Sorrento SAPEM'23 常熟

Symposium on the Acoustics of Poro-Elastic Materials

Multi-Functional Porous Materials: Characterization, Modeling and Potential in System-Level Noise Control

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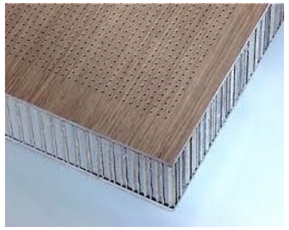
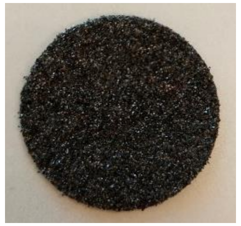
Introduction

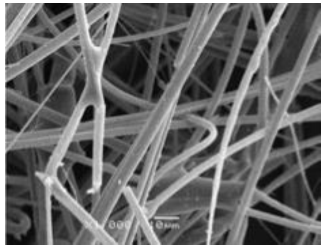
Acoustic Materials Design and Optimization for Noise and Vibration Control in Complex Systems

- **Factor (Design Constraints) to Consider**
  - Cost
  - Safety
  - Weight
  - Volume
  - Recyclability
  - Manufacturability

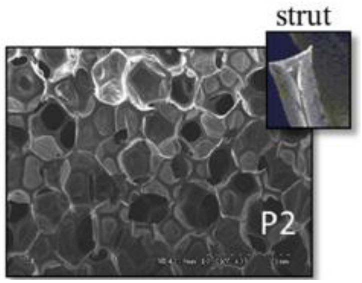



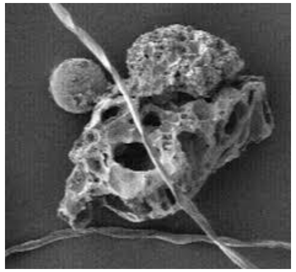

Porous Materials



Fiber



Foam



Particle

Fiber / strut / particle / pore size
Solid material density, etc.

elastic { limp { rigid {

- -Thickness
- -Flow resistivity
- -Porosity
- -Tortuosity
- -Viscous characteristic length
- -Thermal characteristic length

} -Bulk density

} -Young's modulus
- -Poisson's ratio
- -Loss factor (mechanical)

}

Microscopic geometry ⇦ **Characterization** ⇨ Macroscopic (bulk) properties

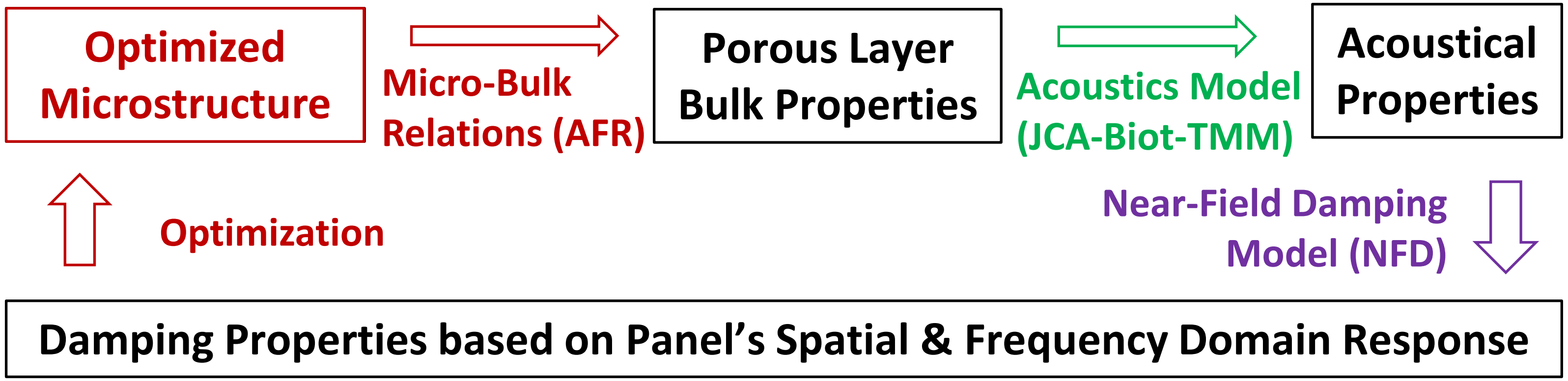
⇳ **Building Connections (Modeling for Design)**

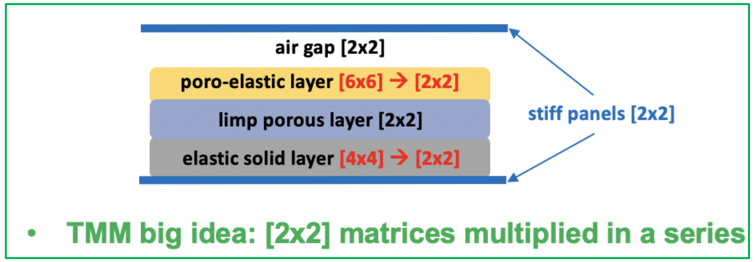
Acoustical properties ⇦ **Prediction** ⇨ Damping properties

Acoustic pressure / particle velocity
Acoustic impedance / intensity
Sound absorption / Transmission loss

Structural vibration response
Power dissipation
System equivalent energy loss factor

Modeling of Acoustical-Damping Layered Structures





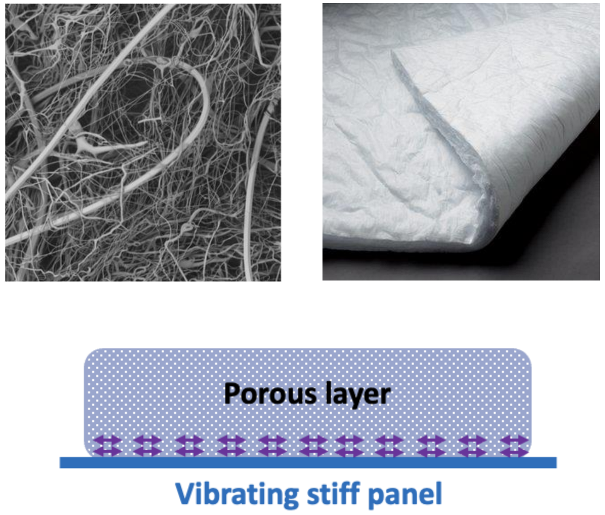
* *Applied Acoustics*, **134** 145-153 (2018)
** *Journal of Applied Physics*, **126** 165012 (2019)
*** *Journal of Sound and Vibration*, **459** 114866 (2019)

- **AFR:** micro-bulk relations for porous media *
- **TMM:** bulk-acoustical relations including Johnson-Champoux-Allard (JCA) model, Biot theory and B.C.s interpreted by transfer matrices of layered elements **
- **NFD:** acoustical-damping relations including Euler-Bernoulli beam theory, wavenumber-space Fourier transform and statistical energy analysis ***

➢ **TMM** + **NFD** + **AFR** provides a tool to predict and maximize porous media's damping performance by optimizing their microstructures

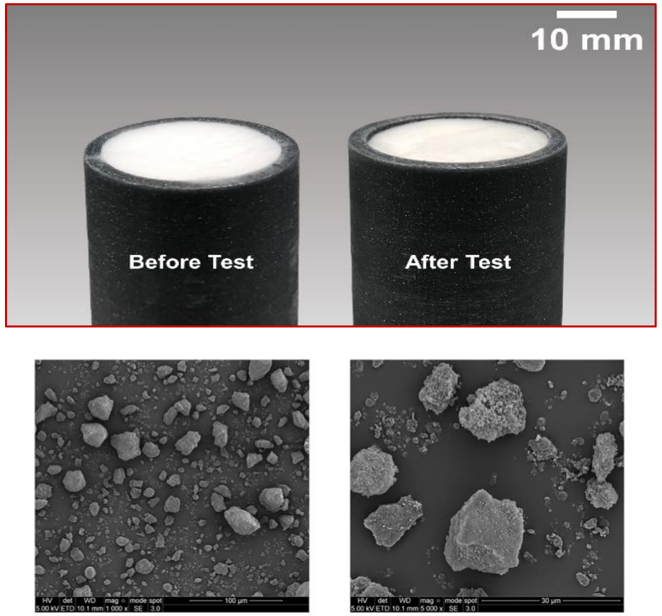
Porous Materials: Acoustics and Beyond

Porous damping materials



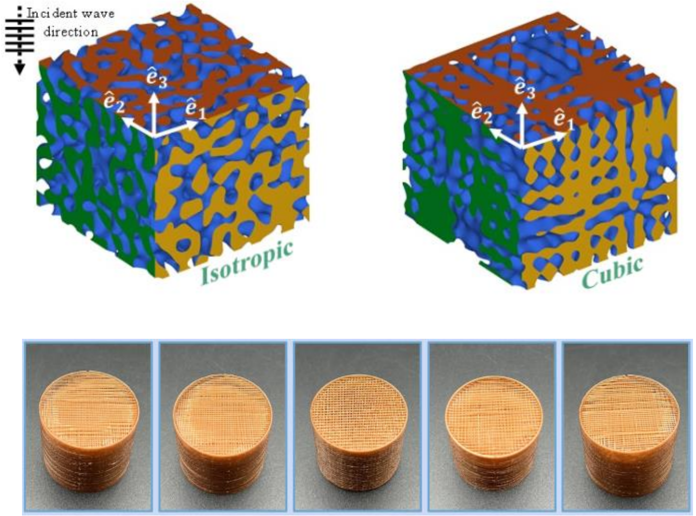
PURDUE UNIVERSITY Mechanical Engineering | 3M

Granular acoustic material



PURDUE UNIVERSITY Mechanical Engineering | The University Of Sheffield. | WSU Wichita State University

3D printing materials



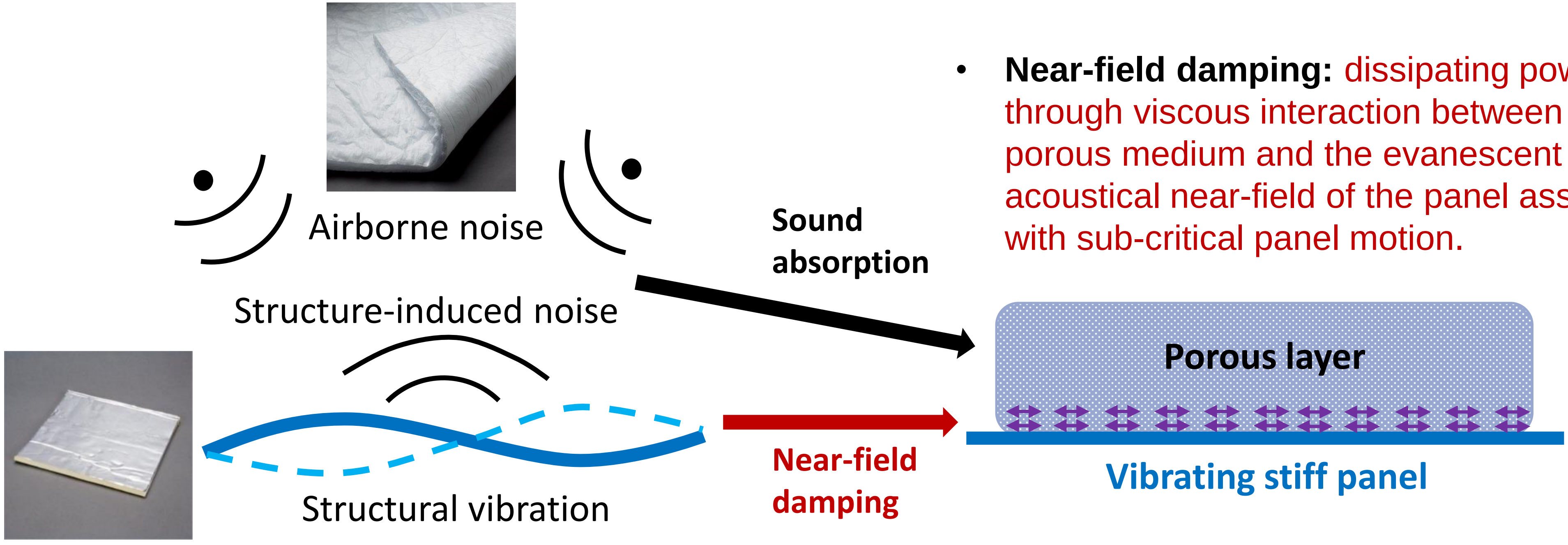
PURDUE UNIVERSITY Mechanical Engineering | WSU Wichita State University | UNIVERSITY OF LEEDS

Porous Damping Materials

Sound Absorption + Structural Damping

Near-Field Damping (NFD)

- **Near-field damping:** dissipating power through viscous interaction between the porous medium and the evanescent acoustical near-field of the panel associated with sub-critical panel motion.

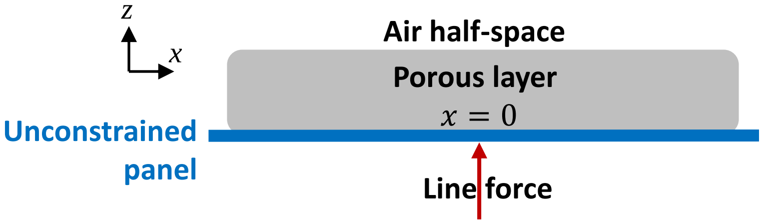


- **Objectives: modeling and optimizing** the near-field damping performance of lightweight sound absorbing porous materials (fiber, foam, etc.) to achieve acoustical-damping multifunctionality

Acoustical-Structural Coupling

- **TMM / ACM + NFD – modeling of different target structures**

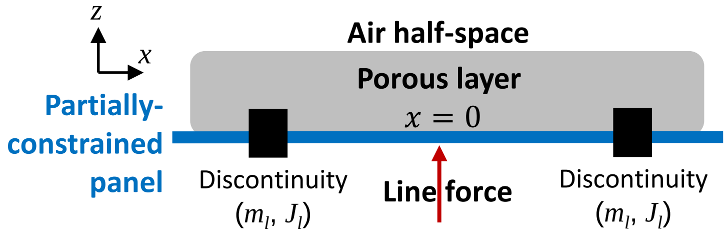
* *Journal of Sound and Vibration*, **14(4)** 525–541 (1971)



Governing Equation: unconstrained panel

Line force

$$D\frac{\partial^4 w_t(x,t)}{\partial x^4} + m_s\frac{\partial^2 w_t(x,t)}{\partial t^2} = -\boldsymbol{p_1(x,t)} + Fe^{+i\omega t}\delta(x)$$

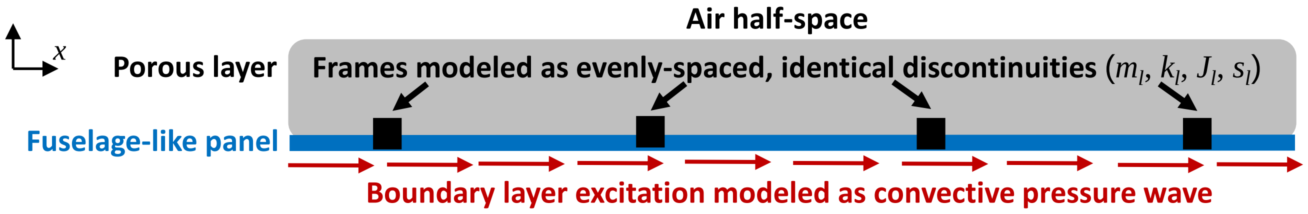


Governing Equation: adding two identical constraints

Reaction forces due to discontinuities

Line force

$$D\frac{\partial^4 w_t(x,t)}{\partial x^4} + m_s\frac{\partial^2 w_t(x,t)}{\partial t^2} = -\boldsymbol{p_1(x,t)} + Fe^{+i\omega t}\delta(x) + \sum_{j=1}^{2} F_{l,j}\delta(x - x_{l,j}) + \sum_{j=1}^{2} M_{l,j}\delta'(x - x_{l,j})$$

