Sorrento SAPEM'23 常熟

Experimental study of granular activated carbon stacks' level- and time-dependent behavior

PURDUE MECHANICAL ENGINEERING

RAY W. HERRICK LABORATORIES

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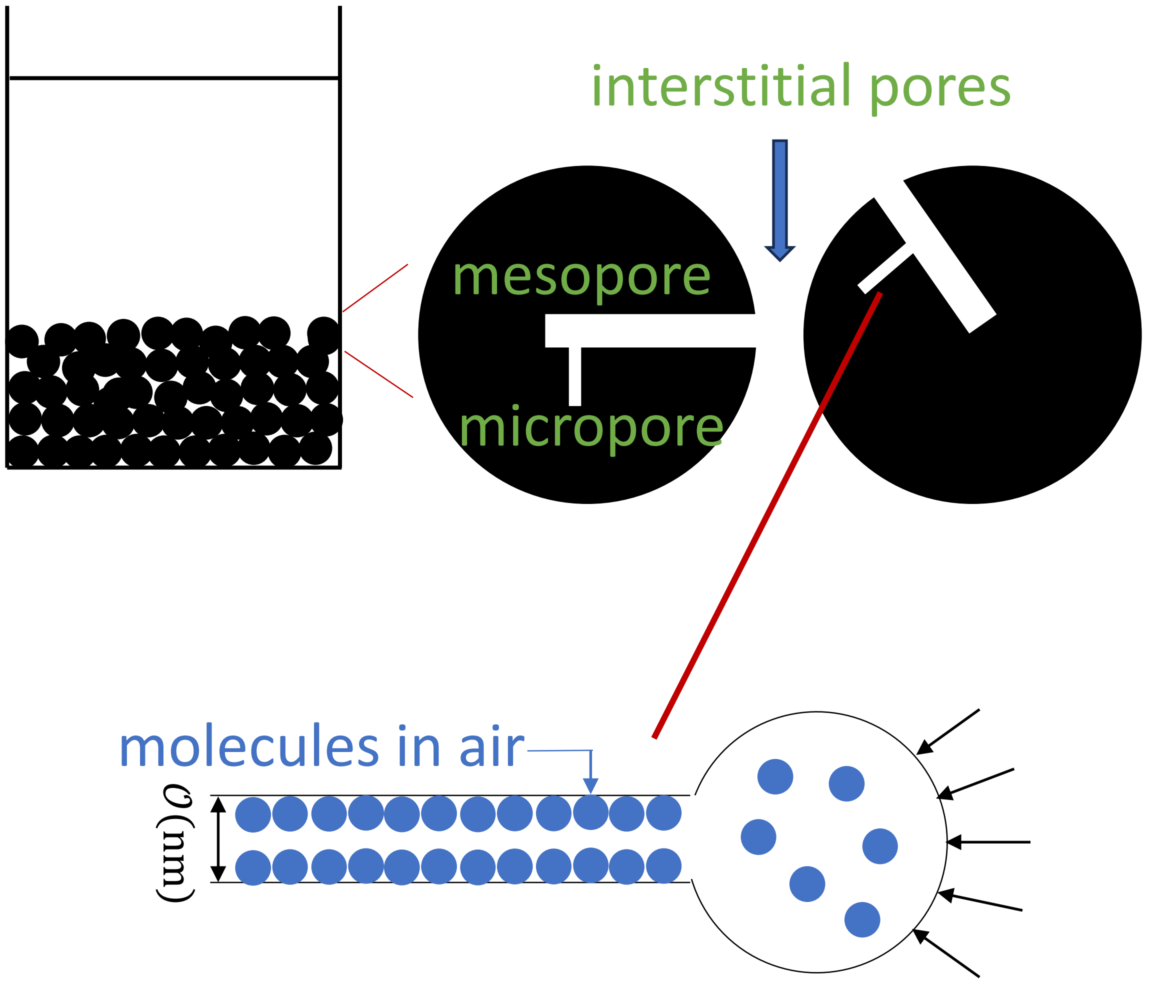
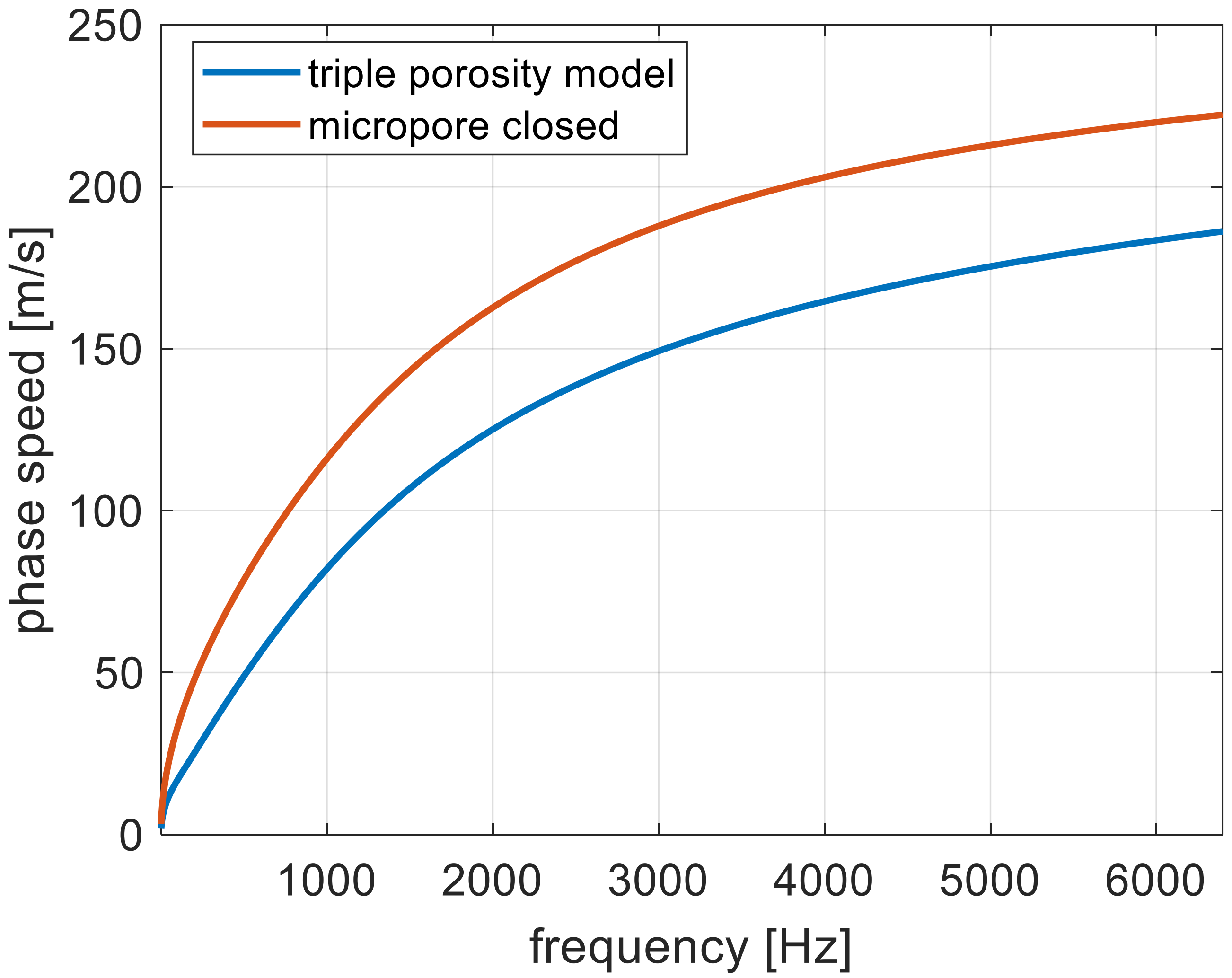
Agenda

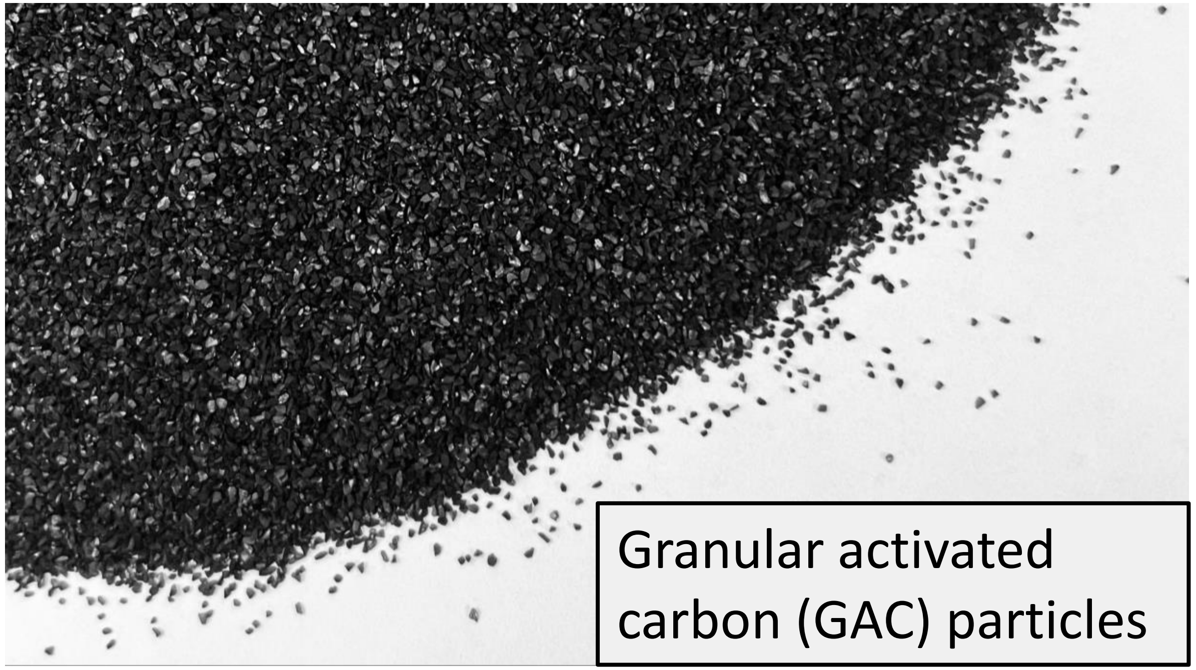
- Motivation & test setup
- Circumferential edge-constraint effect
- Level-dependent behavior
- Time-dependent behavior
- Conclusions

