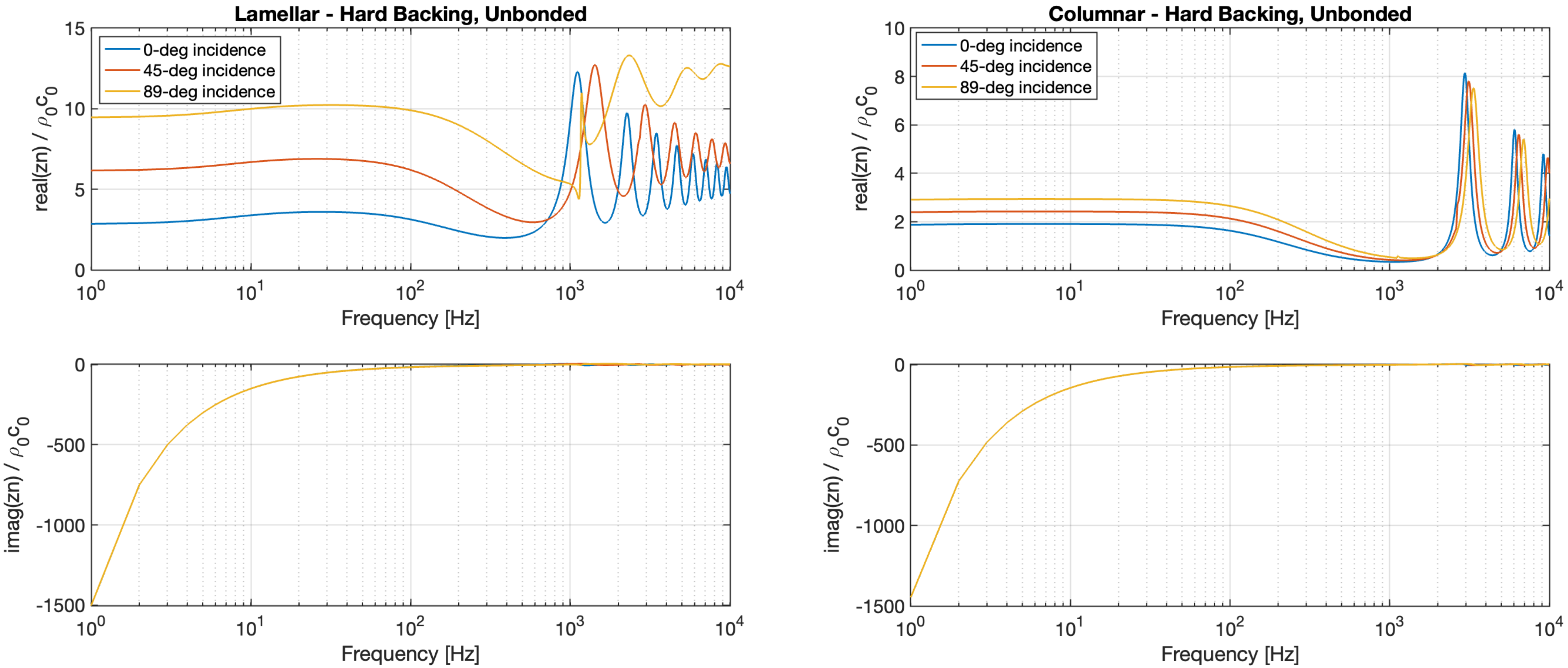
- **As incident angle ↑,** depth resonance frequency ↑ & impedance-matching absorption peak frequency ↓

Surface Normal Impedance Normalized by $\rho_0 c_0$



- ➢ **Columnar is almost locally reacting, and may potentially perform well in duct lining applications**

Summary

- 3D printed spinodoid shows good broadband sound absorption performance, while holding potentials in such as optimization flexibility, structural durability, etc.
- Fully-isotropic spinodoids' acoustical performance can be accurately characterized and predicted by the JCA model
- **Transversely-isotropic poro-elastic (TIP) model developed based on the Biot theory** is capable of predicting sound absorption for anisotropic spinodoids: i.e., columnar and lamellar
- The **acoustic anisotropy analyzed by the TIP model** proved locally-reacting acoustical feature and random incidence sound absorption potentials of columnar spinodoids
- Future work:
  - Examine columnar locally-reacting advantage by random incidence and duct lining tests
  - 3D printing and acoustic modeling of gradient spinodoid

- **For more information, please refer to the our publication in *Additive Manufacturing* [23] and Brittany's thesis [30]**
- **Presentation will be available on Herrick E-Pubs: http://docs.lib.purdue.edu/herrick/**

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THANK YOU
FOR YOUR ATTENTION!