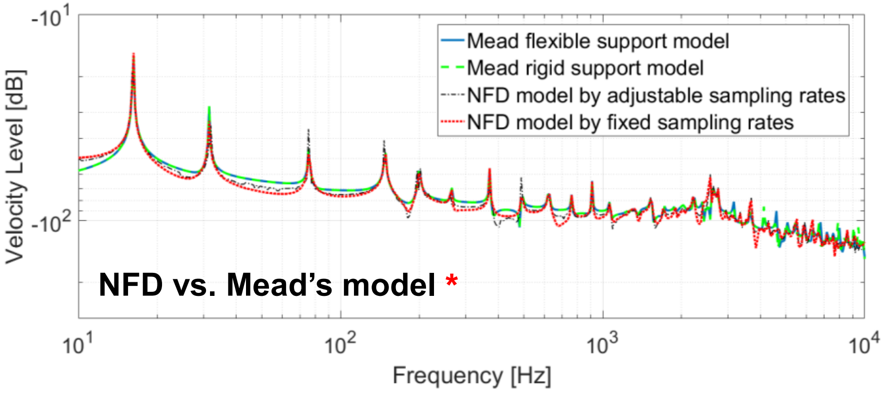


Governing Equation: adding periodic identical constraints

Convective pressure

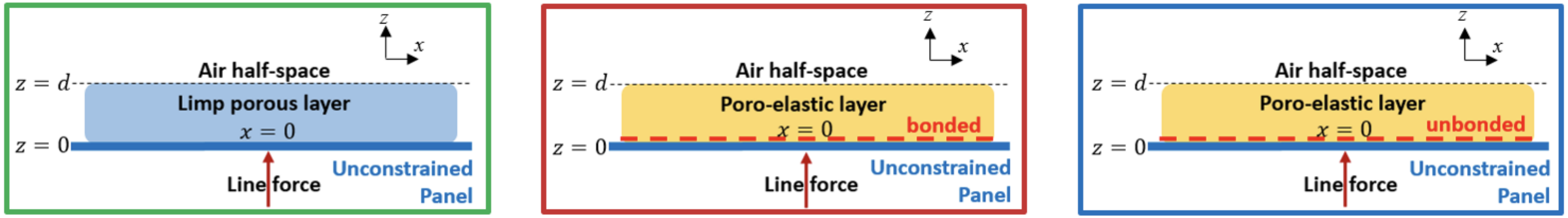
Reaction forces due to discontinuities

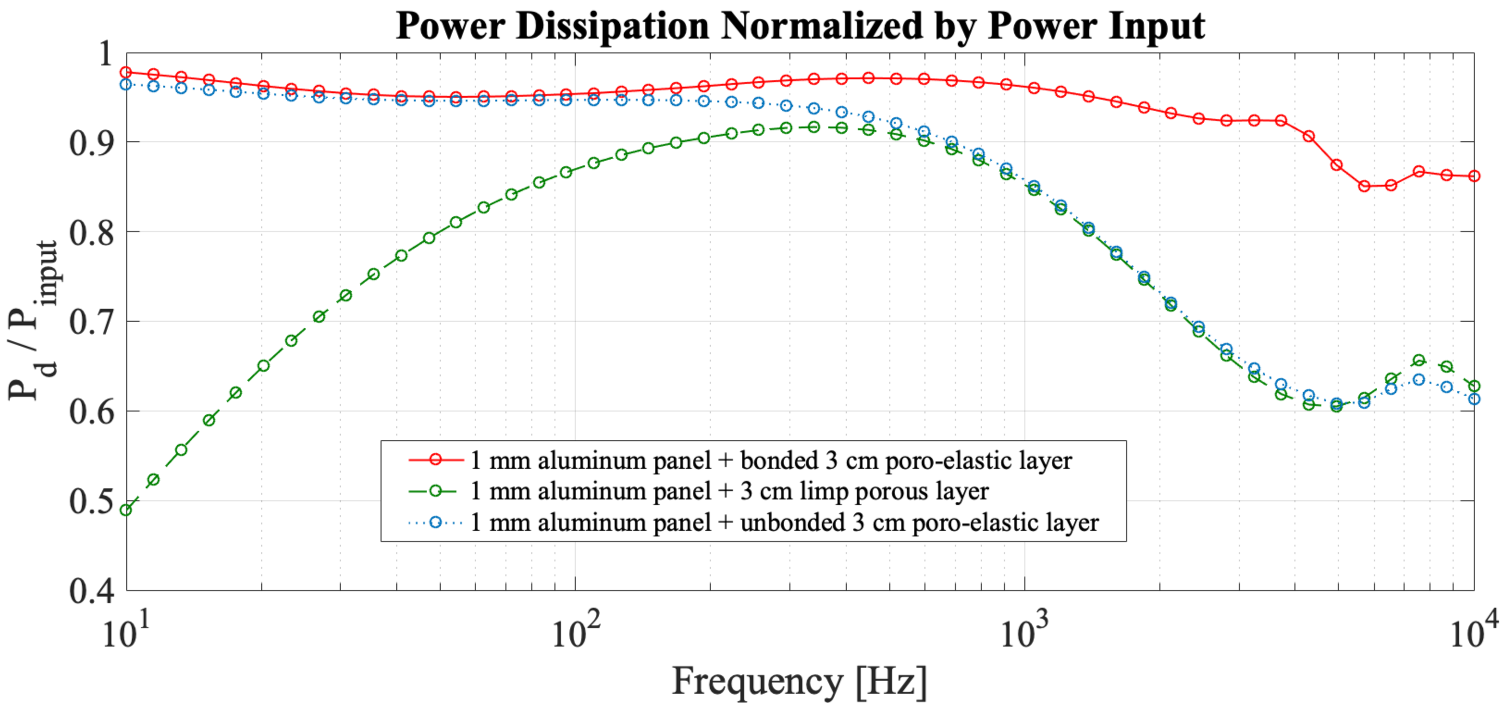
$$D\frac{\partial^4 w_t(x,t)}{\partial x^4} + m_s\frac{\partial^2 w_t(x,t)}{\partial t^2} = -\boldsymbol{p_1(x,t)} + Fe^{+i\omega t}e^{-ik_v x} + \sum_{j=1}^{N_l} F_{l,j}\delta(x - x_{l,j}) + \sum_{j=1}^{N_l} M_{l,j}\delta'(x - x_{l,j})$$



Damping Effectiveness: Limp vs. Elastic

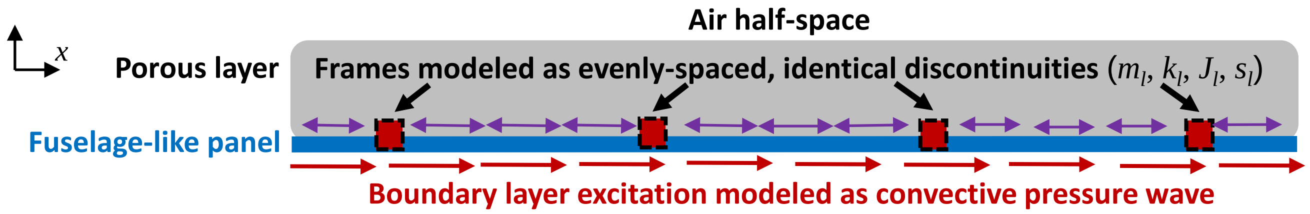
- Adding bulk stiffness to the porous layer and bonding it to the panel will create additional structural dissipation

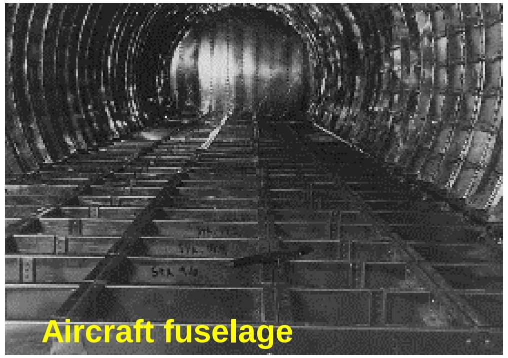




NFD Optimization on a Periodic Vibrating Structure *

* *Journal of Physics: Conf. Series* **1264**, 012043 (2019)

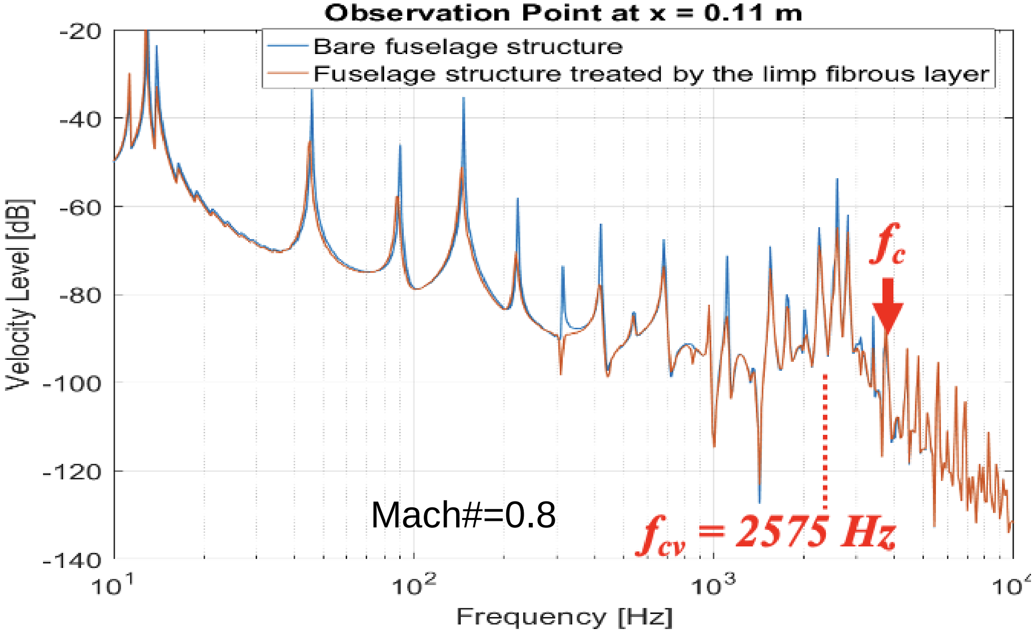


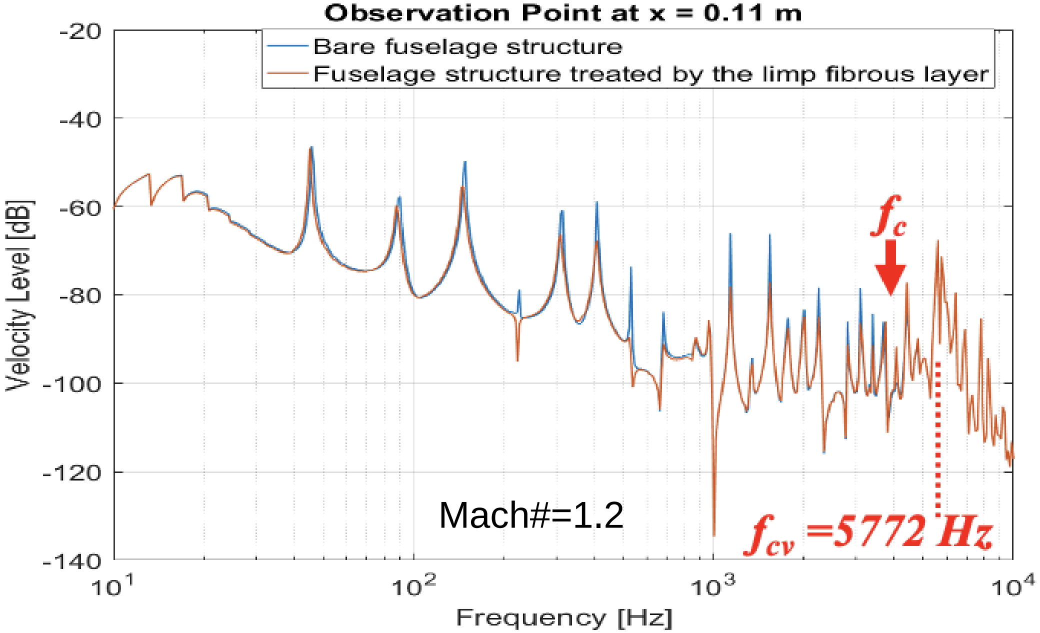


Governing Equation: adding periodic identical constraints

Convective pressure — Reaction forces due to discontinuities

$$D\frac{\partial^4 w_t(x,t)}{\partial x^4} + m_s\frac{\partial^2 w_t(x,t)}{\partial t^2} = -p_1(x,t) + Fe^{+i\omega t}e^{-ik_v x} + \sum_{j=1}^{N_l} F_{l,j}\delta(x - x_{l,j}) + \sum_{j=1}^{N_l} M_{l,j}\delta'(x - x_{l,j})$$





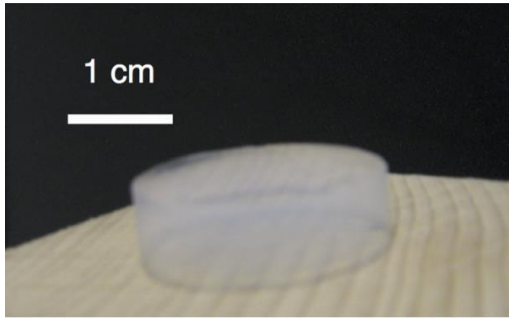
➢ **Significant attenuation in sub-critical frequency region**

Granular Aerogel

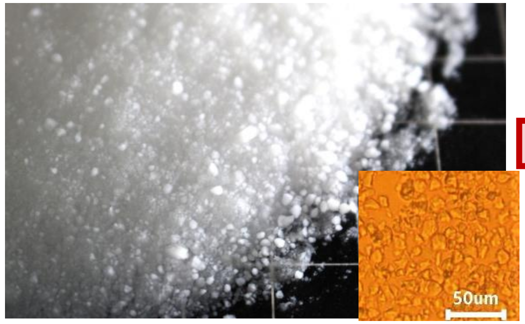
Thermal Insulation + Low Frequency Sound Absorption

Granular Aerogel *

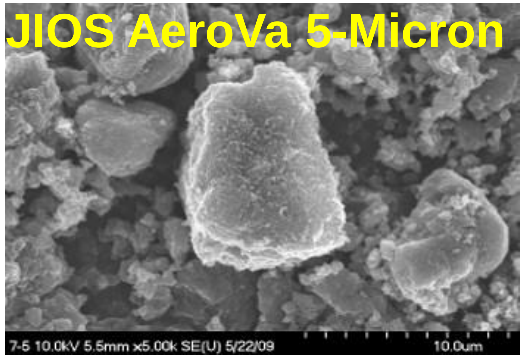
* *Appl. Sci.* **11** 4593 (2021)
* Proceedings of SAPEM 2021



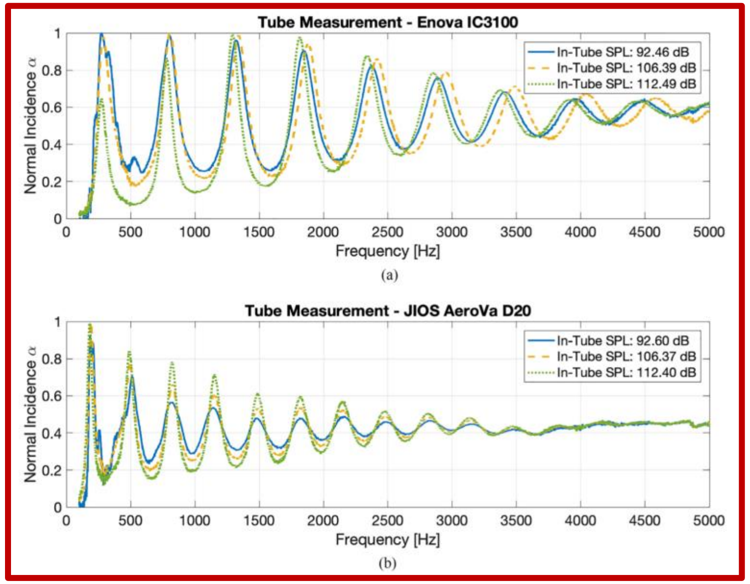
Silica aerogel solid



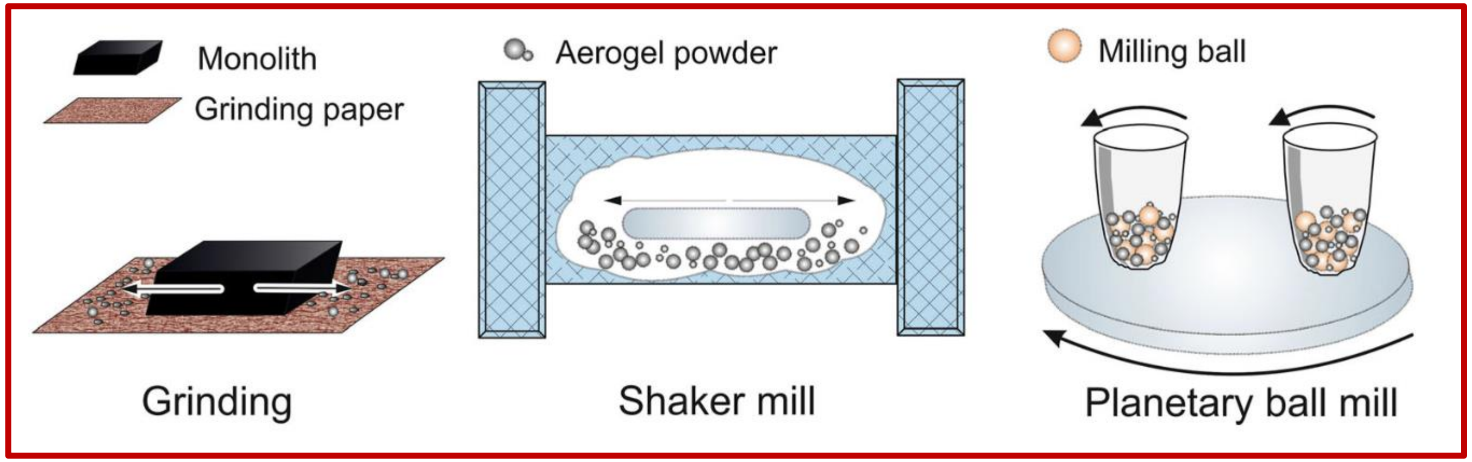
Silica aerogel granules



SEM of granules



Level-dependent acoustical performance **

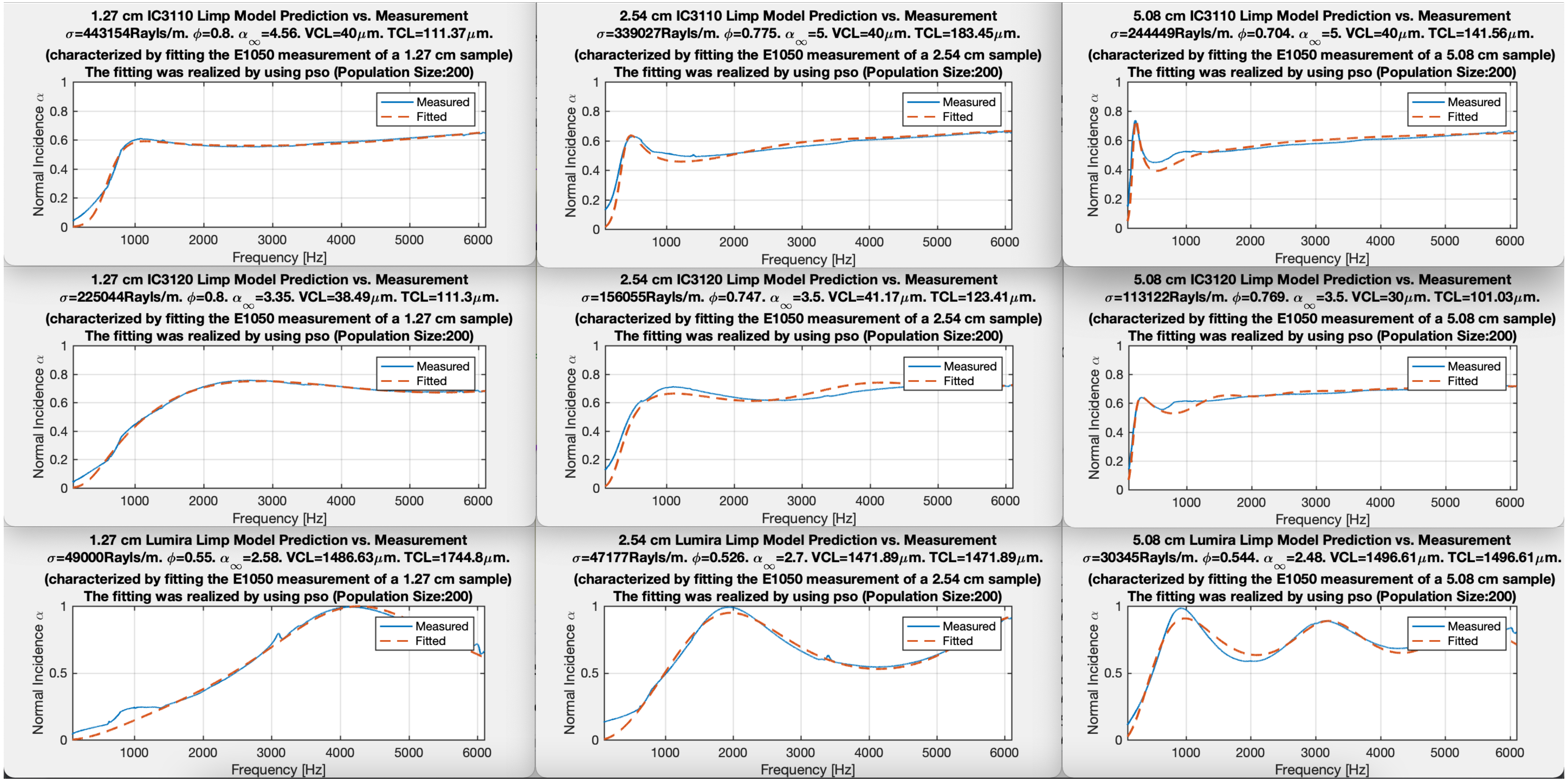


Target granular aerogel in a bulk form

Acoustics of Granular Aerogel

* *J. Non-Crys. Solids*, **598**, 121942 (2022)