Motivation (1/3): hierarchical porosity of the activated carbon particles





Motivation (2/3): particle stacks' benefits & applications



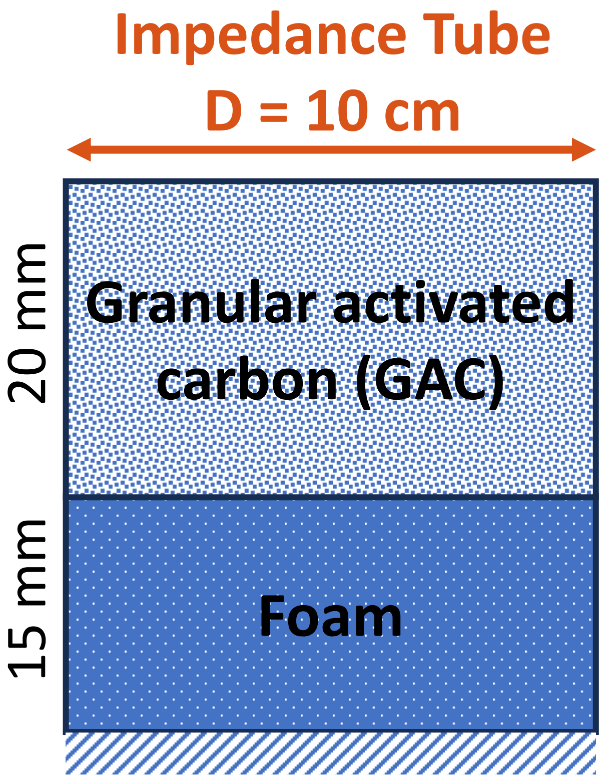
Benefits of high surface area particles:

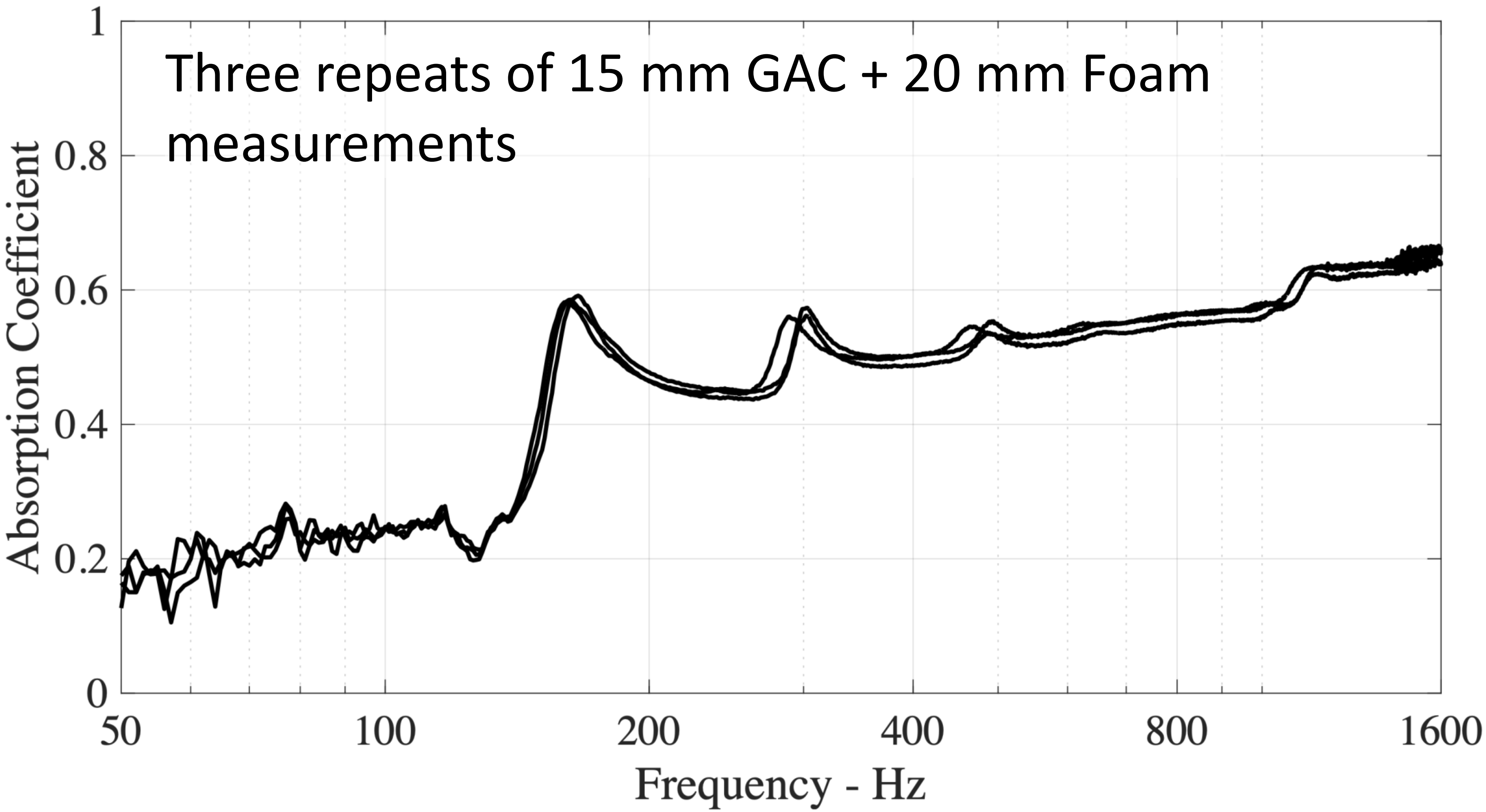
1. Remarkable sorption characteristics
2. Better low frequency sound absorption

Applications:

1. when the space to apply the acoustical treatment is limited (e.g., micro-speakers)
2. when one wants to enhance the low-frequency performance of the acoustical treatment (embed particles within the matrix)
3. when the granular particle has already been adopted in various fields, e.g., for thermal insulation (extend it also as an acoustic treatment)