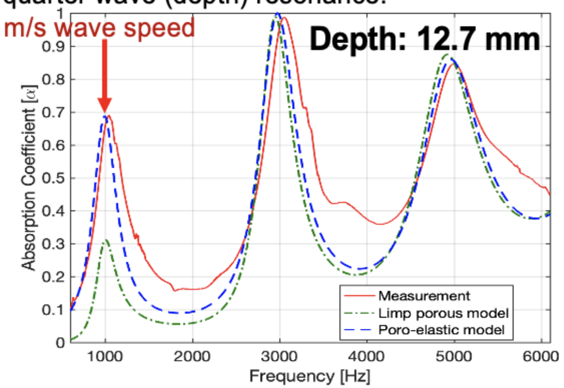
- Normal sound absorption measurement vs. Biot limp theory + particle swarm fitted results show that aerogel stacks with larger (diameter > 100μm) particles behaves like limp-porous media (negligible bulk stiffness of frame) *

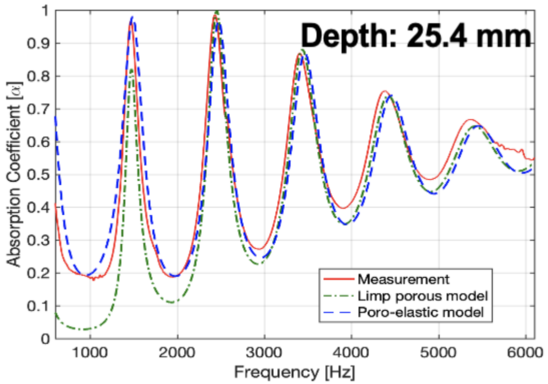


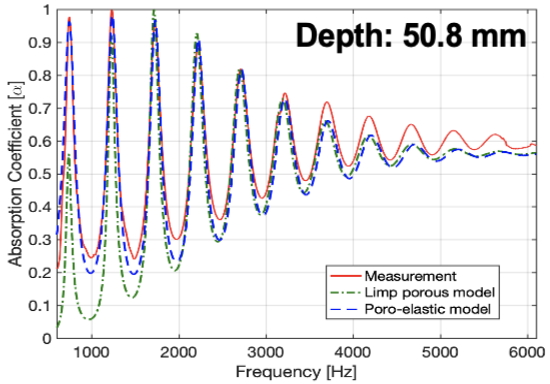
Acoustical Non-linearity (Loss Factor) and Level-Dependence for Granular Aerogel *

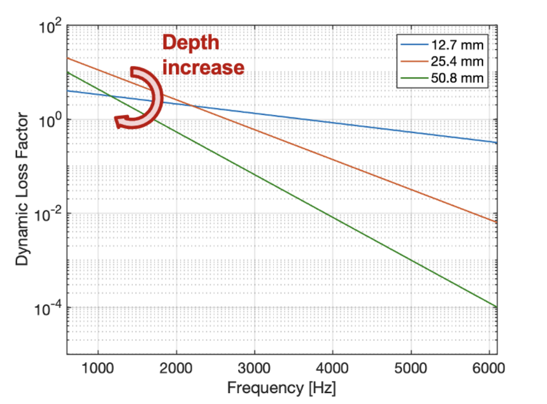
* *JASA*, **151**, 1502-1515 (2022)
* *J. Non-Crys. Solids*, **598**, 121942 (2022)

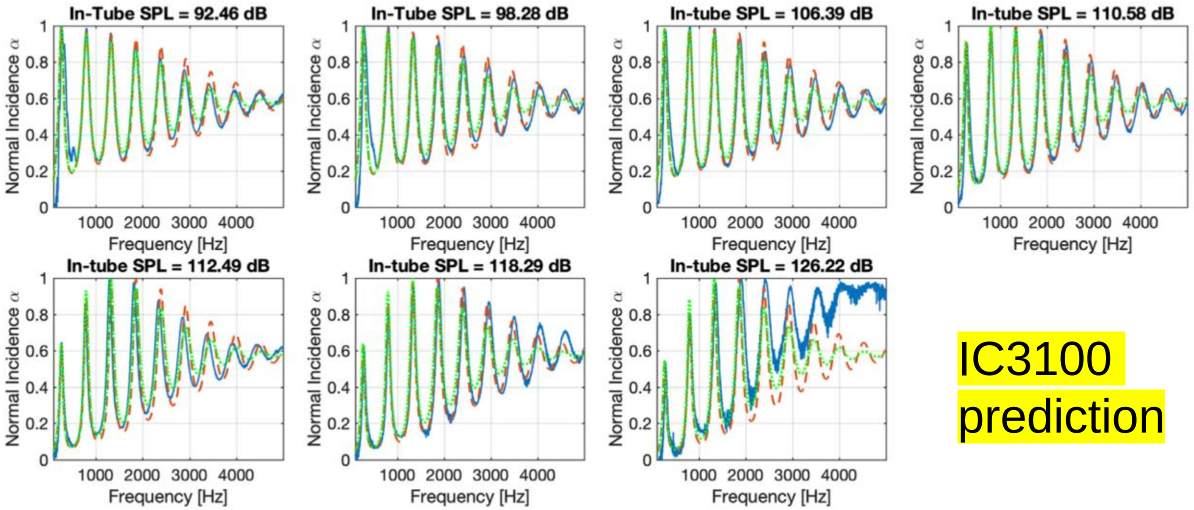
1st quarter wave (depth) resonance:
50 m/s wave speed



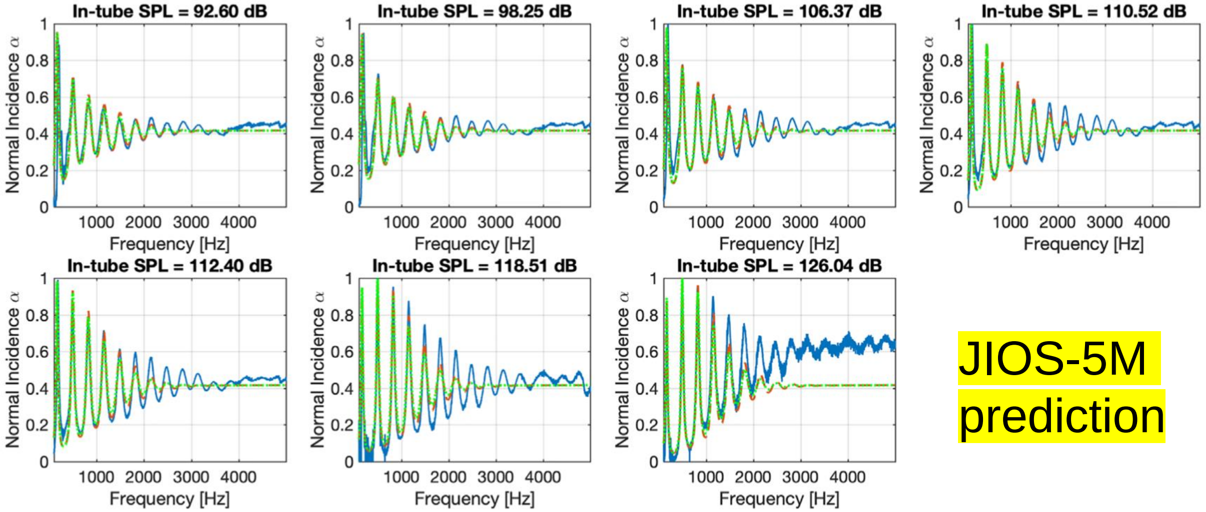








IC3100 prediction



JIOS-5M prediction

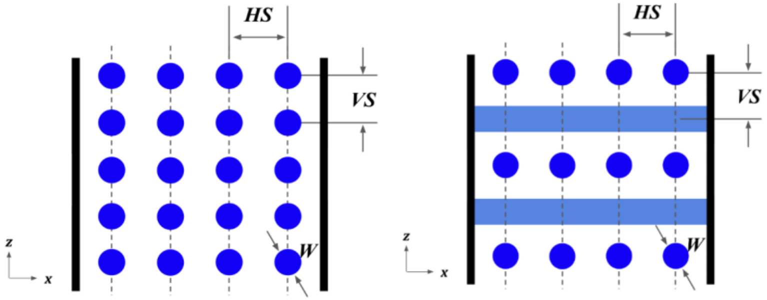
- **The model accurately captures the level-dependence and evaluates low frequency losses for sub-50μm granular aerogels – powerful tool for us to quantify, optimize and gain understanding of granular aerogel's acoustics**

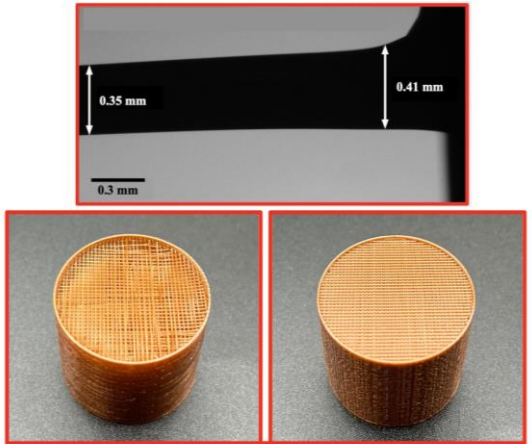
3D Printed Porous Materials

Tunable Acoustical Performance

“Print” Acoustics into Fibers – Recent Findings *

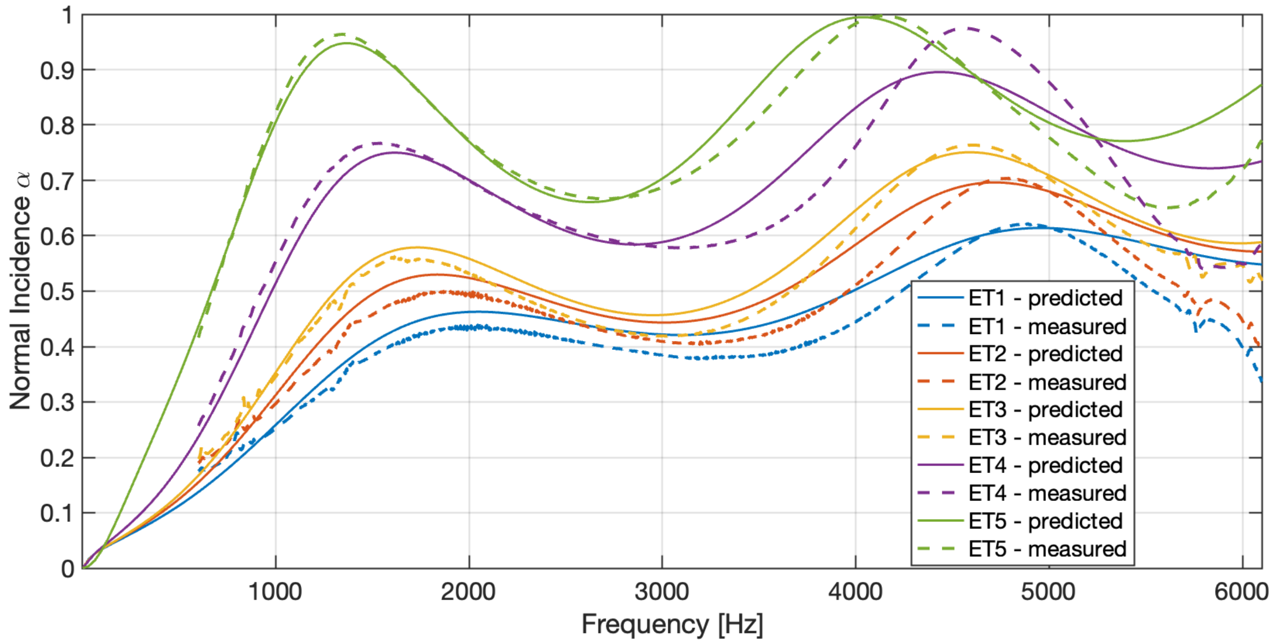
* Additive Manufacturing, **41** 101984 (2021)
* Proceedings of NOVEM 2023
** J Acoust Soc Am, 100(6):3706–3713 (1996)





JCA parameters (marked in blue) calculations

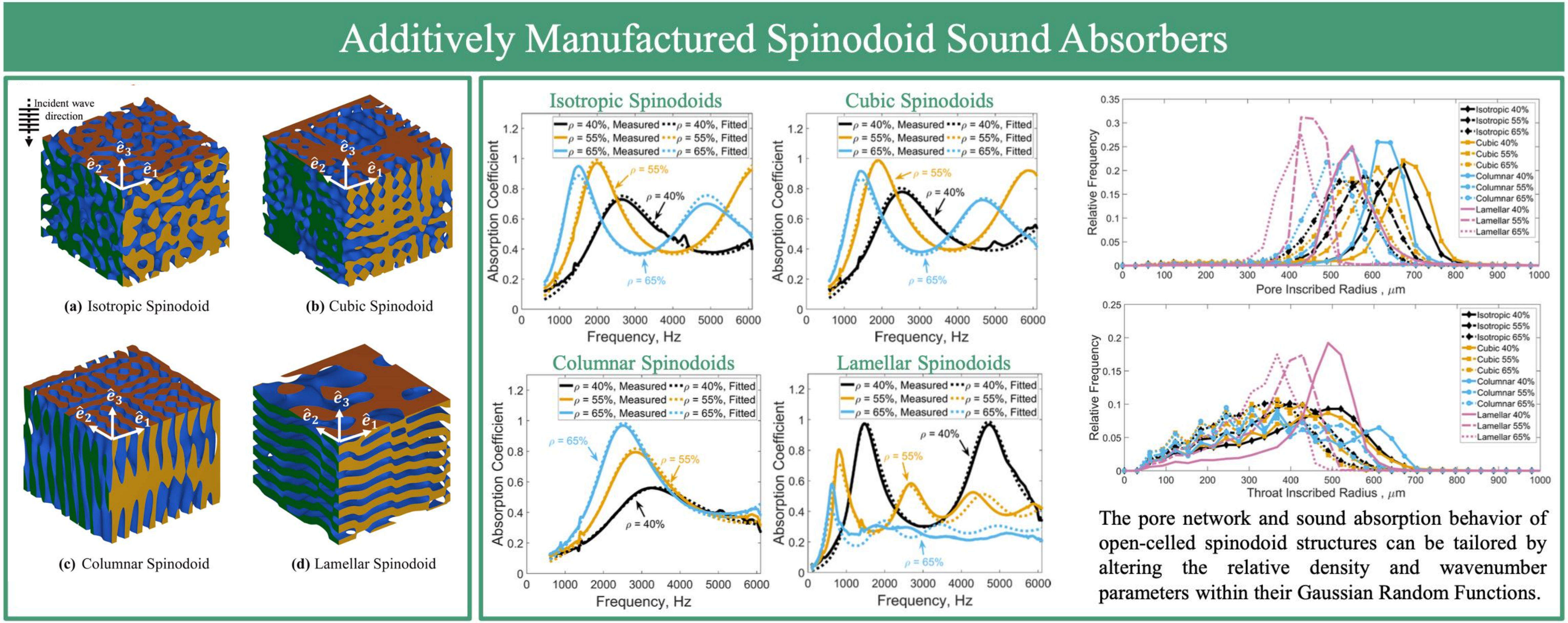
- Expected fiber diameter, ***df***
- Area of single fiber cell, ***S = HS*VS***
- Solidity, $C = \frac{\pi(df/2)^2}{S}$
- Pore size parameters, ***CLa = HS – df, CLb = VS – df***
- Airflow Resistivity, $\sigma = \frac{4\eta C}{(df/2)^2\left[-\frac{1}{2}\ln C - \frac{3}{4} + C - \frac{1}{4}C^2\right]}$, where dynamic viscosity of air $\eta = 1.846\times10^{-5}\ \mathrm{kg/(m\cdot s)}$ in room temperature
- Porosity, $\phi = 1 - C$
- Tortuosity, $\alpha_\infty = 2 - \phi$
- Viscous Characteristic Length, Λ = whichever is smaller between ***CLa*** and ***CLb***
- Thermal Characteristic Length, Λ' = whichever is larger between ***CLa*** and ***CLb***



Rayls/m MKS	σ – Analytical**	σ – COMSOL
ET1	533	439
ET2	771	610
ET3	962	742
ET4	1990	3548
ET5	6745	6055

3D Printing Spinodoid Structure – Structurally-Enhanced Sound Absorber *

* Additive Manufacturing, **71**, 103608 (2023)



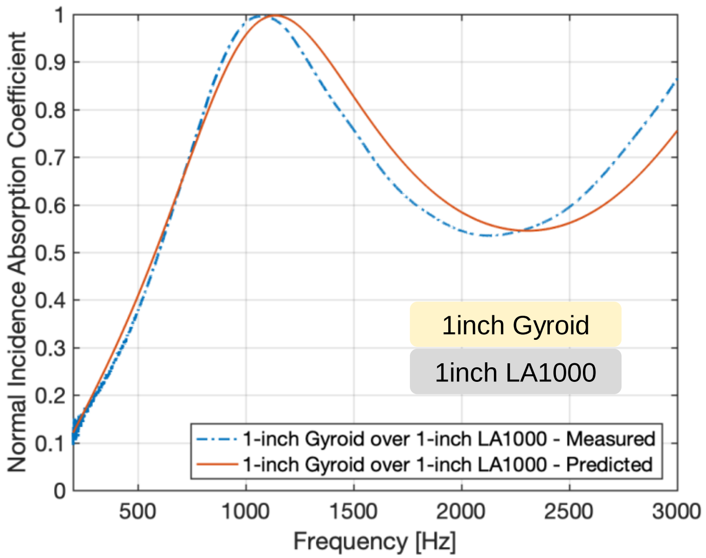
- ➢ **Transversely-Isotropic Poro-elastic (TIP) material model was developed for us to understand more of porous media's anisotropy – to be introduced in the following presentation**

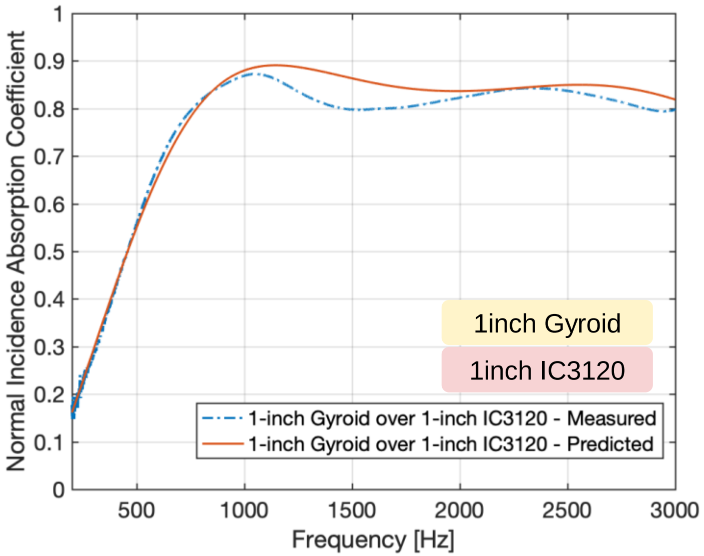
Tunable Sound Package – Bulk Properties Characterization

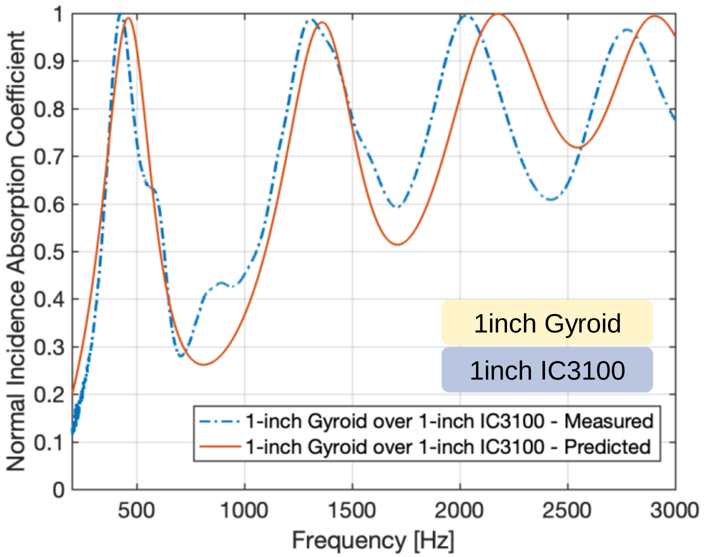
- **Measured sound absorption data based on 2”x2” Squared Tube E1050 Test**
- **Inverse characterization of bulk properties for different porous materials**
  - Modified Biot Poro-Elastic Model (Dynamic Loss Factor) for Aerogel Stacks Smaller Particles (IC3100)
  - Biot Limp Model for Aerogel Stacks of Larger Particles (IC3120, LA1000)
  - Biot Rigid Model (JCA) for 3D Printing Materials (Gyroid)

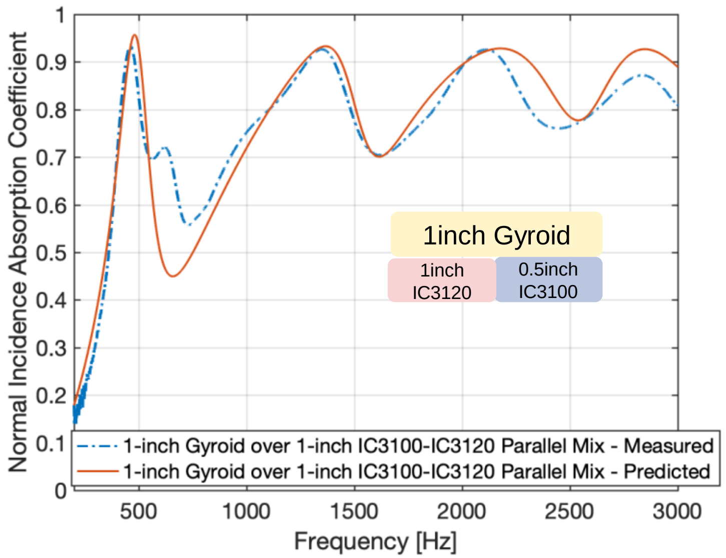
Property \ Material	Bulk Density (kg/m3)	Porosity	AFR (Rayls/m)	Tortuosity	VCL (Micron)	TCL (Micron)	Young’s Modulus (Pa)	Poisson’s Ratio	Loss Factor
IC3100	37.53	0.999	10457000	3.0	36.08	36.08	775	0.396	10-2.51
IC3120	73.57	0.769	108689	3.69	199.31	931.53	N/A	N/A	N/A
LA1000	66.03	0.671	28074	2.53	1912.82	4875.11	N/A	N/A	N/A
Gyroid	N/A(601)	0.520	12513	1.84	133.85	148.72	N/A	N/A	N/A

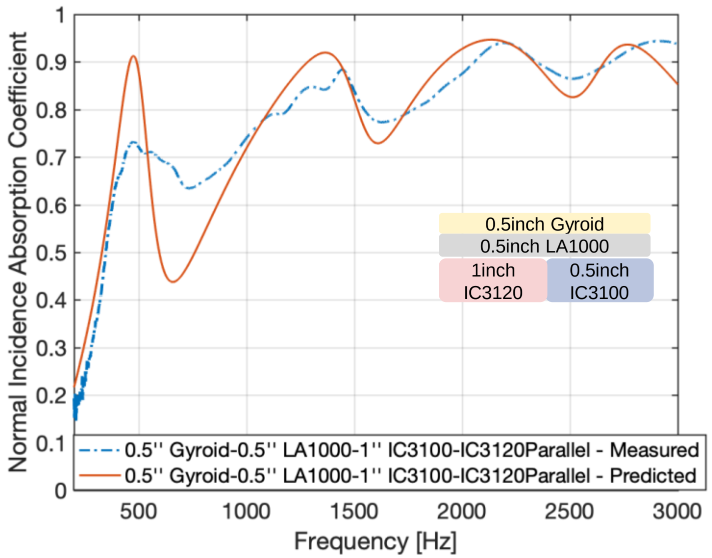
Tunable Sound Package Design – Measurement vs. Prediction











- Aerogel + 3D printed structure*
- Aerogel + fibrous layer**
- Low frequency noise control given weight and volume constraints ***

* Proceedings of ASA Chicago 2023
** *NCEJ* **70**(5), 406-415 (2022)
*** Proceedings of NoiseCon 2020

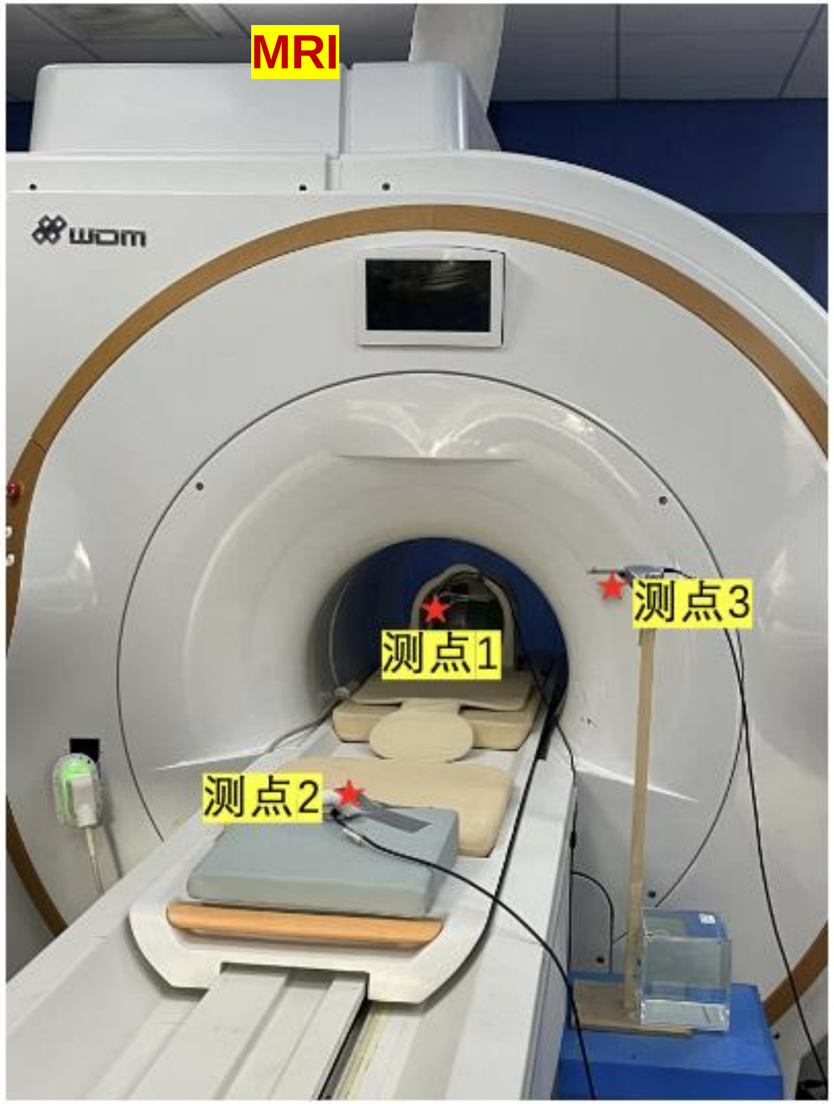
Noise Control in Complex Systems

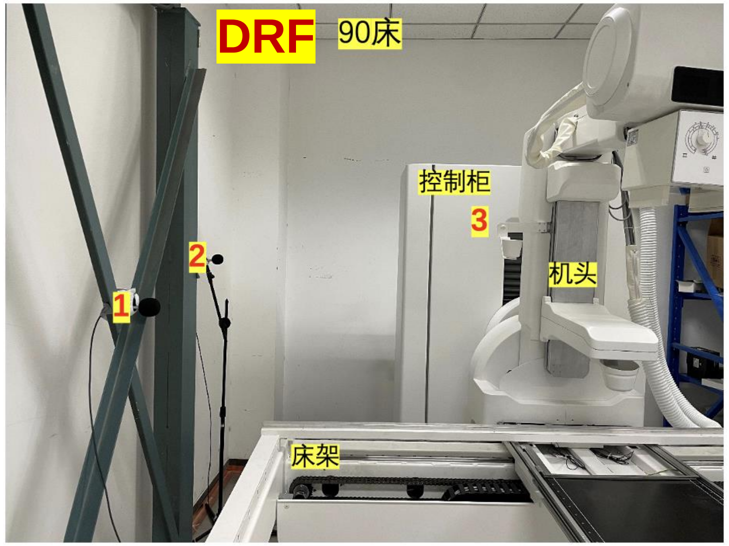
Practical Cases of Medical Imaging Devices

Noise Control in Medical Imaging Industry

https://www.wandong.com.cn/index.php/Show/index/aid/1195

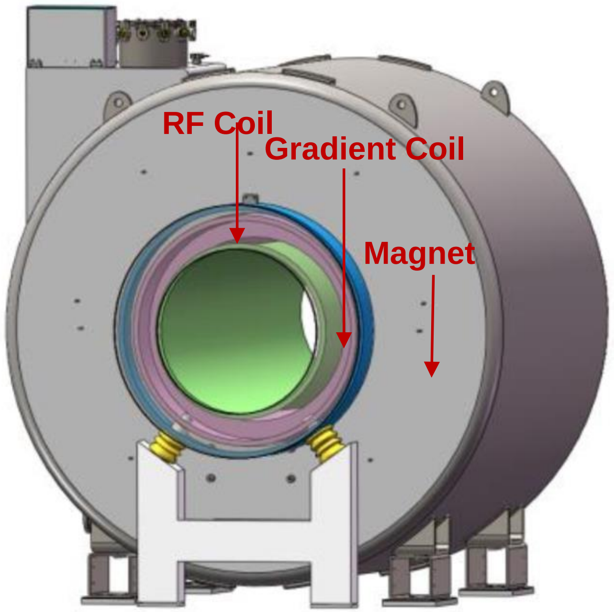
https://new.qq.com/rain/a/20211101A0AQV400