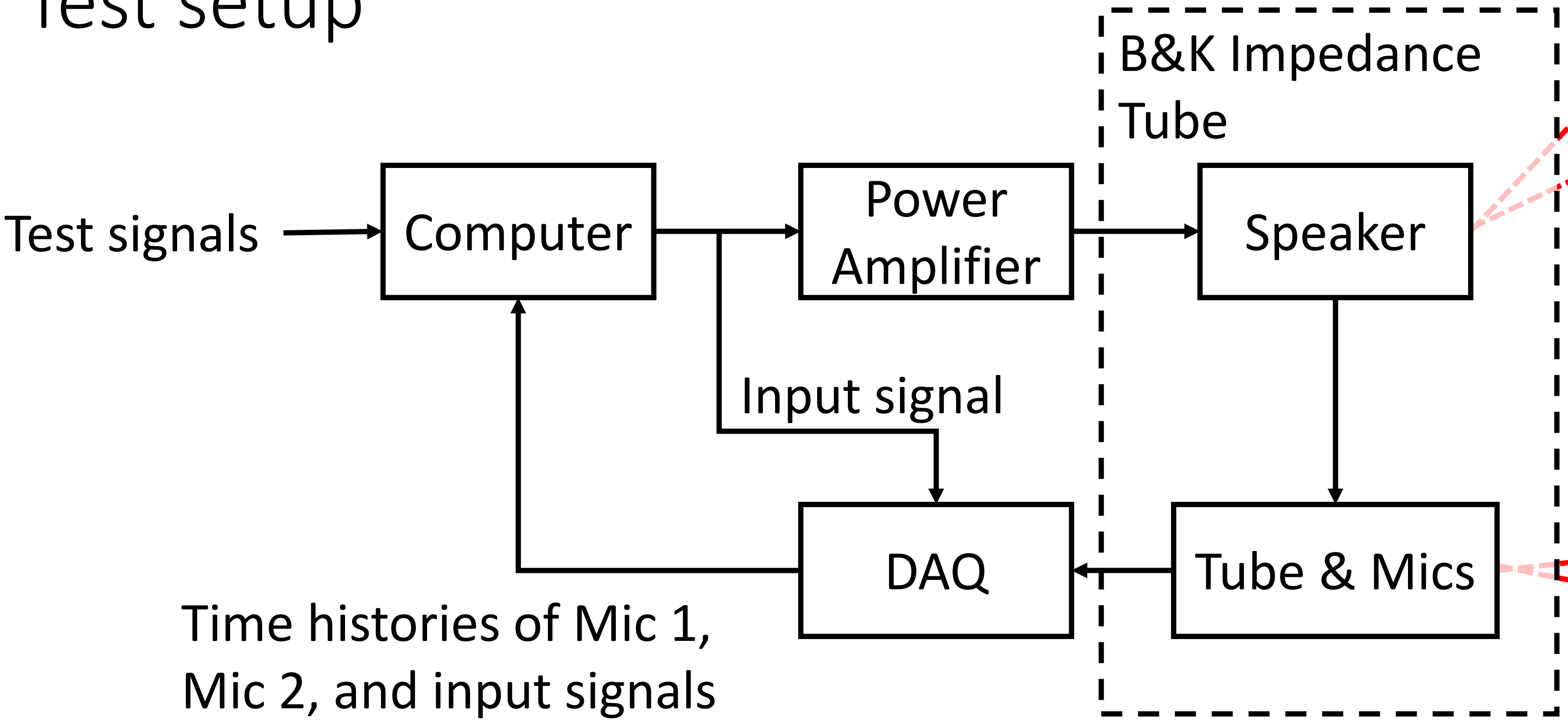
Motivation (3/3): one more thing…

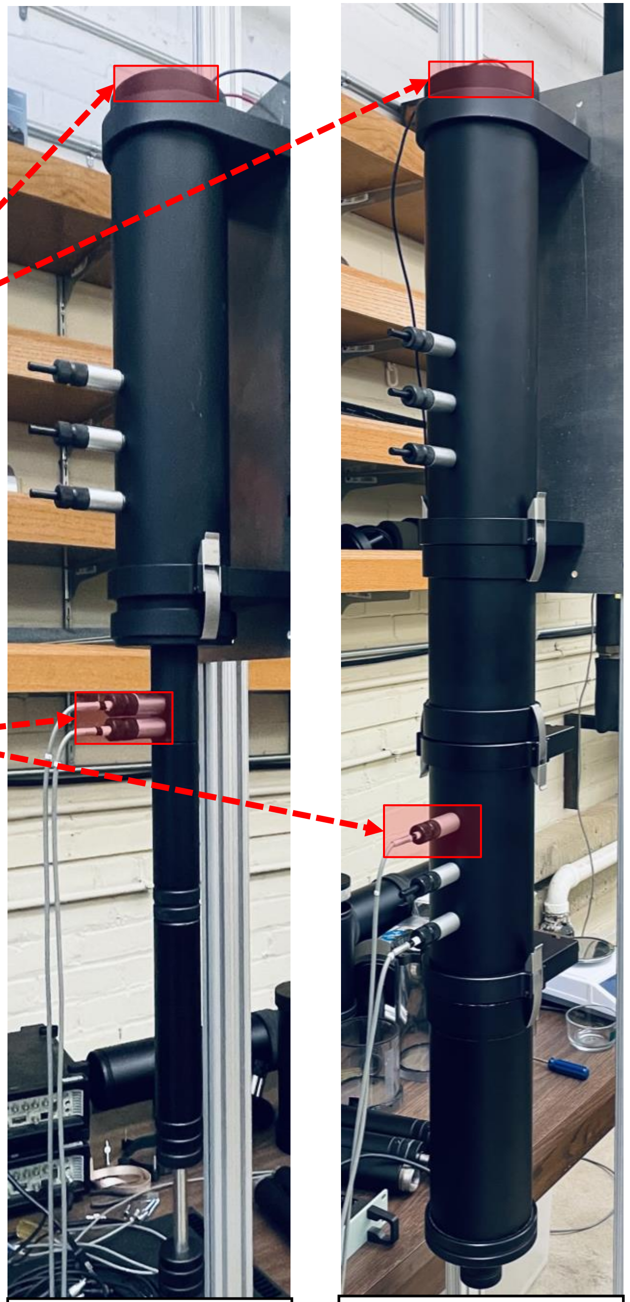




- Need to develop accurate models to allow treatment optimization.
- Must allow for unique behavior of particle stacks: edge effect, level- and time-dependence

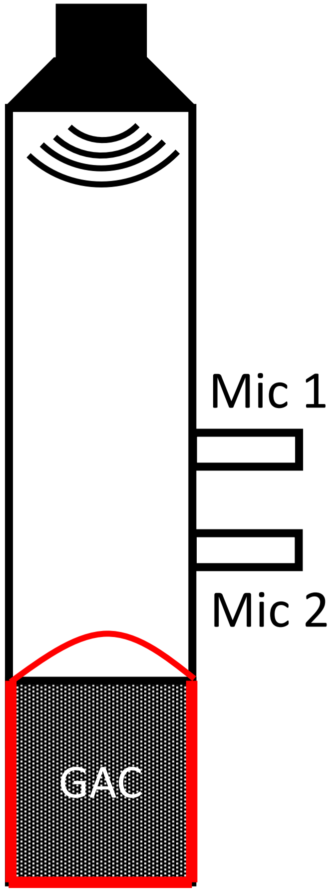
Test setup




Small Tube
Large Tube

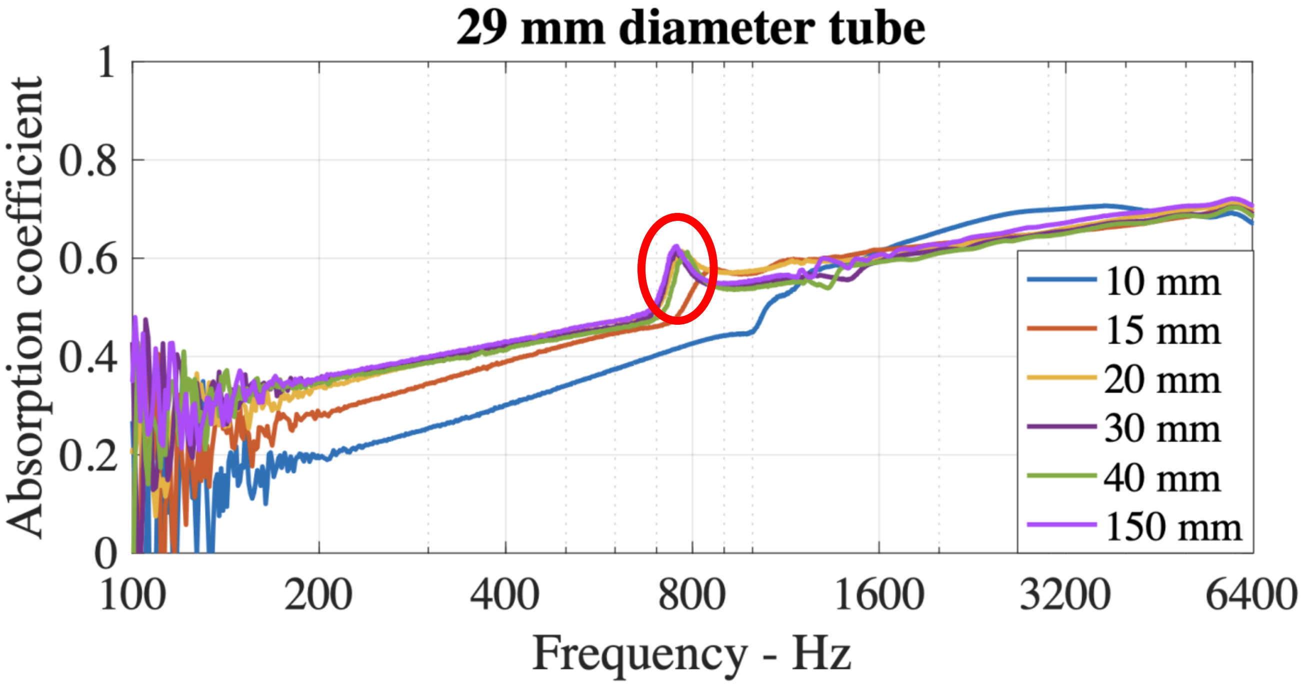
Granular material	GAC [Type A]	GAC [Type B]	GAC [Type C]	GAC [Type D]
Particle diameter [μm]	250-500	150-300	250-500	150-300
Bulk density [kg/m³]	520	530	440	410

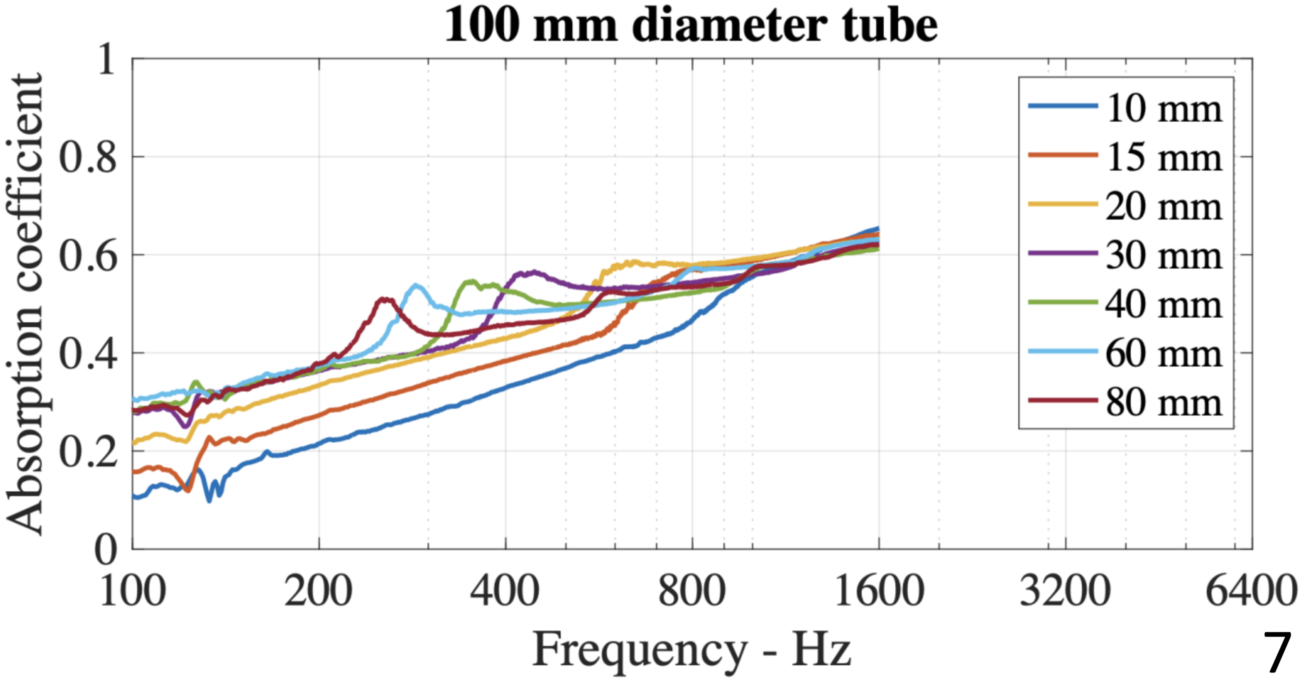
Edge-Constraint Effect
Type A GAC particle stack



- Particle stacks tend to <u>stick to the wall</u>.
- This edge constraint effect can affect the absorption spectrum.