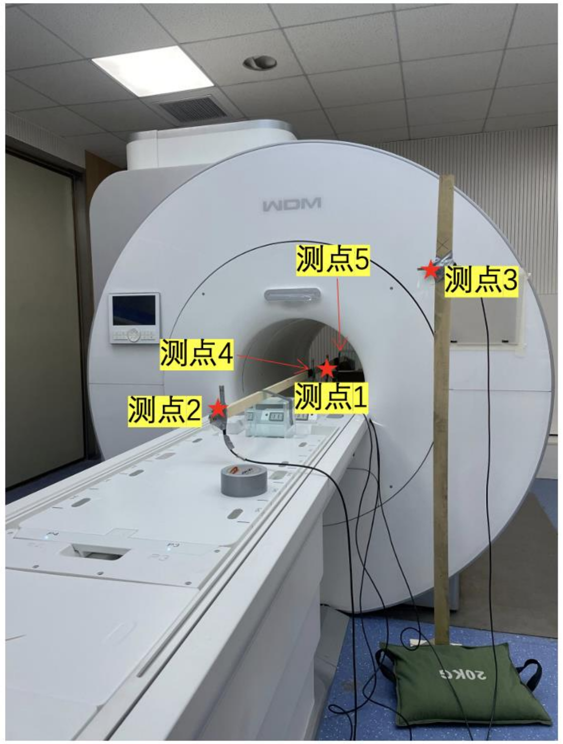


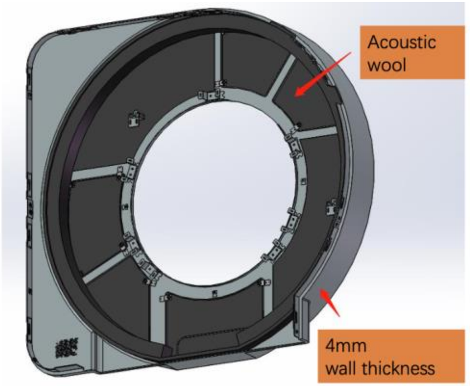


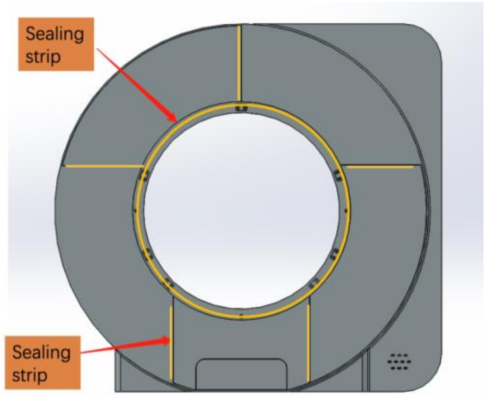
SAPEM 2023

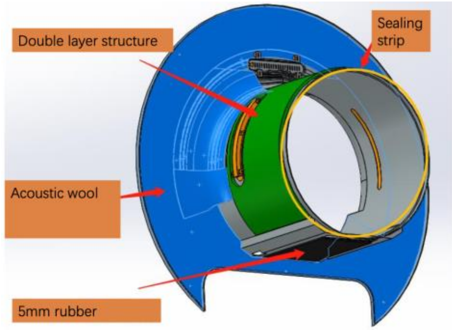
NVH in Medical Imaging Industry – MRI

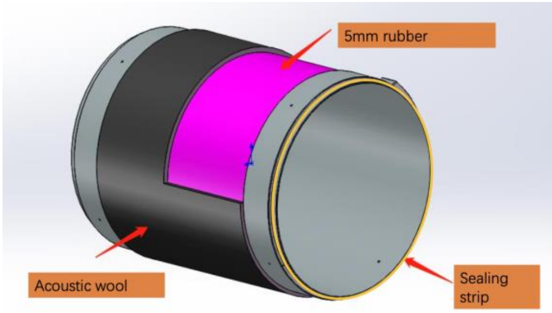


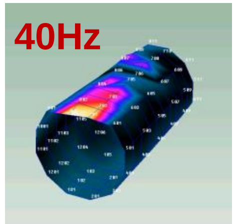


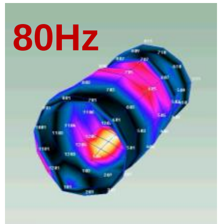


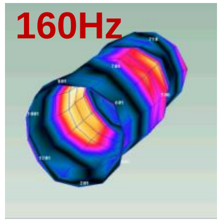


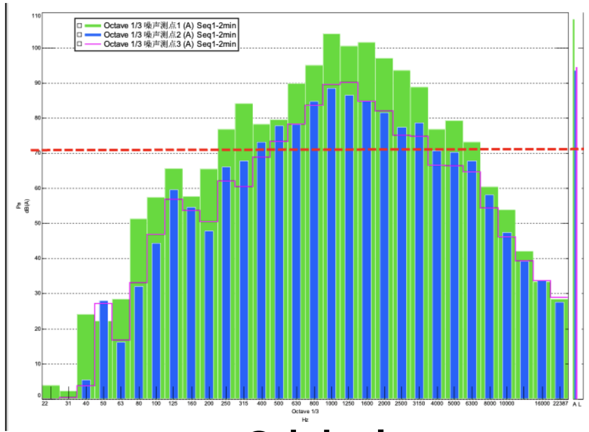




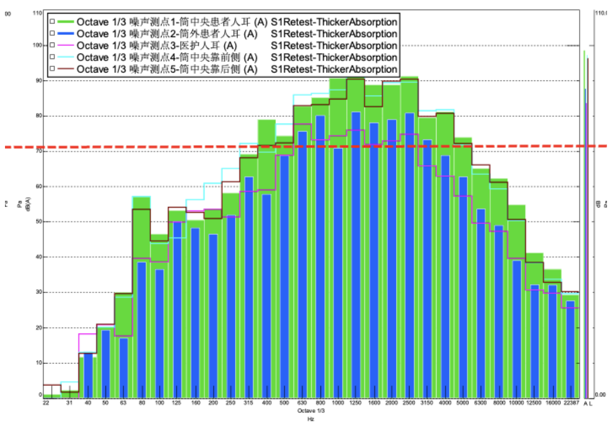




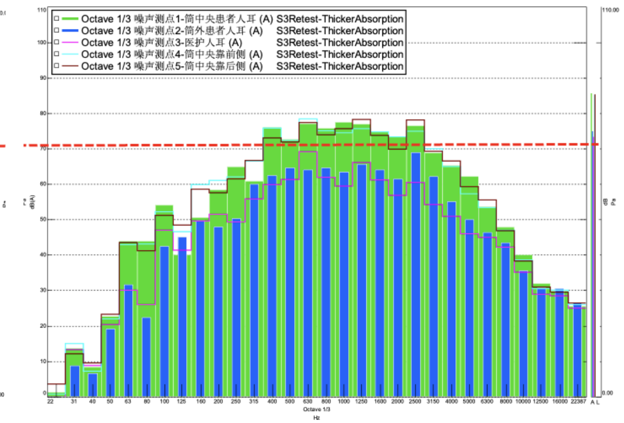




Original



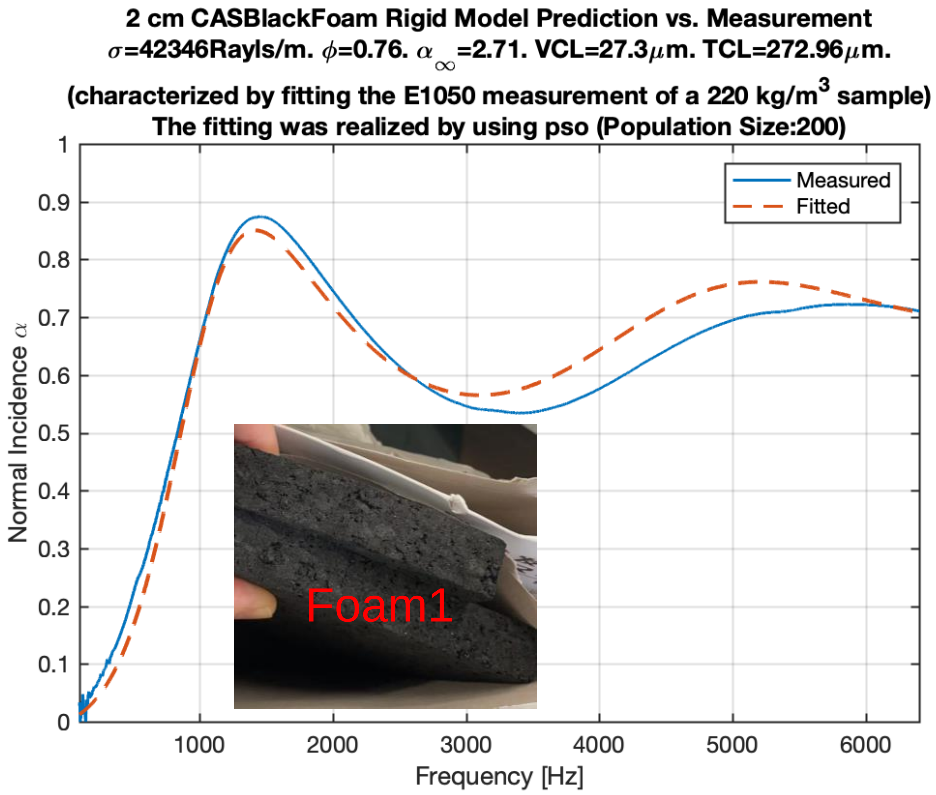
Modified Sequence

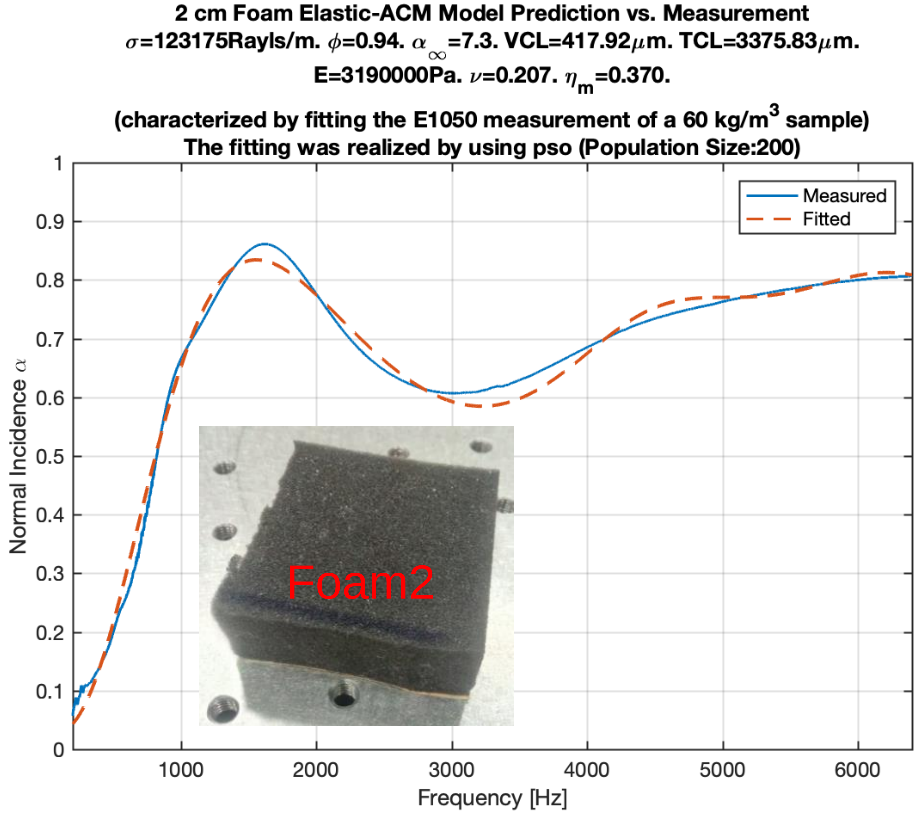


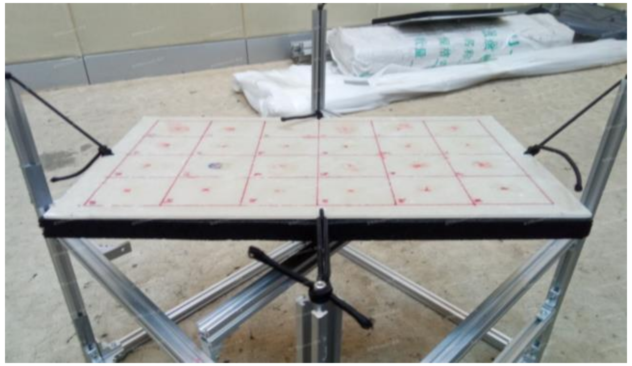
Modified Sequence + Acoustic Treatment

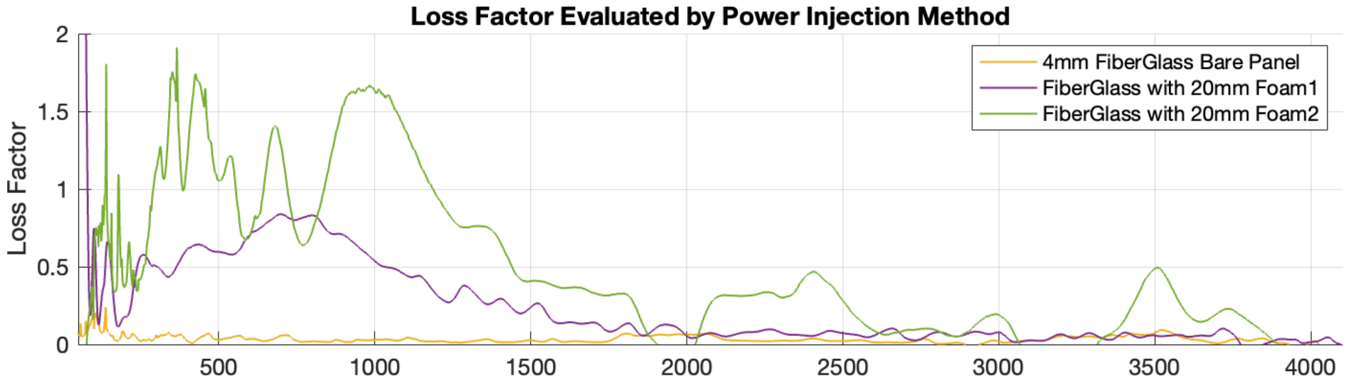
NVH in Medical Imaging Industry – MRI

WDM Midea



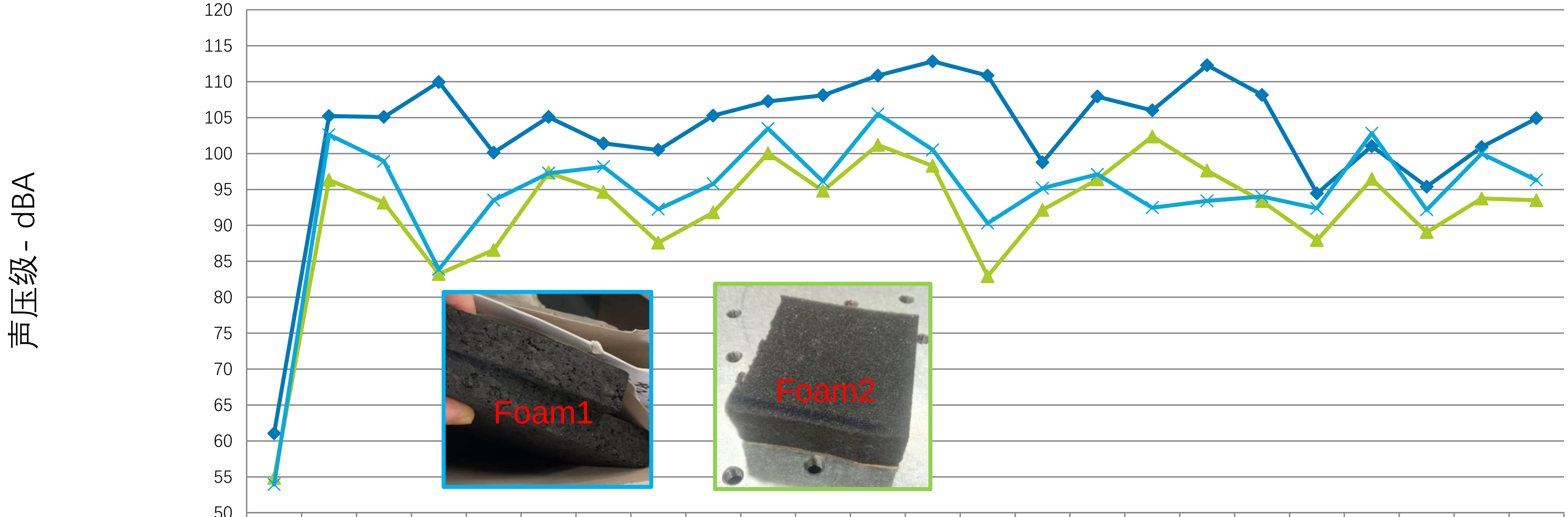






NVH in Medical Imaging Industry – MRI

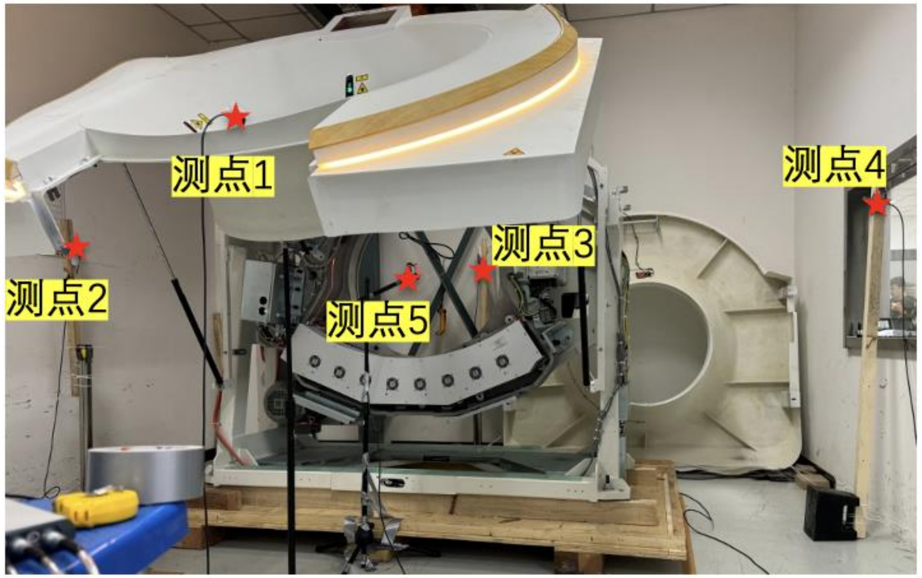
- Foam2 outperforms Foam1 on system-level noise control



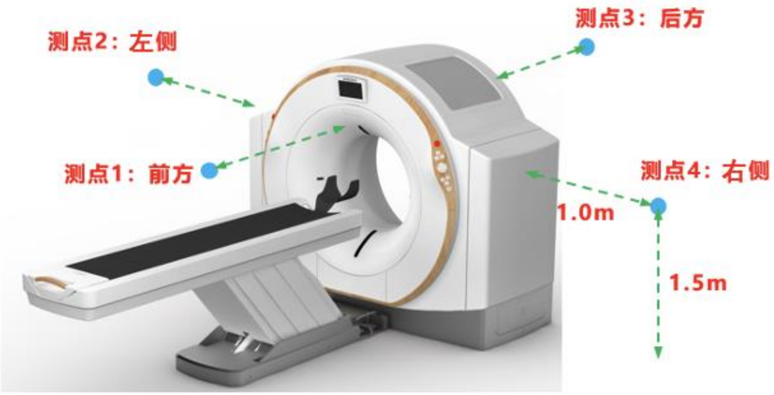
	待机/背景噪声	序列1	序列2	序列3	序列4	序列5	序列6	序列7	序列9	序列10	序列11	序列12	序列13	序列14	序列15	序列16	序列17	序列18	序列19	序列20	序列22	序列23	序列24	平均值
Original	61.04	105.21	105.07	109.94	100.12	105.08	101.4	100.49	105.27	107.26	108.1	110.84	112.82	110.84	98.77	107.93	106.01	112.29	108.15	94.44	101.01	95.39	100.9	104.9
Foam 2	54.83	96.31	93.17	83.22	86.58	97.34	94.64	87.59	91.8	100.03	94.8	101.19	98.28	82.92	92.15	96.39	102.36	97.62	93.36	87.94	96.45	89.04	93.73	93.5
Foam 1	53.93	102.61	98.92	83.87	93.51	97.25	98.15	92.26	95.79	103.48	96.1	105.51	100.51	90.3	95.18	97.09	92.47	93.41	94.01	92.36	102.82	92.16	99.97	96.3

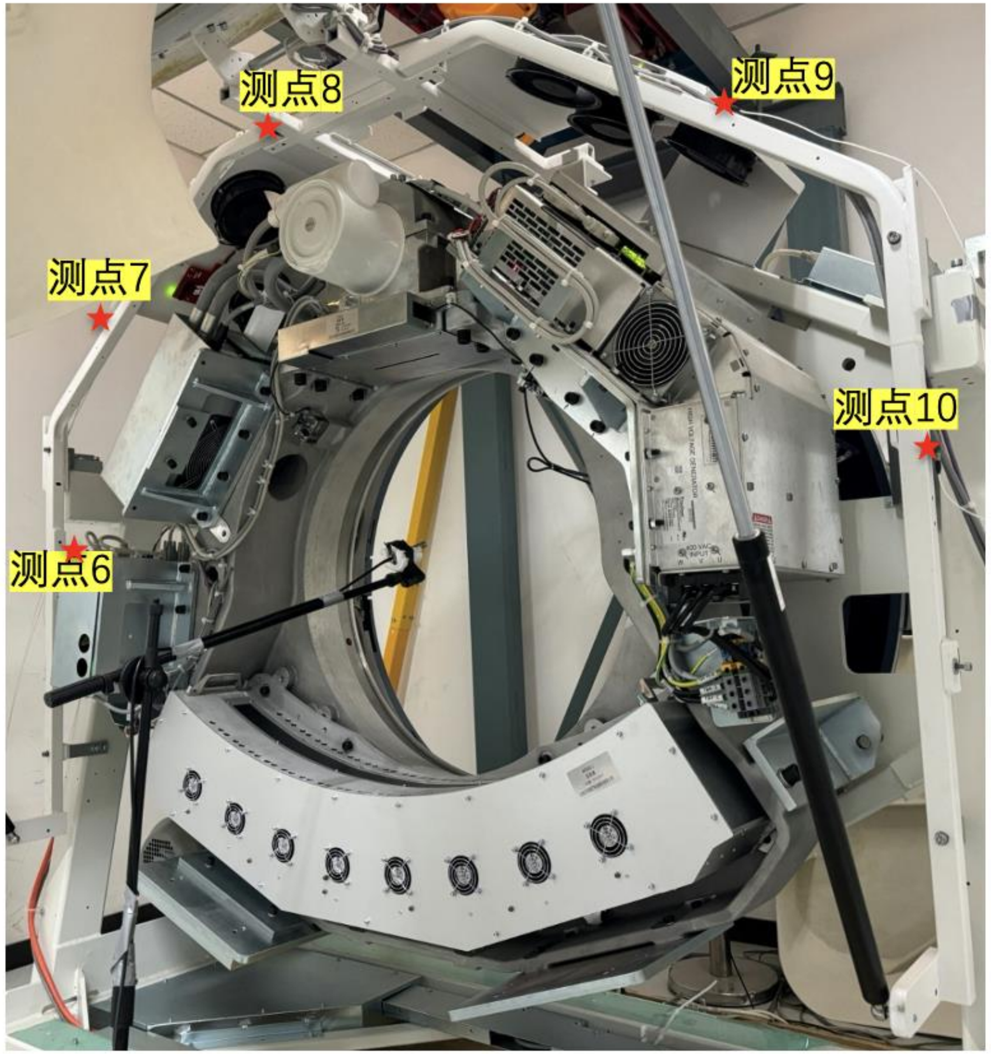
NVH in Medical Imaging Industry – CT

WDM Midea



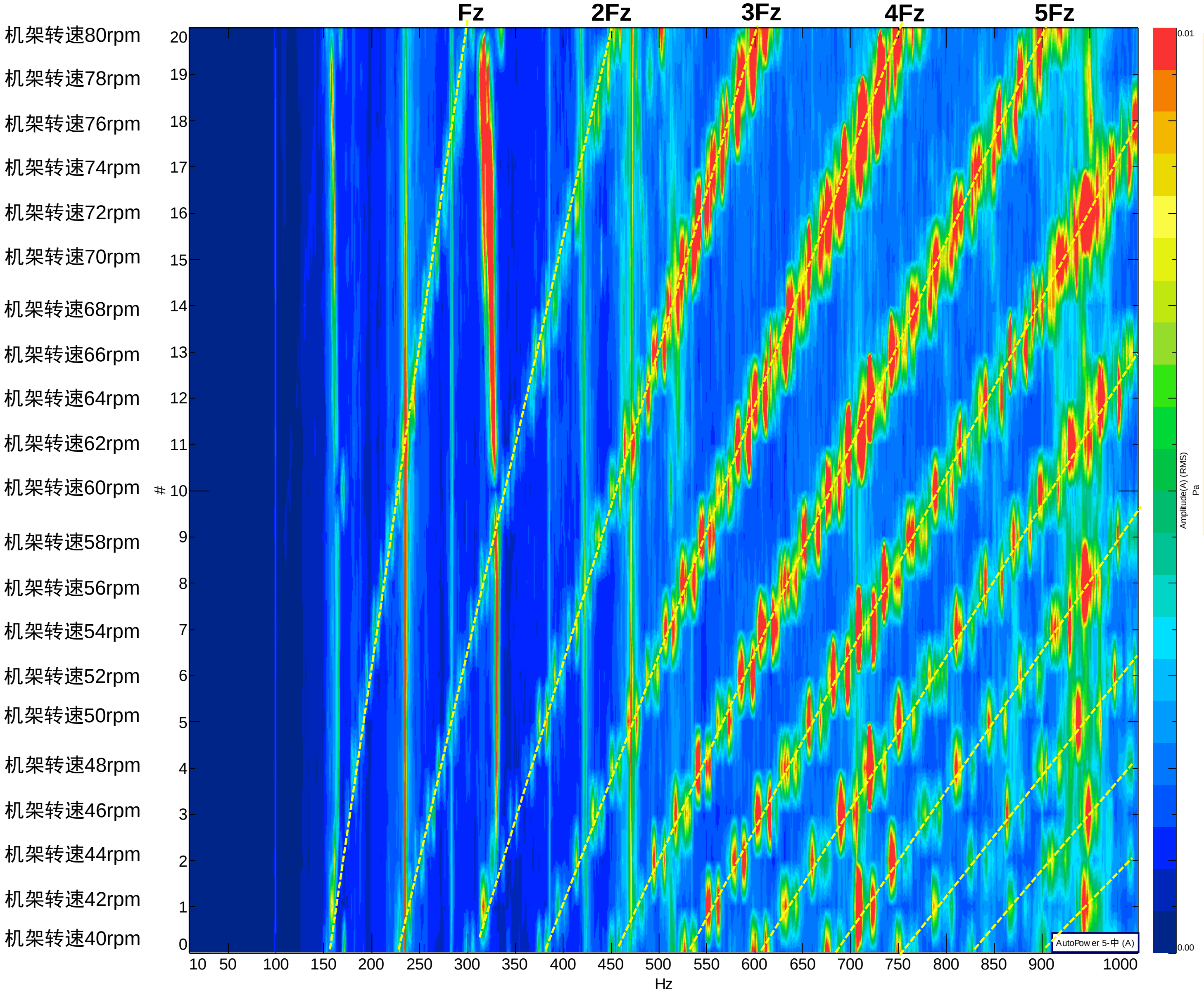
噪声传感器位置（测点1-5）
(参照下图中国标GB17589-2011，加设机架中心测点5)