- When the stack depth is greater than the tube diameter, the <u>quarter wave resonance</u> transitions to <u>the first radial model</u>.
- Conventional <u>1-D models</u> only work when <u>stack depth smaller than the tube diameter</u>





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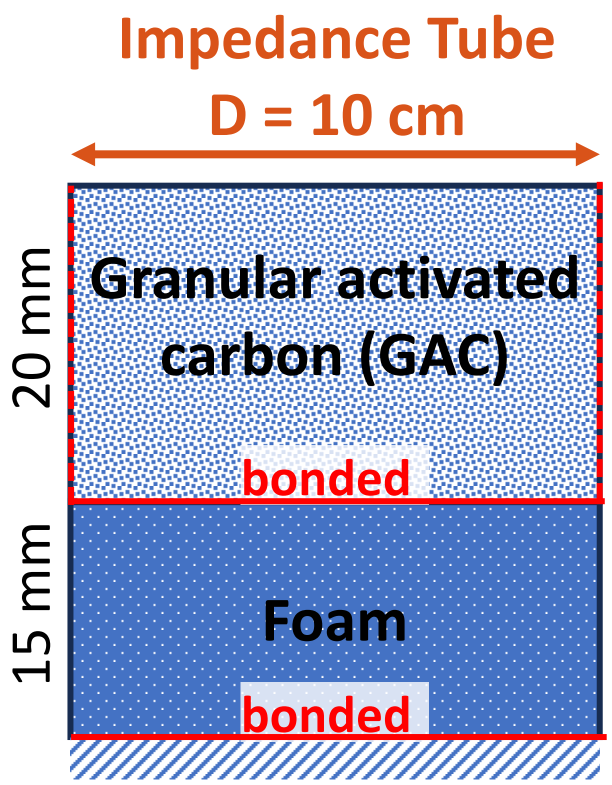
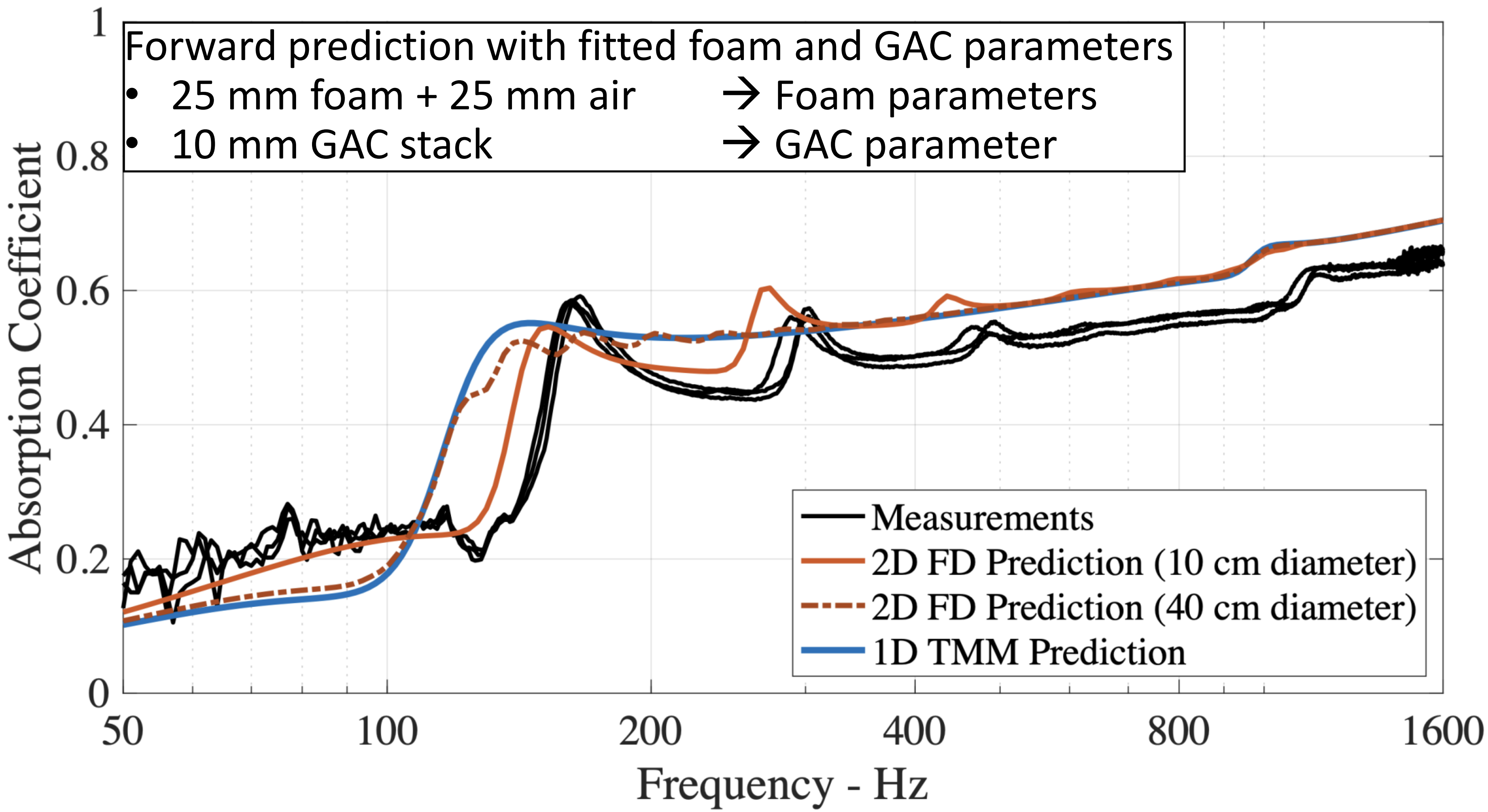
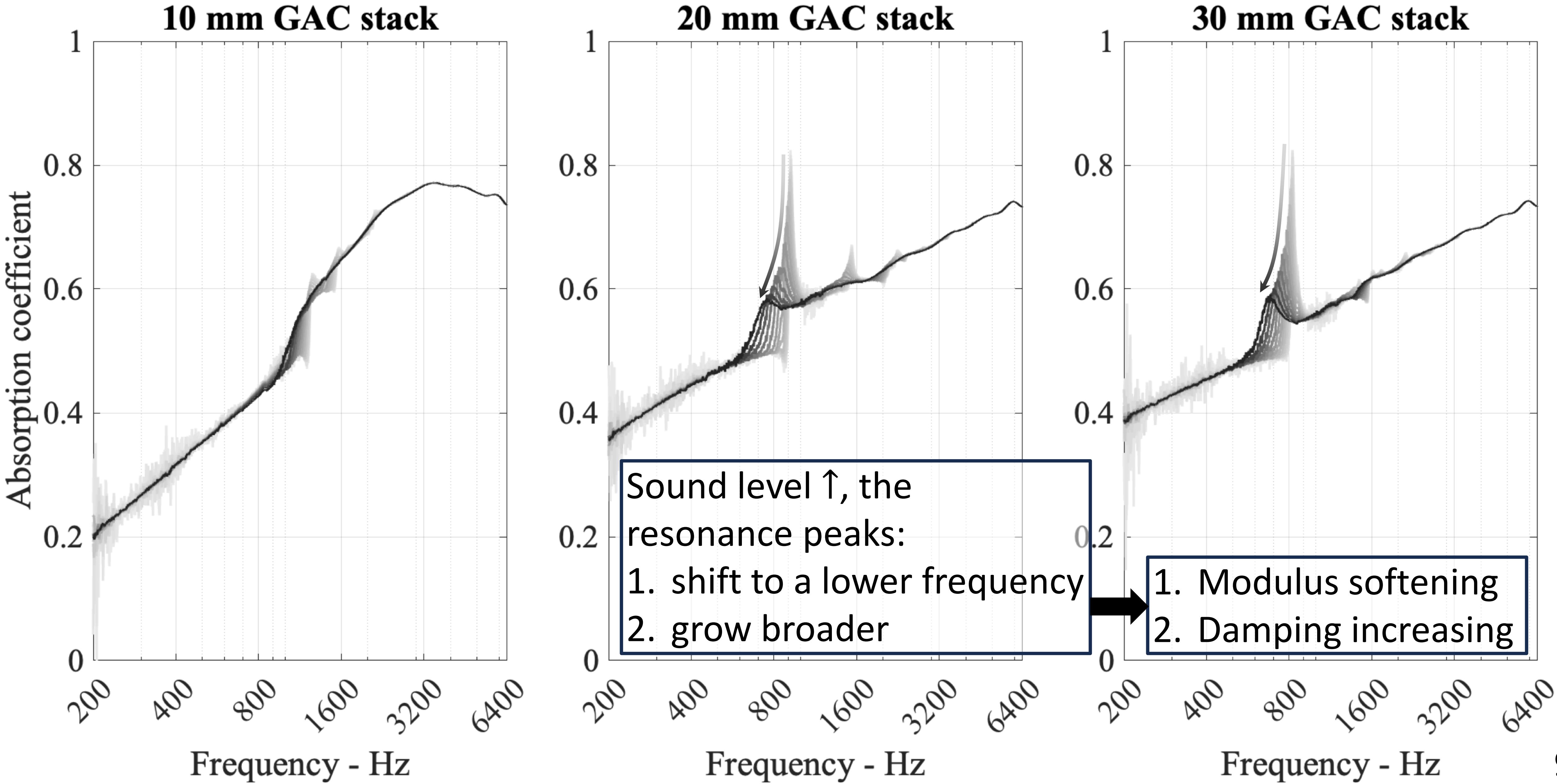
Recap on motivations