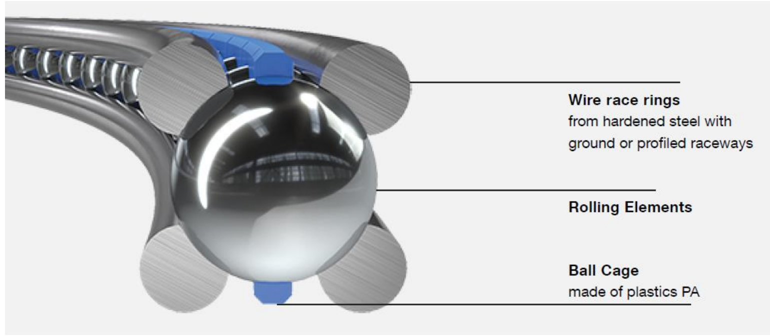


振动传感器位置（测点6-10），分布于外框架周围

NVH in Medical Imaging Industry – CT



- Gantry bearing, total number of balls = 400



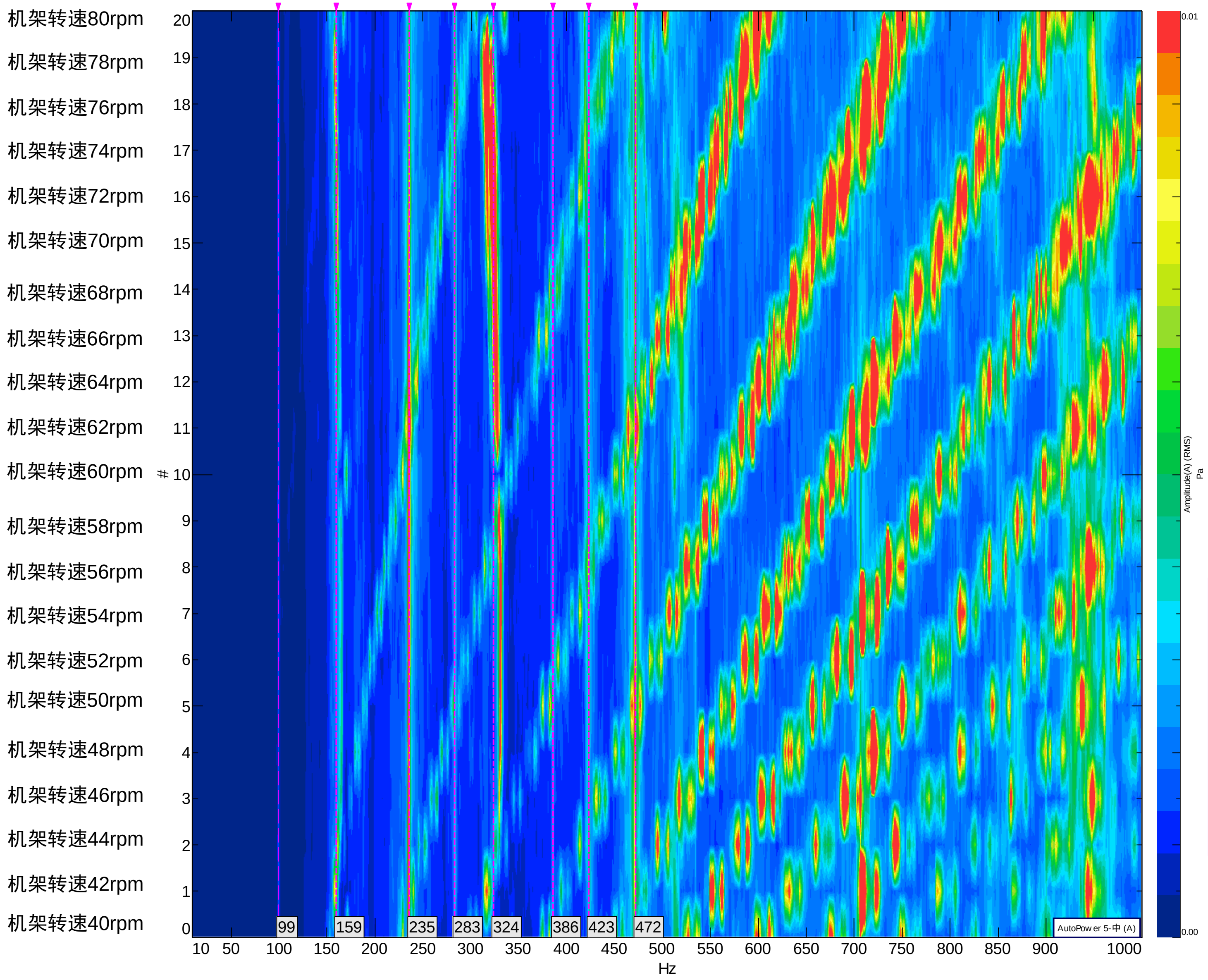
- Order Analysis

→ Fz = nZ/60 = 80***225**/60 = 300 Hz
（n: rotational speed，Z: **Broken balls**）

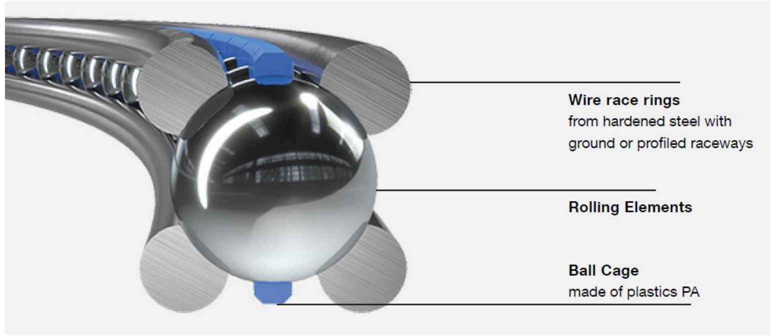
SAPEM 2023

NVH in Medical Imaging Industry – CT

WDM Midea



- Gantry bearing, total number of balls = 400



- Order Analysis

→ Fz = nZ/60 = 80***225**/60 = 300 Hz

（n: rotational speed，Z: **Broken balls**）

- **Fan Noise：99Hz, 235Hz, 283Hz, 472Hz**（ 2nd Harmonic of 235Hz）
- **Tube Noise：170Hz**（matched cathode rpm）**，340Hz**（2nd harmonic of 170Hz） - **Broken tube**
- **Gantry resonance：159Hz, 386Hz, 423Hz**

SAPEM 2023

Summary

- **Noise control on a system level is more complex than optimizing porous material's acoustical performance**
- **Powerful analytical and design tools were developed for us to understanding and design porous media's multi-functionality**
  - Near-field damping of porous sound absorbing material
  - Low frequency noise control by granular aerogel
  - Tunable sound package design involving 3D printed porous structure
- **System-level noise control needs comprehensive and diagnostic understanding of the system as a preliminary knowledge in order to design good treatments**
- **To look forward: from material-level to system level "digital twin" model combining multi-physics (next keynotes)**

List of Relevant Publications & Presentations

1. Y. Xue and J. S. Bolton, "Structural vibration damping by the use of poro-elastic layers: a summary," Technical Report of Inter-Noise, Chiba, Japan, August 2023.
2. Y. Xue and J. S. Bolton, "Design and optimization of lightweight porous dampers," Technical Report of the 184th ASA Meeting, Chicago, IL, USA, May 2023, https://docs.lib.purdue.edu/herrick/265/.
3. Y. Xue, J. S. Bolton and Y. Liu, "Modeling and coupling of acoustical layered systems that consist of elements having different transfer matrix dimensions", *Journal of Applied Physics*, **126**, 165012 (2019), https://doi.org/10.1063/1.5108635.
4. Y. Xue, J. S. Bolton, T. Herdtle, S. Lee and R. Gerdes, "Structural damping by layers of fibrous media on a periodically-constrained vibrating panel," *Journal of Physics: Conference Series* **1264**, 012043 (2019), https://iopscience.iop.org/article/10.1088/1742-6596/1264/1/012043.
5. Y. Xue, J. S. Bolton and T. Herdtle, "Design of lightweight fibrous vibration damping treatments to achieve optimal performance in realistic applications," *SAE Technical Paper*, https://doi.org/10.4271/2019-01-1524.
6. Y. Xue, J. S. Bolton, T. Herdtle, S. Lee and R. Gerdes, "Structural damping by lightweight poro-elastic media," *Journal of Sound and Vibration*, **459**, 114866 (2019), https://doi.org/10.1016/j.jsv.2019.114866.
7. Y. Xue and J. S. Bolton, "Microstructure design of the lightweight fibrous material acting as a layered damper for a vibrating stiff panel," *Journal of the Acoustical Society of America*, **143**(6), 3254-3265 (2018), https://doi.org/10.1121/1.5038255.
8. Y. Xue, J. S. Bolton, R. Gerdes, S. Lee and T. Herdtle, "Prediction of airflow resistivity of fibrous acoustical media having two fiber components and a distribution of fiber radii," *Applied Acoustics*, **134**, 145-153 (2018), https://doi.org/10.1016/j.apacoust.2018.01.011.
9. Y. Xue, J. S. Bolton and Y. Liu, "The acoustical coupling of poro-elastic media in a layered structure based on the transfer matrix method," *Proceedings of Inter-Noise*, paper 1857, Madrid, Spain, June 2019, https://docs.lib.purdue.edu/herrick/200/.
10. Y. Xue, J. S. Bolton, T. Herdtle, S. Lee and R. Gerdes, "A comparison between glass fibers and polymeric fibers when serving as a structural damping medium for fuselage-like structures," *Proceedings of Inter-Noise*, paper 1478, Chicago, IL, August 2018, https://docs.lib.purdue.edu/herrick/179.
11. Y. Xue and J. S. Bolton, "Fibrous material microstructure design for optimal structural damping," *Journal of the Acoustical Society of America*, **143**(3), 1715; *Proceedings of the 175th ASA Meeting*, Minneapolis, MN, May 2018, https://docs.lib.purdue.edu/herrick/176.
12. Y. Xue and J. S. Bolton, "Fibrous material microstructure design for optimal damping performance," *Proceedings of the Symposium on the Acoustics of Poro-Elastic Materials (SAPEM)*, Le Mans, France, December 2017, http://docs.lib.purdue.edu/herrick/168.
13. T. Herdtle, Y. Xue and J. S. Bolton, "Numerical modeling of the acoustics of low density fibrous media having a distribution of fiber sizes," *Proceedings of the SAPEM*, Le Mans, France, December 2017, http://docs.lib.purdue.edu/herrick/167.
14. Y. Xue, J. S. Bolton, R. Gerdes, S. Lee and T. Herdtle, "Prediction of airflow resistivity of fibrous acoustical media having double fiber components and a distribution of fiber radii," *Proceedings of Inter-Noise*, pages 5649-5657, Hong Kong, China, August 2017, http://docs.lib.purdue.edu/herrick/165.

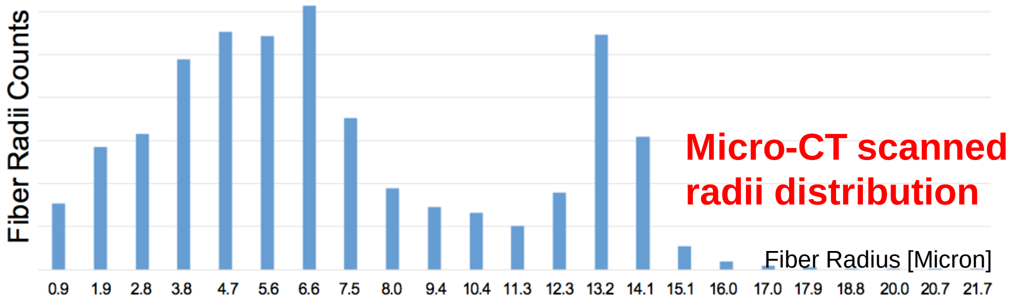
List of Relevant Publications & Presentations

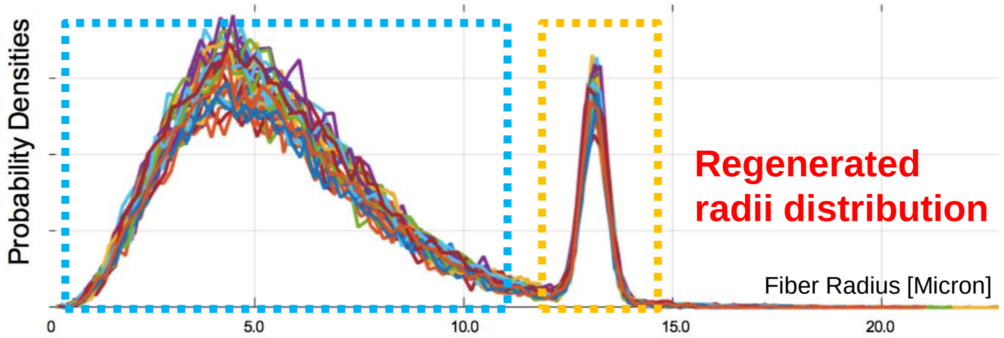
15. B. Wojciechowski, Y. Xue, A. Rabbani, J. S. Bolton and B. Sharma, "Additively manufactured spinodoid sound absorbers," *Additive Manufacturing*, **71**, 103608 (2023), https://doi.org/10.1016/j.addma.2023.103608.
16. L. P. Nobles, B. Sharma, Y. Xue and J. S. Bolton, "Combining granular aerogels with additively manufactured porous structures for broadband sound absorption," *Proceedings of the 184th ASA Meeting*, Chicago, IL, USA, May 2023, https://docs.lib.purdue.edu/herrick/273.
17. Y. Xue, B. Sharma and J. S. Bolton, "Low frequency, wideband noise control by tunable aerogel layers and the potential of multi-functional acoustic materials," Keynotes at the 30th Vibration and Noise Technology Advances (VNTA), Xi'an, China, July 2023, https://mp.weixin.qq.com/s/7aV2C0Zj6a093GH8QC7vAg.
18. Y. Xue, J. S. Bolton and B. Sharma, "Tunable sound packages made of granular aerogels and fibrous media," *Noise Control Engineering Journal* (2022), https://doi.org/10.3397/1/377035.
19. H. Begum, Y. Xue, J. S. Bolton and K. V. Horoshenkov, "The acoustical properties of air-saturated aerogel powders," *Journal of the Acoustical Society of America*, **151**, 1502 (2022), https://doi.org/10.1121/10.0009635.
20. A. Dasyam, Y. Xue, J. S. Bolton and B. Sharma, "Effect of particle size on sound absorption behavior of granular aerogel," *Journal of Non-Crystalline Solids*, **598**, 121942 (2022), https://doi.org/10.1016/j.jnoncrysol.2022.121942.
21. W. Johnston, Y. Xue, B. Sharma and J. S. Bolton, "Programmable sound absorption performance enabled by 3D printing fibers," *Proceedings of NOVEM,* Auckland, New Zealand, January 2023, https://docs.lib.purdue.edu/herrick/263/.
22. H. Begum, Y. Xue, J. S. Bolton, K. V. Horoshenkov, "A key physical mechanism that controls the sound absorption of aerogel powders," *Proceedings of Inter-Noise*, Glasgow, Scotland, August 2022, https://docs.lib.purdue.edu/herrick/257/.
23. A. Dasyam, Y. Xue, B. Sharma and J. S. Bolton, "Acoustical properties of granular aerogel agglomerates," *Proceedings of the* 182^{nd} *ASA Meeting*, Denver, CO, May 2022, https://docs.lib.purdue.edu/herrick/247/.
24. Y. Xue, B. Sharma and J. S. Bolton, "Tunable aerogel-fiber sound packages for low frequency noise control," *Proceedings of the Symposium on the Material Acoustics, Technologies and Industrialization (MATI)*, Suzhou, China, April 2023.
25. Y. Xue, A. Dasyam, J. S. Bolton and B. Sharma, "Low-frequency noise control using layered granular aerogel and limp porous media," *Proceedings of Inter-Noise*, online conference, August 2021, https://doi.org/10.3397/IN-2021-2215.
26. Y. Xue, A. Dasyam, J. S. Bolton and B. Sharma, "Acoustical investigation of aerogel granules modeled as a layer of poro-elastic material," *Proceedings of the Symposium on the Acoustics of Poro-Elastic Materials (SAPEM)*, online conference, March 2021, https://docs.lib.purdue.edu/herrick/235 and https://sapem2021.matelys.com/proceedings/07-05_Xue_etal.mp4.
27. Y. Xue and J. S. Bolton, "Low frequency absorption enhancement by modification of poro-elastic layered sound package," *Proceedings of Noise-Con*, online conference, November 2020, https://docs.lib.purdue.edu/herrick/233/.
28. S. H. Wasala, Y. Xue, L. Stevens, T. Wiegandt, and T. Persoons, "Numerical simulations of flow induced noise from a dual-rotor cooling fan used in electronic cooling systems," *Proceedings of Inter-Noise*, online conference, August 2021, https://doi.org/10.3397/IN-2021-1809.
29. S. H. Wasala, Y. Xue, T. Wiegandt, L. Stevens and T. Persoons, "Aeroacoustic noise prediction from a contra-rotating cooling fan used in data center cooling systems," *AIAA AVIATION Forum Technical Paper*, Washington, D.C. June 2021. https://doi.org/10.2514/6.2021-2313.