- 2D predictions converge to 1D case when sample diameter increases
- Therefore, can use 1D theory to predict and optimize large area treatments

Level-dependent absorption spectral – Type A GAC stacks



Level-dependent test setup

Random noise

↓

Band-pass filters
[4^{th} order Butterworth]

↓

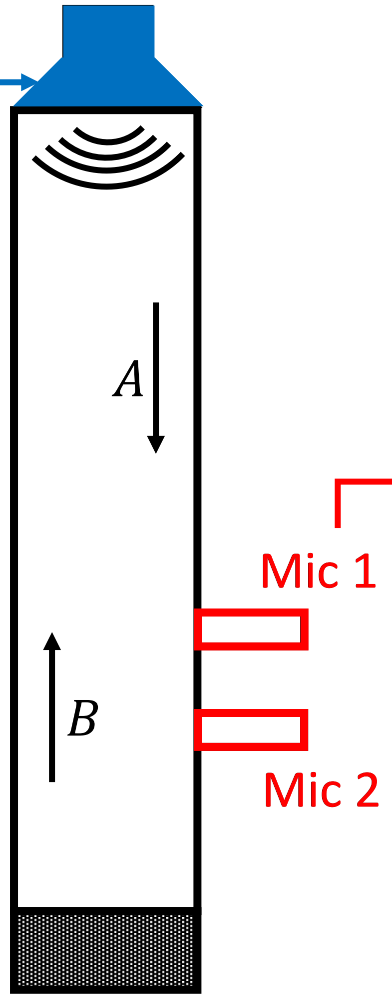
Scale to 12 levels
[in steps of 2 dB]

↓

In total:
4 bands x 12 levels = 48 signals

Frequency bands:

- 500 – 1000 Hz
- 500 – 2000 Hz
- 500 – 4000 Hz
- 500 – 6000 Hz



For each signal:

- Measure material acoustical properties following the ASTM E1050 standard
- Calculate three metrics related to the acoustic field at the surface of the particle stack
- Investigate the particle stack's change of acoustic properties when exposed to different signals

Varying level & bandwidth

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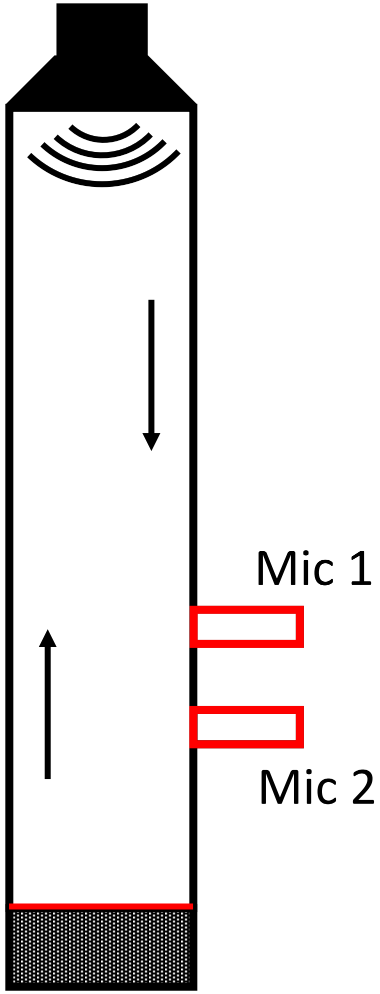
Level metrics – Integrated RMS fluid pressure, velocity, displacement



Complex pressure at Mic 1 & 2, $P_1(f)$ and $P_2(f)$

Complex fluid pressure, velocity, displacement at the of front surface of the material:

- $P_0 = F_{P_0}(P_1, P_2)$
- $v_0 = F_{v_0}(P_1, P_2)$
- $u_0 = F_{u_0}(P_1, P_2)$

Power spectrum of P_0, v_0, u_0 at the of front surface of the material:

$$S_{P_0P_0} = G_{P_0}(S_{P_1P_1}, S_{P_2P_2}, S_{P_1P_2})$$
$$S_{v_0v_0} = G_{v_0}(S_{P_1P_1}, S_{P_2P_2}, S_{P_1P_2})$$
$$S_{u_0u_0} = G_{u_0}(S_{P_1P_1}, S_{P_2P_2}, S_{P_1P_2})$$

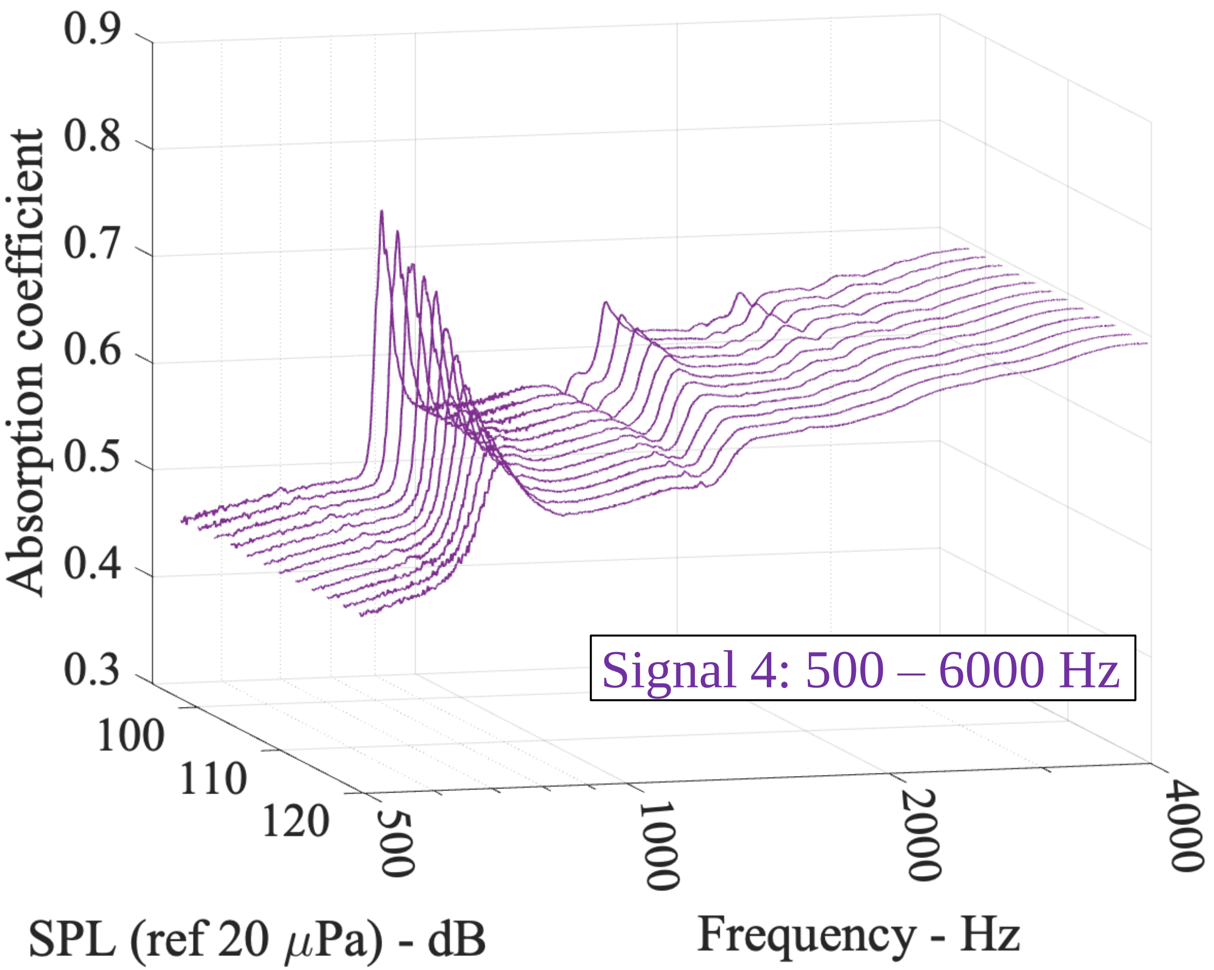
Integrate over frequency:

- $(P_0)^2_{rms} = \int S_{P_0P_0}(f)df$ $\rightarrow SPL$
- $(v_0)^2_{rms} = \int S_{v_0v_0}(f)df$ → Integrated RMS fluid velocity
- $(u_0)^2_{rms} = \int S_{u_0u_0}(f)df$ → Integrated RMS fluid displacement

Edge Effect | Level-dep | Time-dep

Test results: 40 mm Type A GAC stack

Sound pressure level

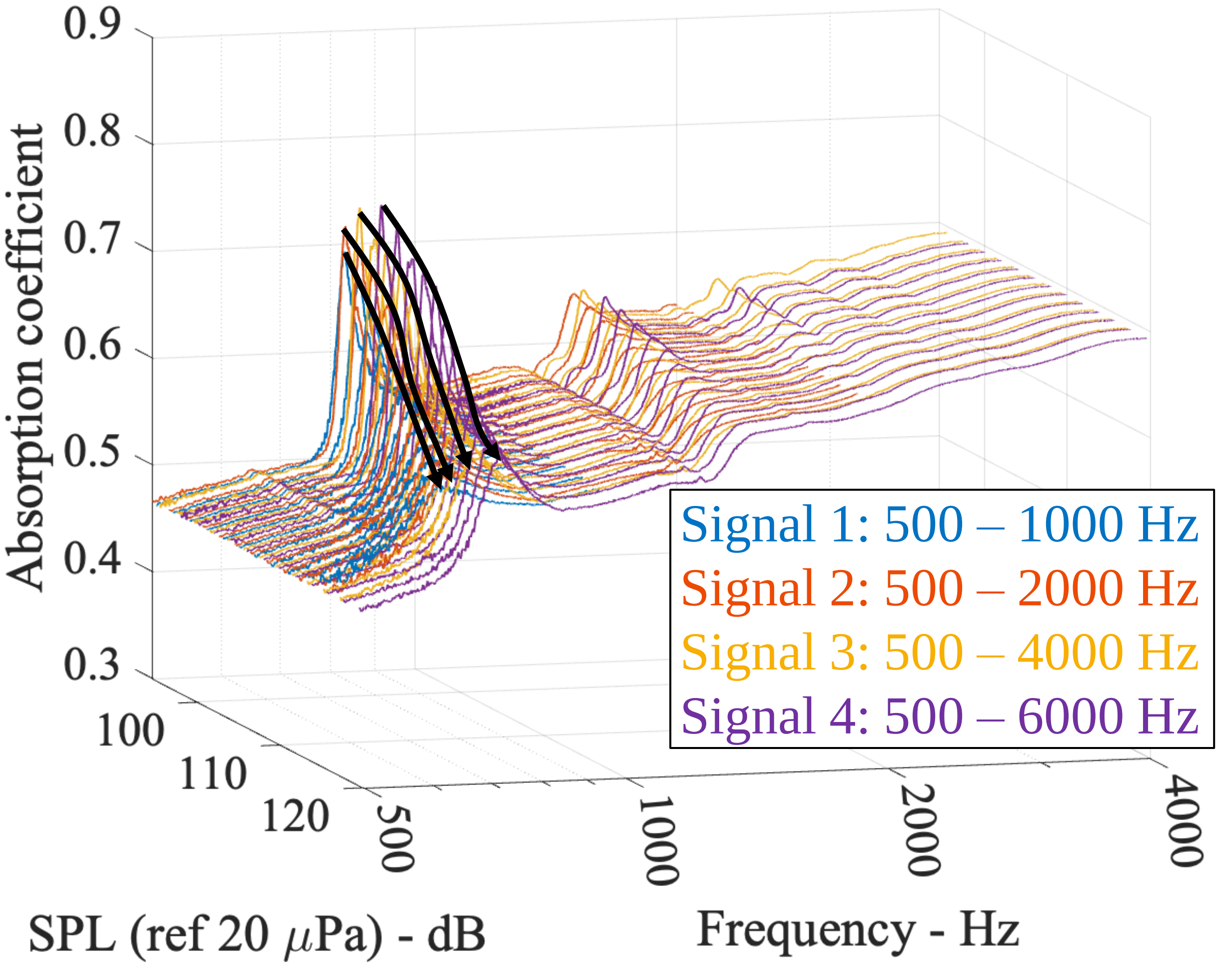


Integrated fluid RMS velocity

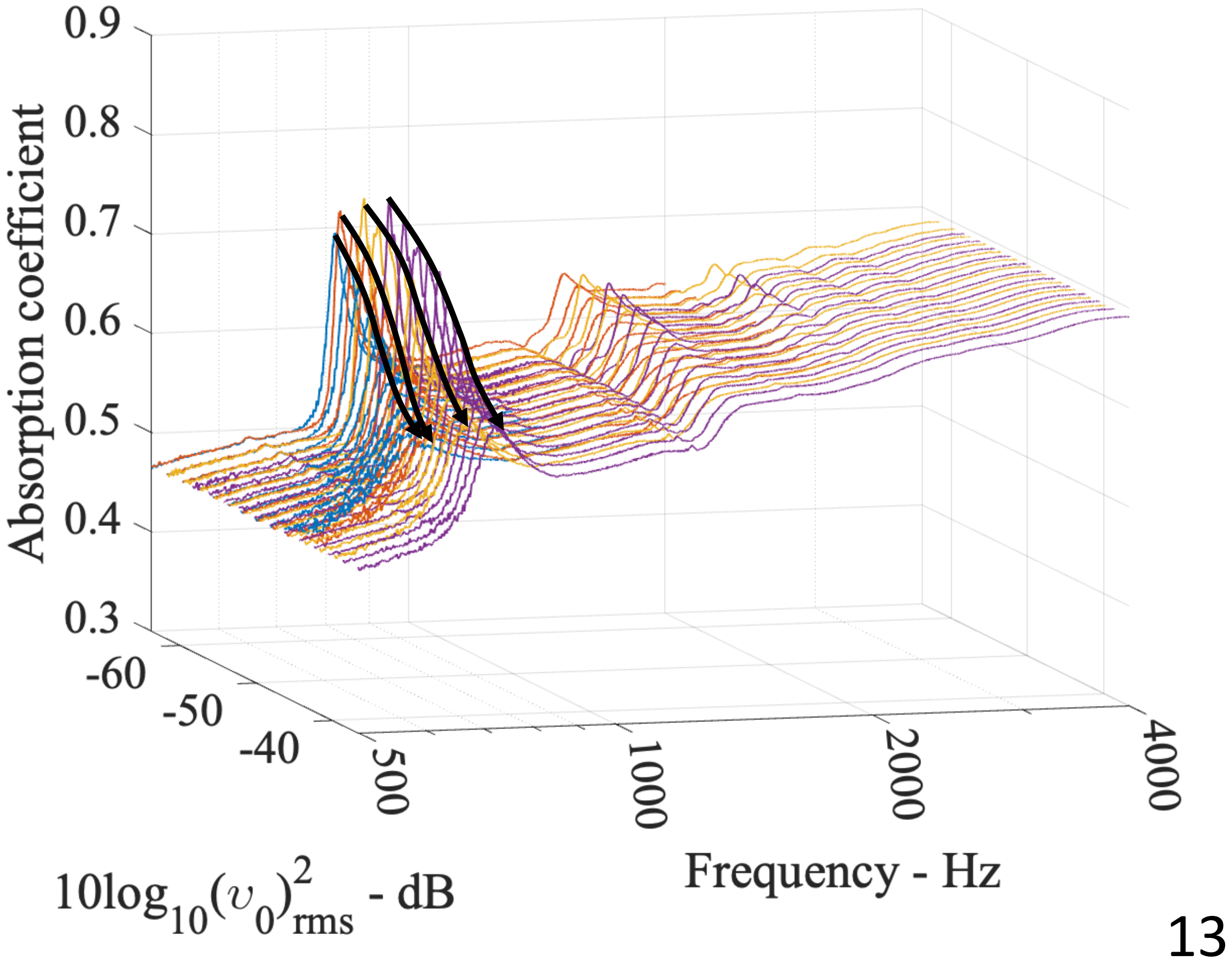
Test results: 40 mm Type A GAC stack

- Peak behavior does not scale with sound pressure level or integrated RMS velocity