Thank you!

Backups

Micro-Macro Relation (AFR)
Transfer Matrix Method (TMM)



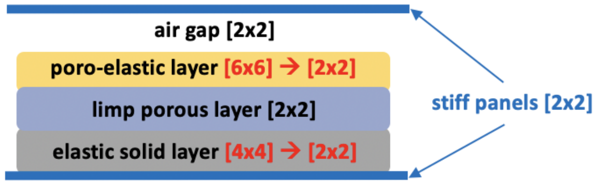


$$f_1(x \mid s_1, \theta) = \frac{1}{\Gamma(s_1)\theta^{s_1}} x^{s_1-1} e^{-\frac{x}{\theta}}$$

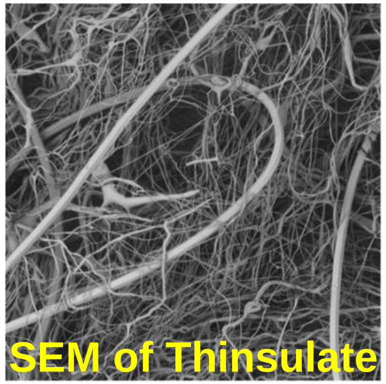
$\theta = r_1/s_1$

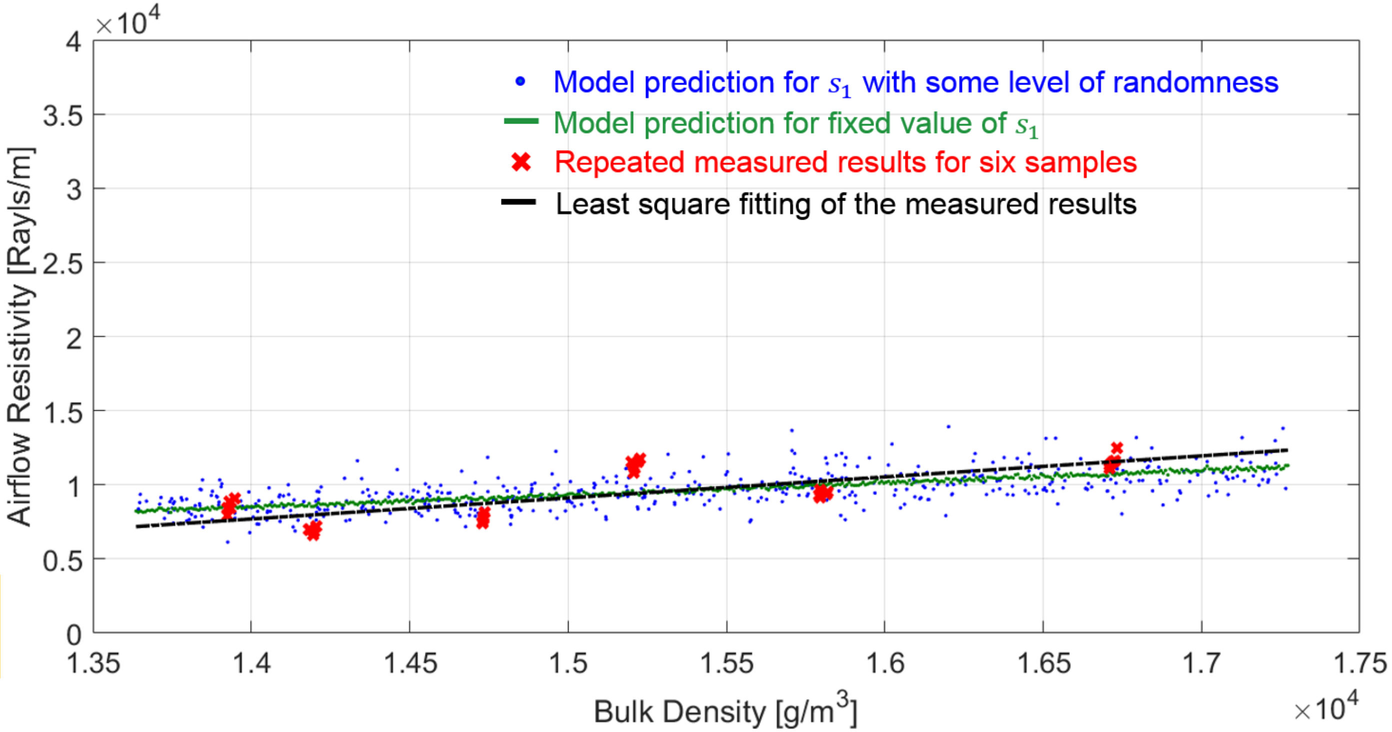
$$f_2(x \mid \mu, s_2{}^2) = \frac{1}{\sqrt{2\pi s_2{}^2}} e^{-\frac{(x-\mu)^2}{2s_2{}^2}}$$

$\mu = r_2$



- TMM big idea: [2x2] matrices multiplied in a series





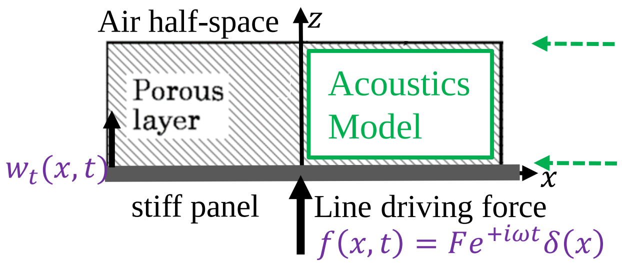
Experimental validation of AFR prediction

Coupling of Acoustic Terms with the NFD Model

- **TMM / ACM + NFD – based on a harmonic line force-driven, unconstrained panel**

Porous medium: thickness (d), AFR (σ), bulk density (ρ_b), porosity (ϕ), tortuosity (α_∞), Young's modulus (E), Poisson's ratio (ν), loss factor (η)

Panel: basis weight (m_s), flexural stiffness per unit width (D), longitudinal stiffness per unit width (D_p)



Acoustic pressure, p_2, and normal velocity, v_{z2}, at $z = d$

Acoustic pressure, p_1, and normal velocity, v_{z1}, at $z = 0$

Euler-Bernoulli beam theory

Governing Equation (GE) at $z = 0$

$$D\frac{\partial^4 w_t(x,t)}{\partial x^4} + m_s\frac{\partial^2 w_t(x,t)}{\partial t^2} = -p_1(x,t) + f(x,t)$$

Governing Equation Fourier Transform (GEFT)

$$(Dk_x^4 - \omega^2 m_s)w_t(k_x,\omega) = -p_1(k_x,\omega) + F$$

Panel mechanical impedance: $Z_m = -i[(D/\omega)k_x^4 - \omega m_s]$

Input N_s, γ_s for IDFT

Wavenumber response of panel velocity

$$v_t = i\omega w_t = v_{z1}$$
$$= F/[Z_{a1}(k_x,\omega) + Z_m(k_x,\omega)]$$

IDFT for spatial response

$$v_t(m\Delta x,\omega) = \frac{1}{N_s\Delta x}\sum_{n=0}^{N_s-1} v_t(n\Delta k_x,\omega)e^{\frac{-i2\pi mn}{N_s}}$$

Power analysis

Power input

$$P_{in}(\omega) = \frac{1}{2}\mathrm{Re}\{Fv_t^*(x=0,\omega)\}$$

Power radiation into the porous layer

$$P_1(\omega) = \frac{1}{2}\mathrm{Re}\left\{\int_{-\infty}^{\infty} p_1 v_{z1}^*\, dx\right\}$$
$$= \frac{1}{4\pi}\mathrm{Re}\left\{\int_{-\frac{\gamma_s}{2}}^{\frac{\gamma_s}{2}} Z_{a1}|v_{z1}(k_x,\omega)|^2\, dk_x\right\}$$

Power radiation into the air

$$P_2(\omega) = \frac{1}{2}\mathrm{Re}\left\{\int_{-\infty}^{\infty} p_2 v_{z2}^*\, dx\right\}$$
$$= \frac{1}{4\pi}\mathrm{Re}\left\{\int_{-\frac{\gamma_s}{2}}^{\frac{\gamma_s}{2}} Z_{a2}|v_{z2}(k_x,\omega)|^2\, dk_x\right\}$$

Power dissipation in the porous layer

$$P_d(\omega) = P_1 - P_2$$

System equivalent damping loss factor

$$\eta_e = \frac{E_{in}}{E_{tot}} = \frac{(P_{in} - P_2)/\omega}{\mathrm{KE} + \mathrm{PE}}$$

Damping performance evaluation

Parameters input

Acoustic impedance at $z = 0$: $Z_{a1} = \frac{p_1}{v_{z1}}$

Acoustic impedance at $z = d$: $Z_{a2} = \frac{p_2}{v_{z2}} = \frac{\omega\rho_{air}}{k_{zair}}$

Input porous medium bulk properties (σ, ρ_b, ϕ, α_∞, E, ν, η)

JCA & Biot theory

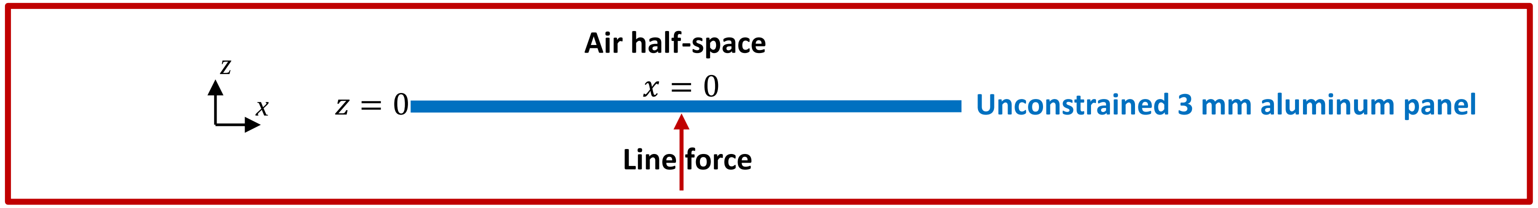
Complex wave numbers (k_i, $i = 1$ for limp frame, $i = 3$ for elastic frame)

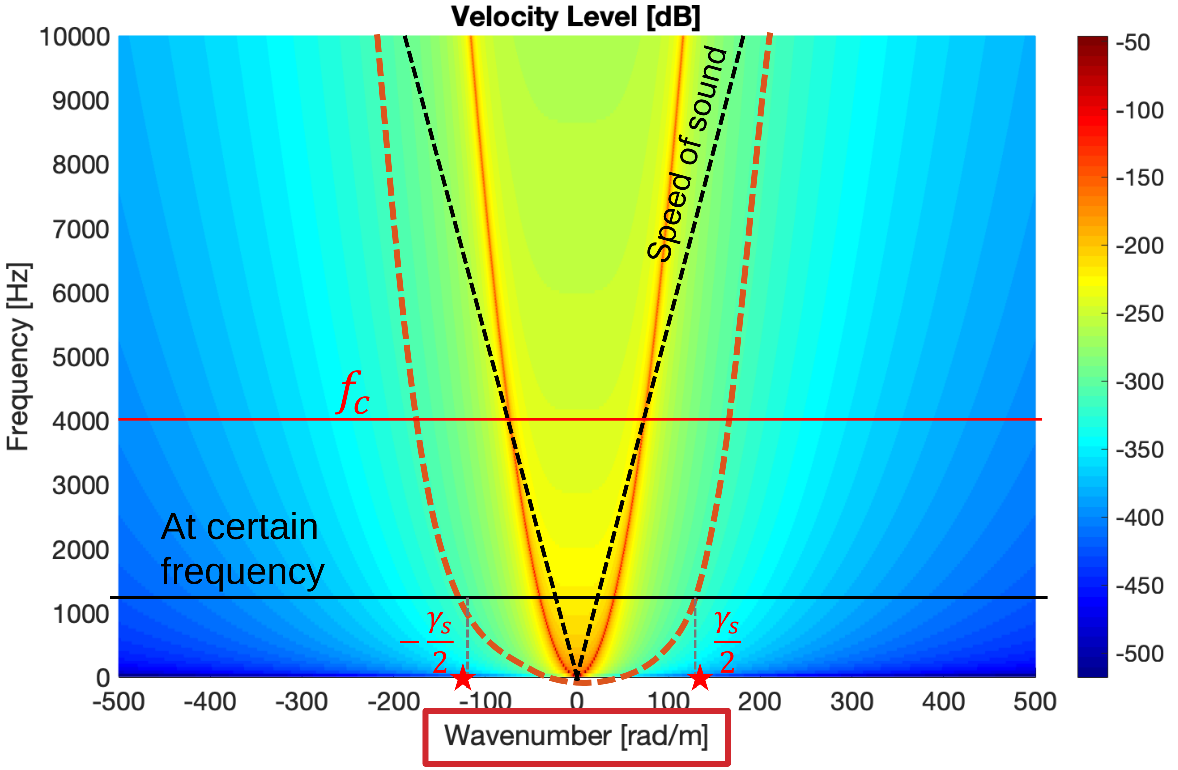
Input d, D, D_p

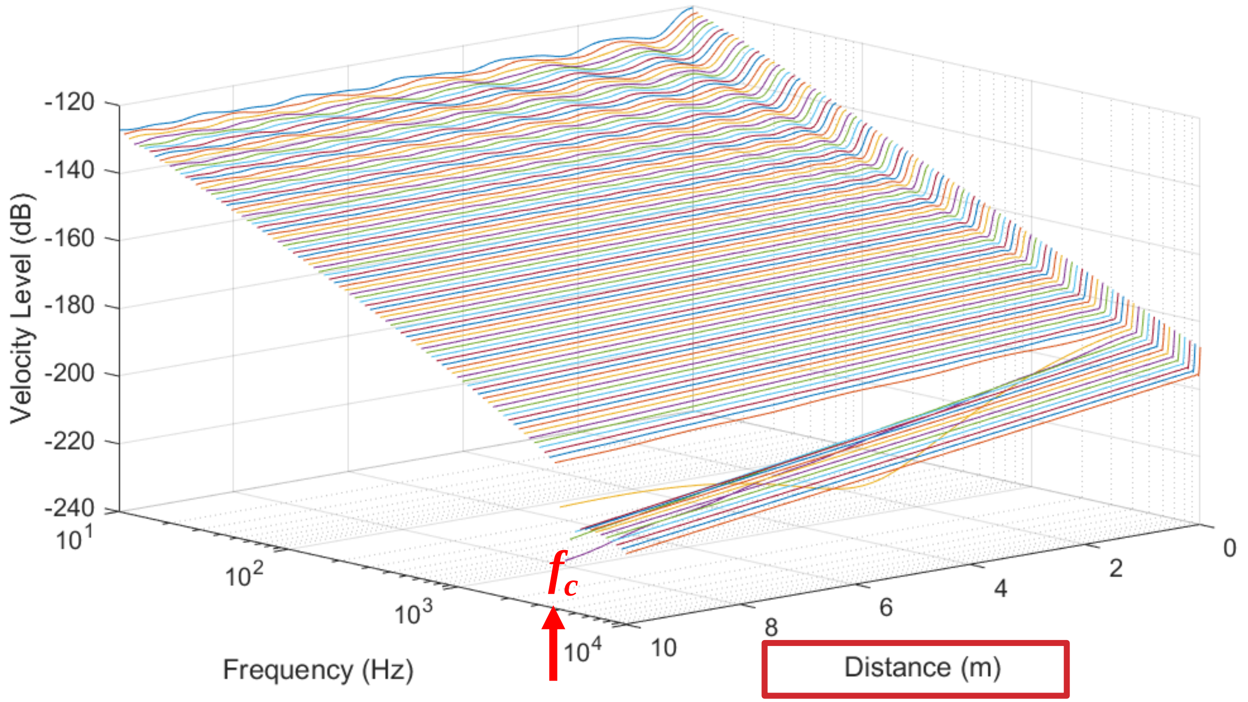
TMM / ACM to solve for the acoustical properties

NFD Modeling Key Point

- An example to show wavenumber ←→ spatial domain Fourier transform



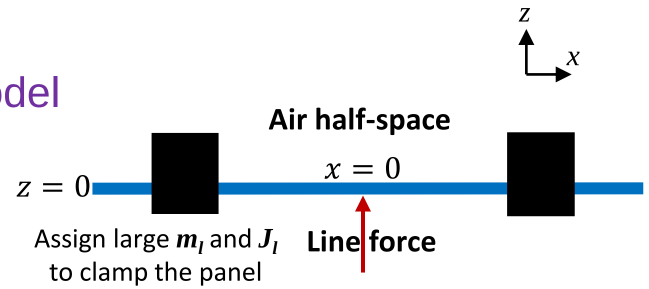


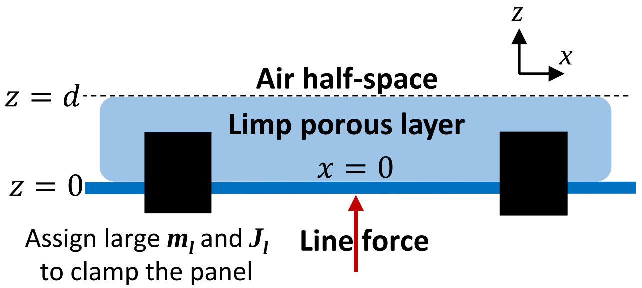


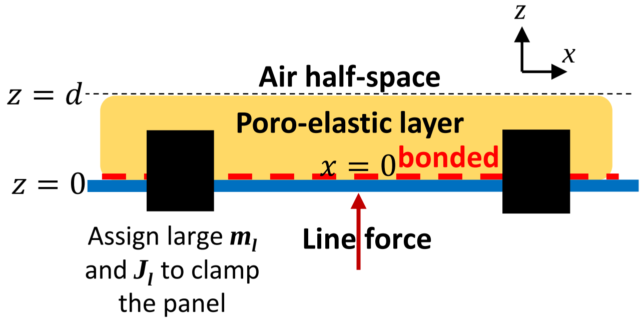
NFD Model Validation

- **Velocity response spectrum at $x = 0$ of a partially-clamped, 1 mm aluminum panel**