Sound pressure level

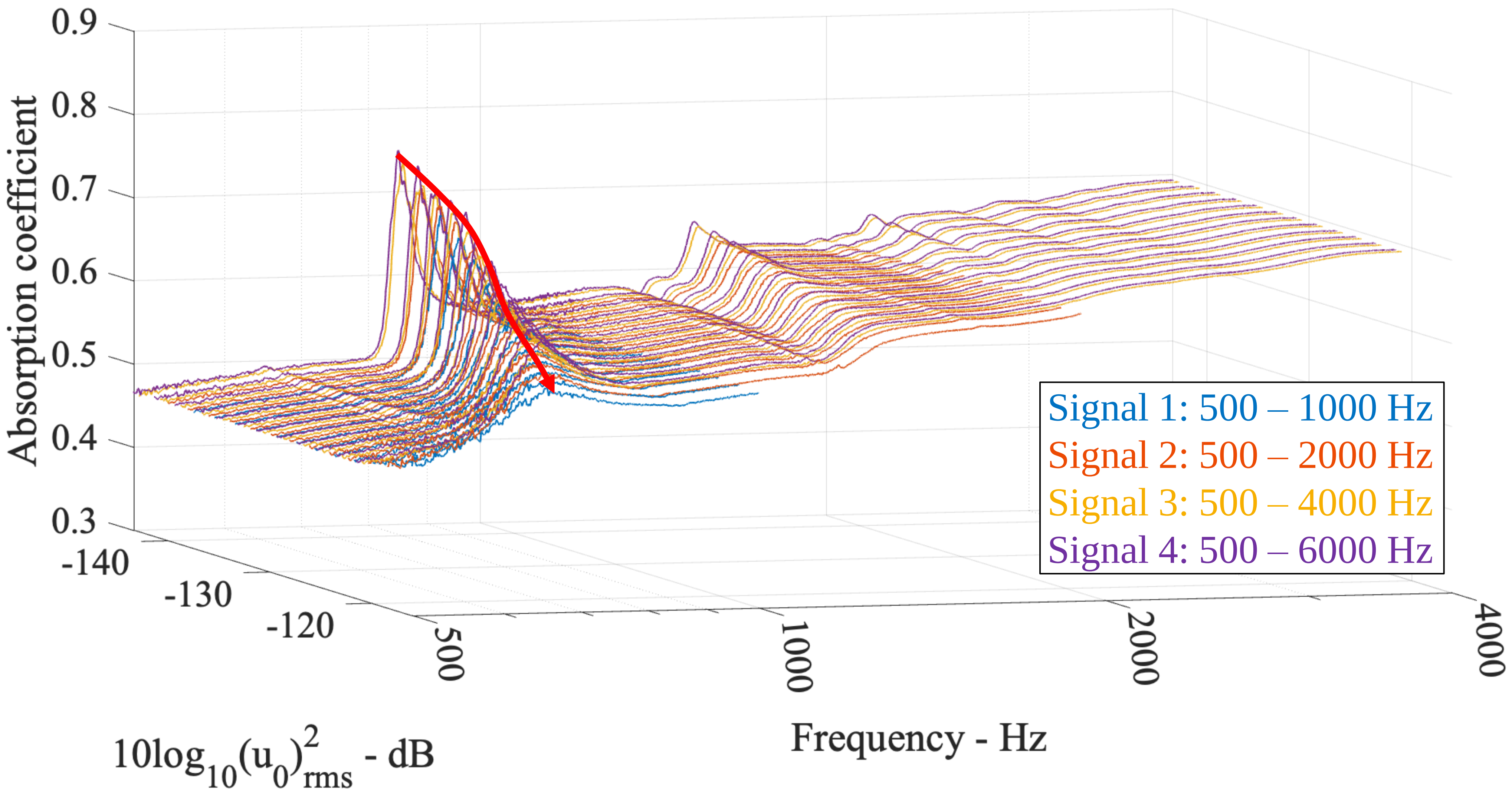


Integrated fluid RMS velocity

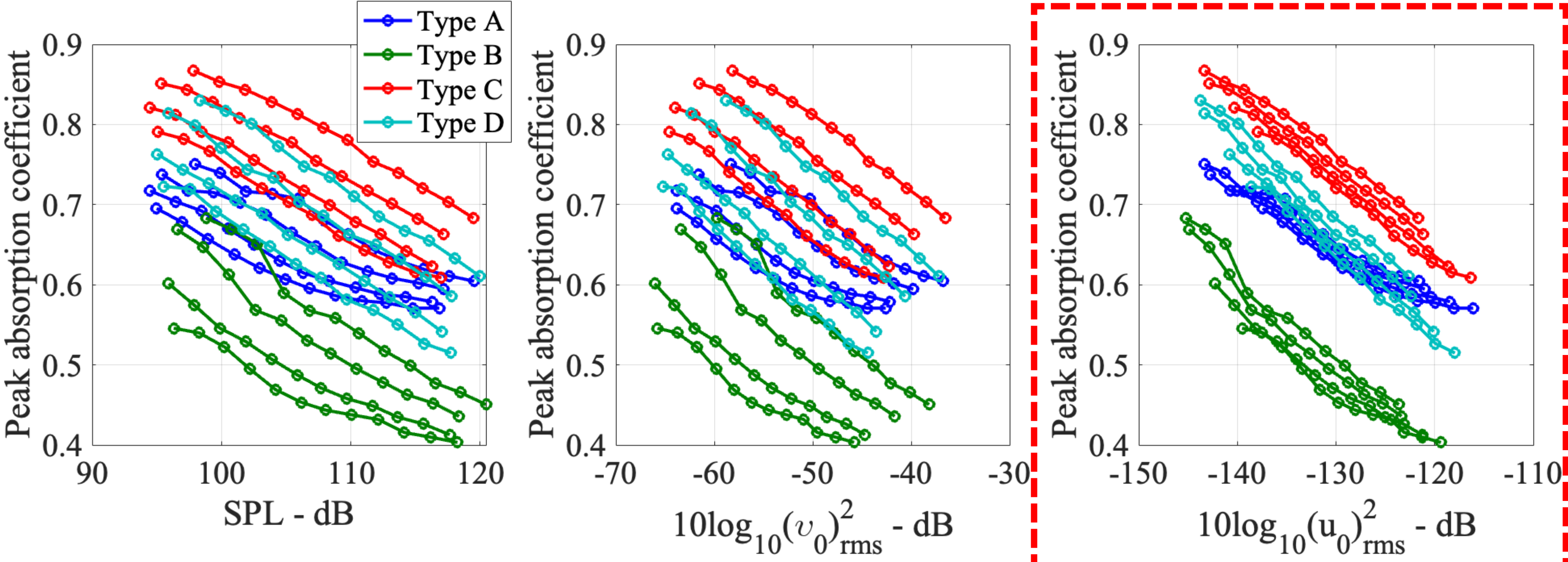


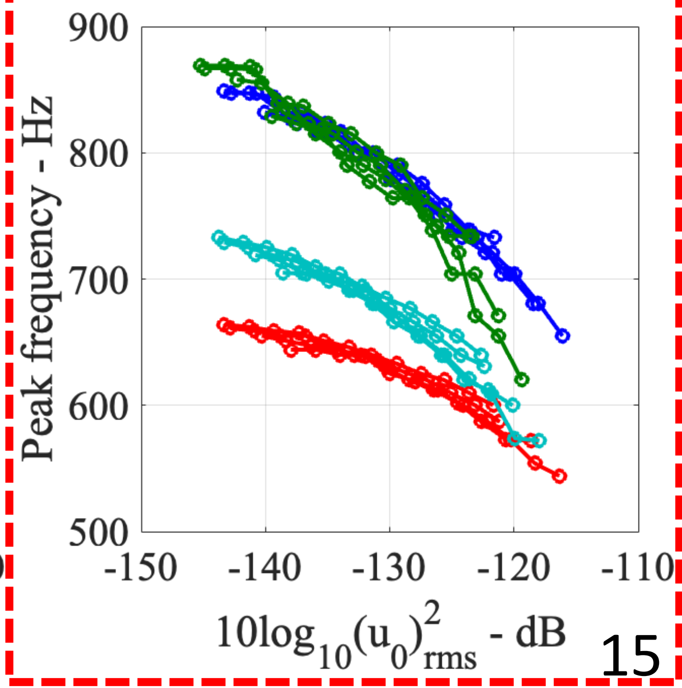
Test results: 40 mm Type A GAC stack

- All the peaks collapse to one single line when plotting against integrated RMS fluid displacement at surface of particle stack, independent of signal bandwidth



Test results: 40 mm Type A-D GAC stacks





- Level-dependent behavior, including stiffness decrease and damping increase as level increases, is accurately characterized by RMS fluid displacement at surface of sample.
- Effect begins to occur when displacement is a small fraction of particle size.

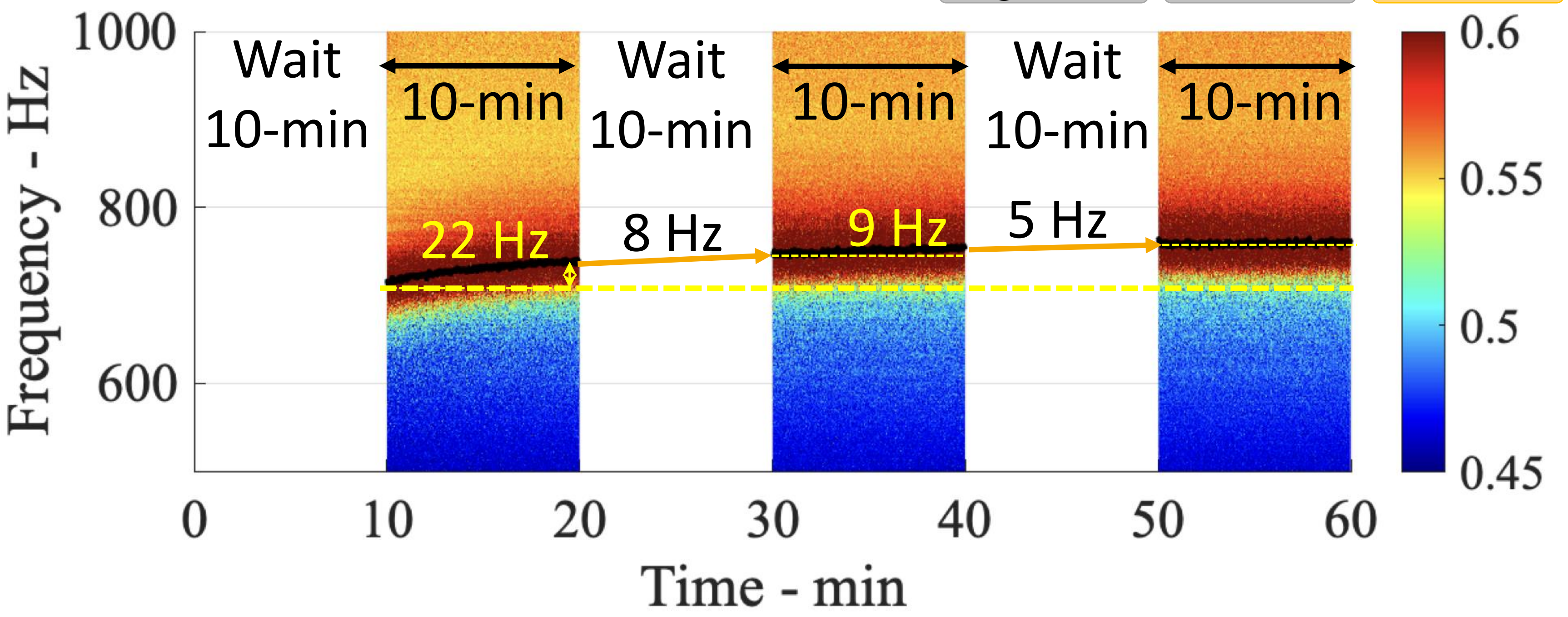
Edge Effect | Level-dep | Time-dep

Time-dependent: 40 mm Type A GAC

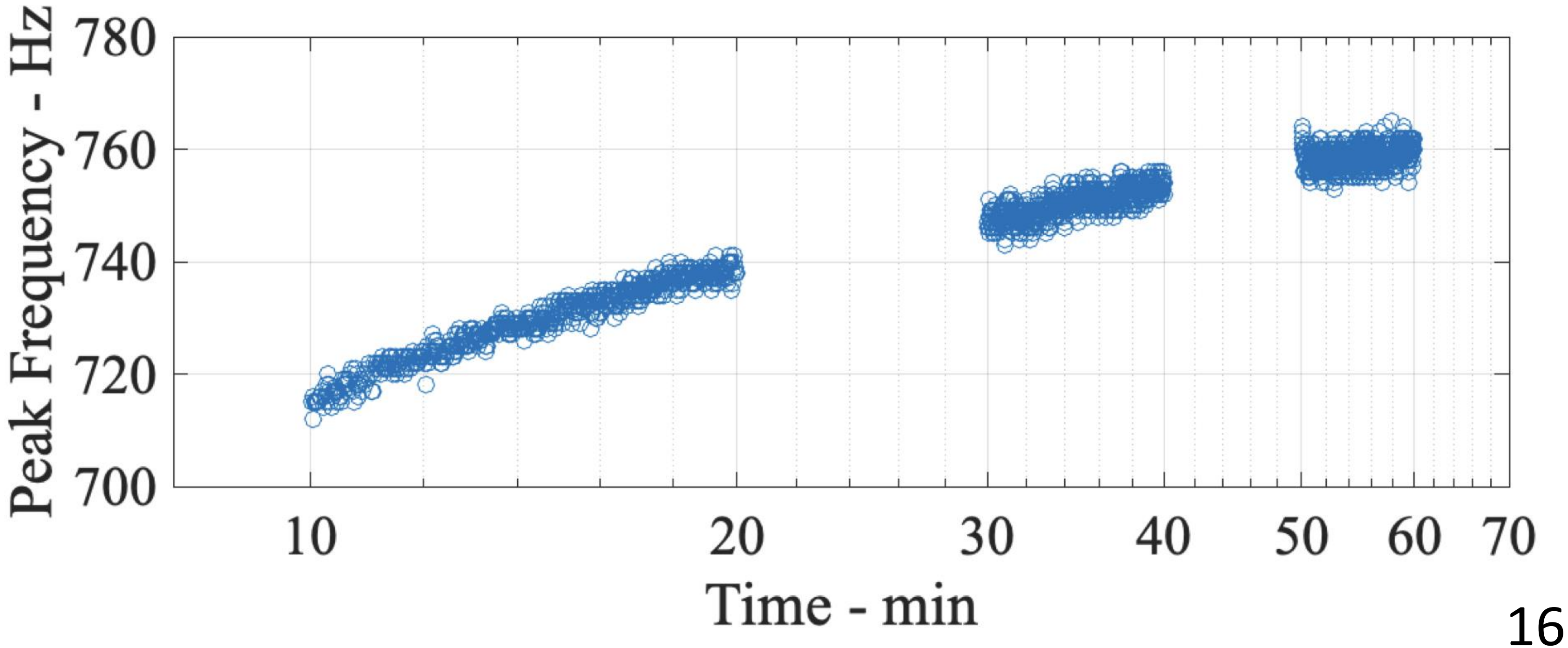
Procedure:

Load the sample

1. Wait 10-min → 10-min noise
2. Wait 10-min → 10-min noise
3. Wait 10-min → 10-min noise



- Particle stack gradually consolidates over minutes and hours whether or not exposed to sound field.
- Increase in peak frequency indicates stiffening of material.



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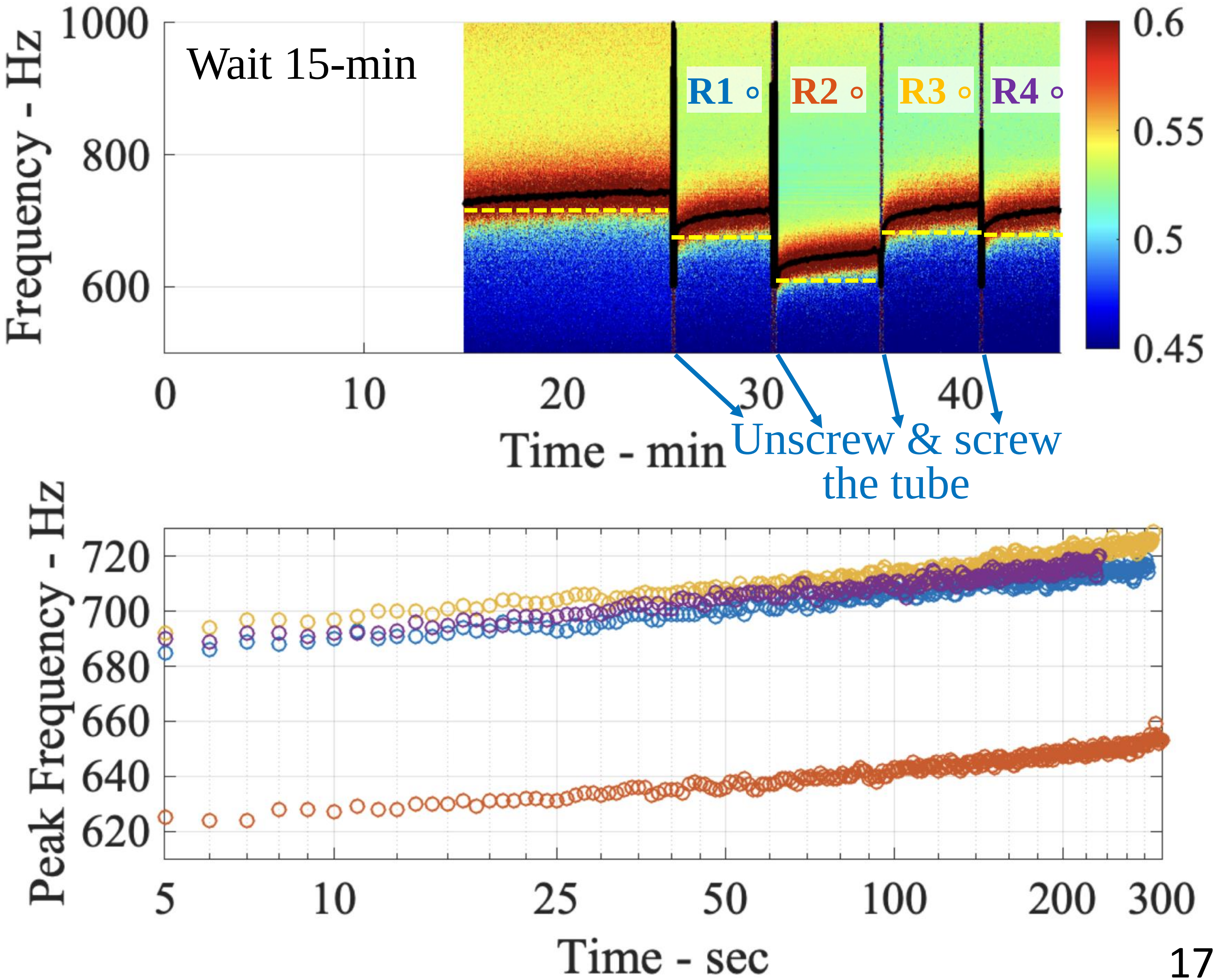
Time-dependent: 40 mm Type A GAC

Procedure:

Load the sample

1. Wait 15-min
2. 30-min white noise

   Vibrate sample 4 times



- This is an example of "slow dynamics"
- Properties changes as a linear function of log(Time)

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Conclusions

- The circumferential edge-constraint has shown a significant impact on the acoustical behavior of granular particle stacks when the stack depth is comparable to or larger than the sample holder size.

- For granular particle stacks: as the input sound level goes up, the resonance peaks: 1. shift to a lower frequency (i.e., modulus softening); 2. grow broader (i.e., increasing damping) The level-dependent modulus and damping of granular material can be characterized with a strain-related metric: i.e., the total RMS fluid displacement at the stack surface.

- It has been found that some granular materials will consolidate over time, resulting in an increase in modulus, and the change of properties is linearly related with the logarithm of time. Such time-varying properties can be "initialized" by vibrating or disturbing the particle stack. This is an example of "slow dynamics".

References

[1] Jingjie Yeo, Zishun Liu, and Teng Yong Ng. Silica Aerogels: A Review of Molecular Dynamics Modelling and Characterization of the Structural, Thermal, and Mechanical Properties. *Handbook of Materials Modeling*, pages 1–21, 2018.

[2] Julian R Wright. The virtual loudspeaker cabinet. *Journal of the Audio Engineering Society*, 51(4):244–247, 2003.

[3] 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.

[4] W. F. Murphy, K. W. Winkler, and R. L. Kleinberg. Acoustic relaxation in sedimentary rocks: dependence on grain contacts and fluid saturation. *Geophysics*, 51(3):757–766, 1986.

[5] G. X. Wang and J. Kuwano. Shear modulus and damping of clayey sands. *Journal of Earthquake Engineering*, 3(2):271–285, 1999.

[6] Takumasa Tsuruha, Yoshinari Yamada, Makoto Otani, and Yasushi 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.

[7] T. Tsuruha, Y. Yamada, M. Otani, Y. Takano, Effect of casing on sound absorption characteristics of fine spherical granular material, The Journal of the Acoustical Society of America 147 (5) (2020) 3418–3428.

[8] 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*, Lexington, KY, USA, 2022.

[9] Guochenhao Song, Zhuang Mo, Tongyang Shi and J. Stuart Bolton, "Experimental study of granular paricle stacks' circumferential edge-constraint effect and the the level- and time-dependent acoustical behavior," Under review, *Powder Technology*, October 2023.

Thanks