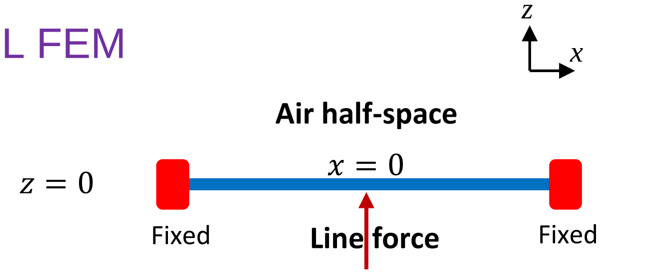
➢ NFD model

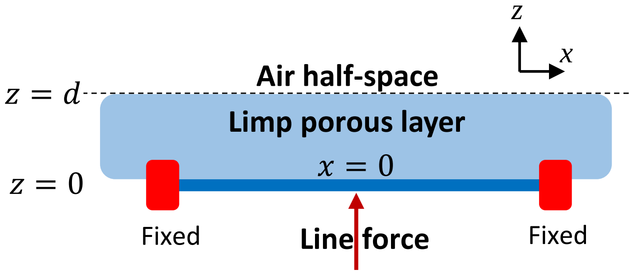


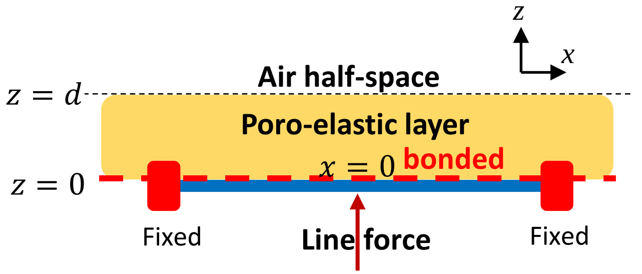




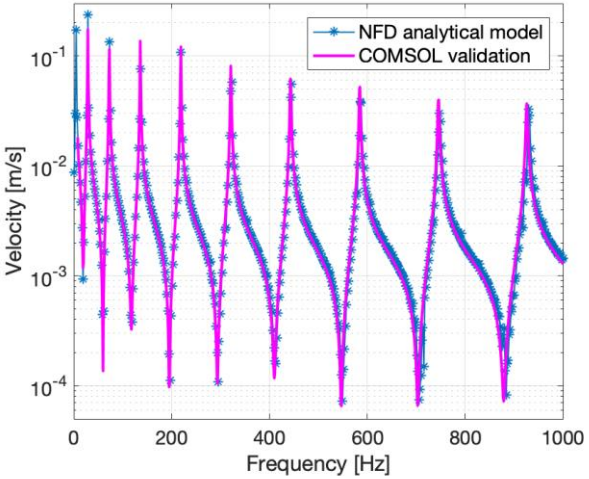
➢ COMSOL FEM

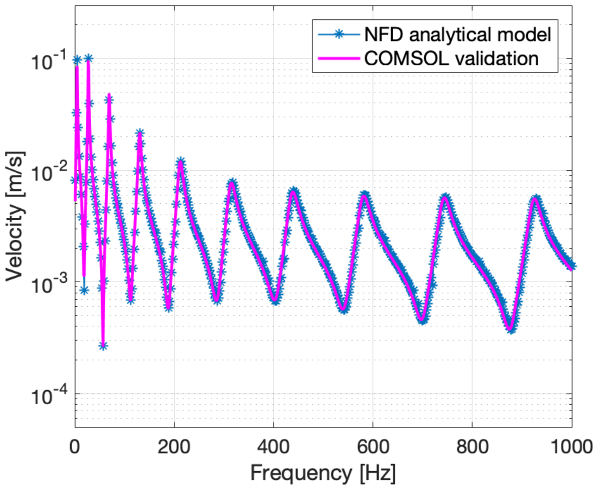


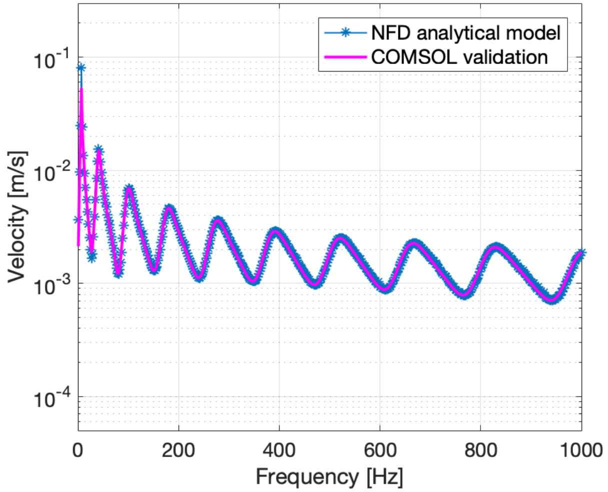




➢ Comparison

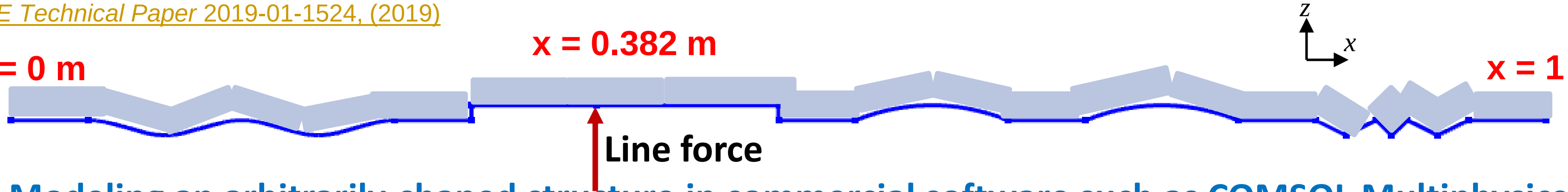






NFD Optimization on an Arbitrarily-Shaped Vibrating Structure

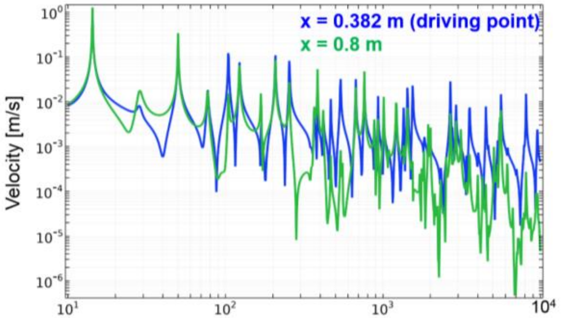
* *SAE Technical Paper* 2019-01-1524, (2019)

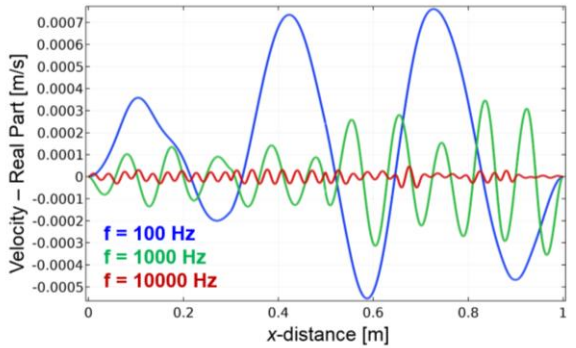


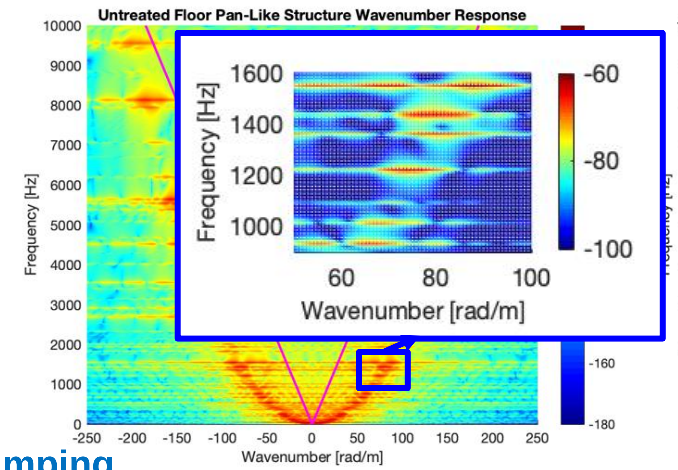
Adding 5 cm, 10 kg/m3 polymeric fibers

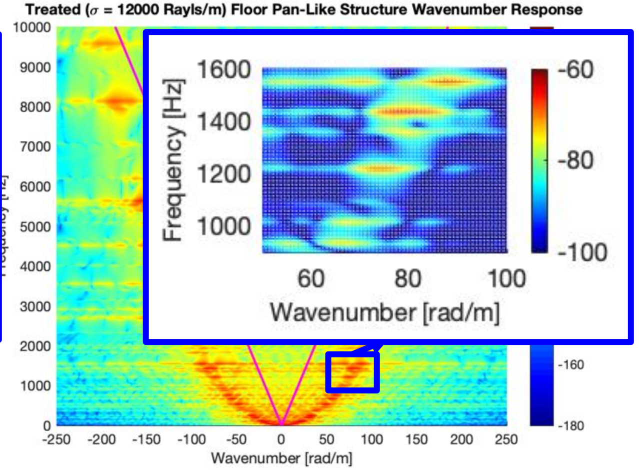
Vehicle floor-pan

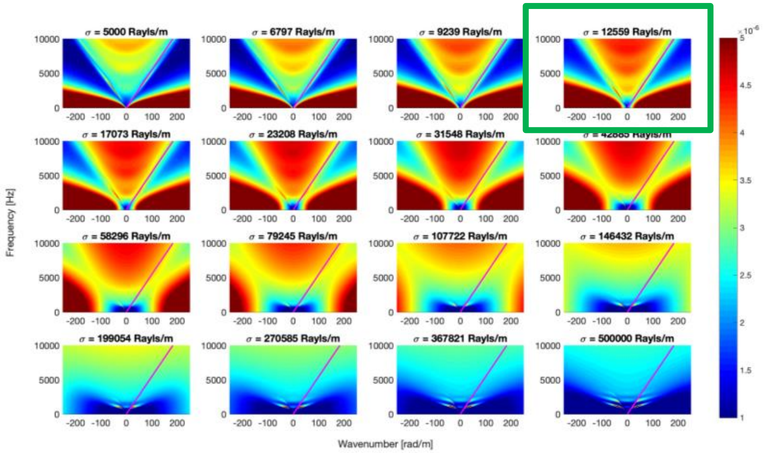
Modeling an arbitrarily-shaped structure in commercial software such as COMSOL Multiphysics



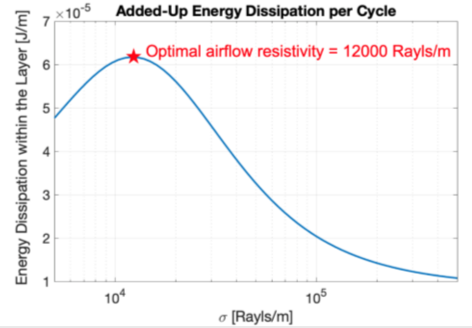


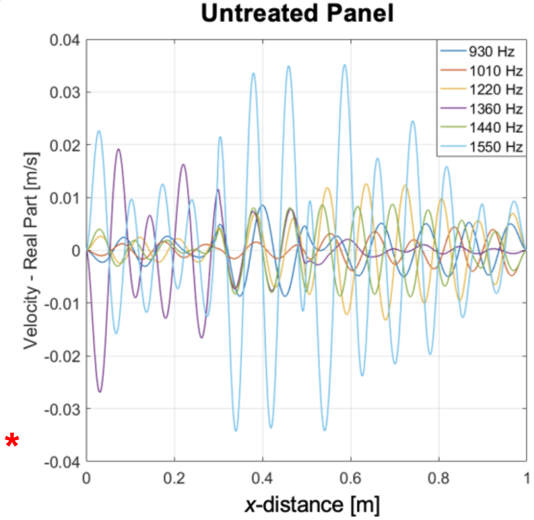


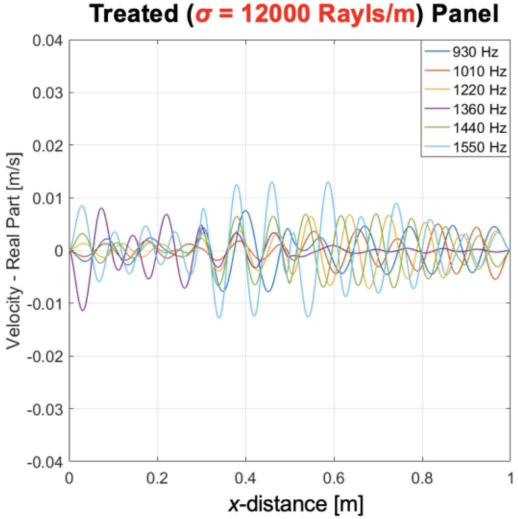




Optimizing averaged-damping in 900-1600Hz, 50-100 rad/m





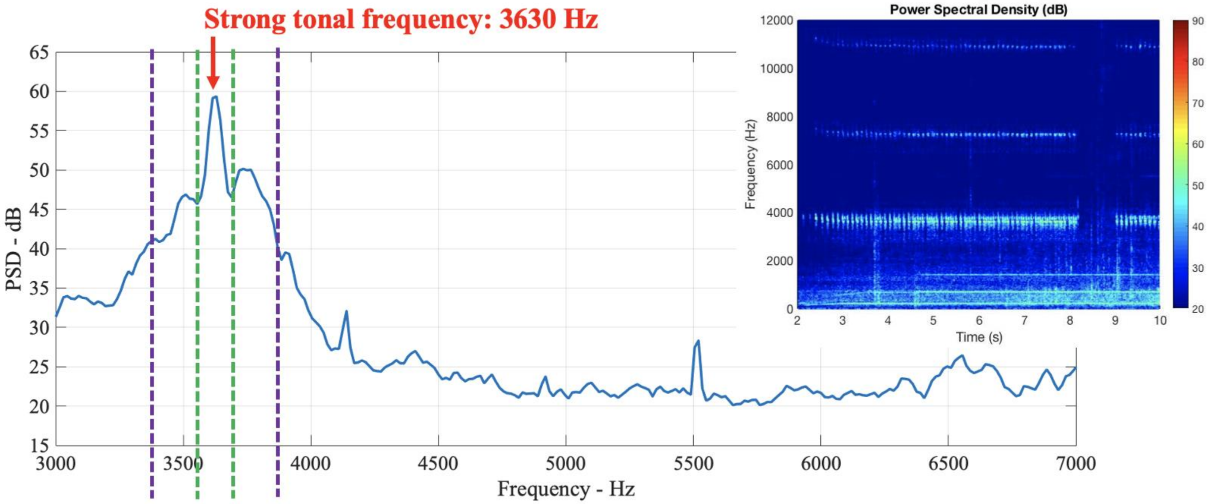


- **Optimal solution:** fibers airflow resistivity~12000 Rays/m (radius 3.6 μm) *

Noise Signal Processing for Faulty Part Diagnosis *

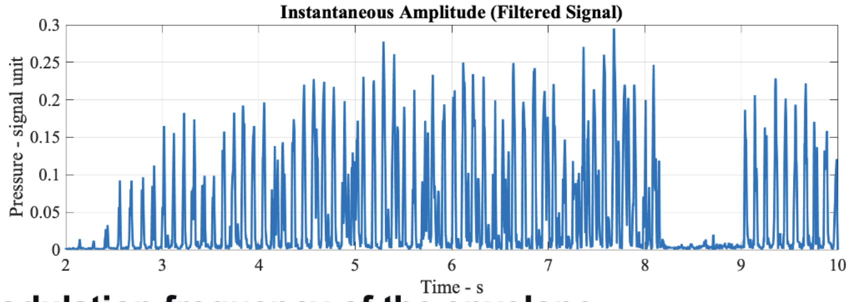
* *Proceedings of Noise-Con*, Paper s76, 2019

- DFT (using FFT algorithm) for PSD analysis & narrowband filtering

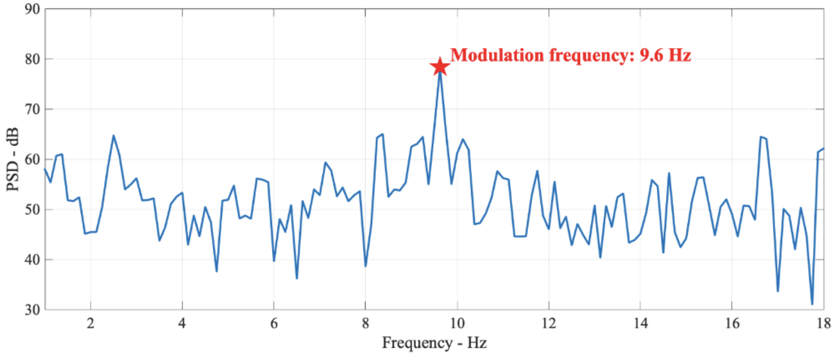


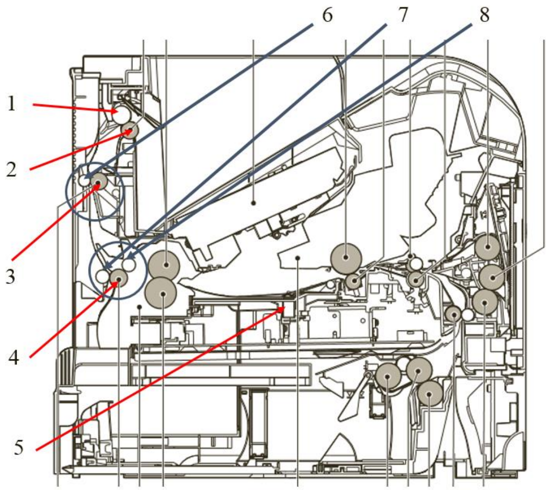
Passband [3580 Hz, 3680 Hz] and **stopband [3380 Hz, 3880 Hz]** **of the Butterworth IIR filter**

- Envelope of the narrowband filtered complex analytic signal



- Modulation frequency of the envelope





1: Face-down delivery roller 1
2: Face-down delivery roller 2
3: Intermediate delivery roller
4: Fuser delivery roller
5: Inner delivery roller
6: Idler roller 1 (not driven)
7: Idler roller 2 (not driven)
8: Idler roller 3 (not driven)

Table 2: Diagnoses results from the squeaking signals.

Noise samples	Strong tonal frequency [Hz]	Modulation frequency [Hz]	Corresponding rotational speed [rps]	Squeaking parts
Squeaking 1	3779	7.93	8.17	Idler roller 3
Squeaking 2	3473	5.80	6.17	Face-down delivery roller 1
Squeaking 3	8797	10.40	10.90	Inner delivery roller
Squeaking 4	3647	5.81	6.17	Face-down delivery roller 1
Squeaking 5	3727	10.40	10.90	Inner delivery roller
Squeaking 6	3617	9.60	9.52	Idler roller 1

Looking at the Fan Noise and its Disturbance from a Hard Drive's Perspective *

* *Proceedings of Inter-Noise*, Paper 1809, 2021
* *AIAA AVIATION Forum* Technical Paper 2021-2313, 2021

HDD's area: highly sensitive to acoustic disturbance

PCB area: cooling target

Axial cooling fan modules

- **Potential extended application in monitoring and controlling UAV / UAM noise, which is being increasingly focused**

Quiet Drones 2022 | NASA Acoustics Working Group and UAM Noise
Hyundai Launches New Company to Advance Urban Air Mobility: Supernal