5-26-2022

Experimental Study of the Level-Dependent Softening of Carbon Particle Stacks

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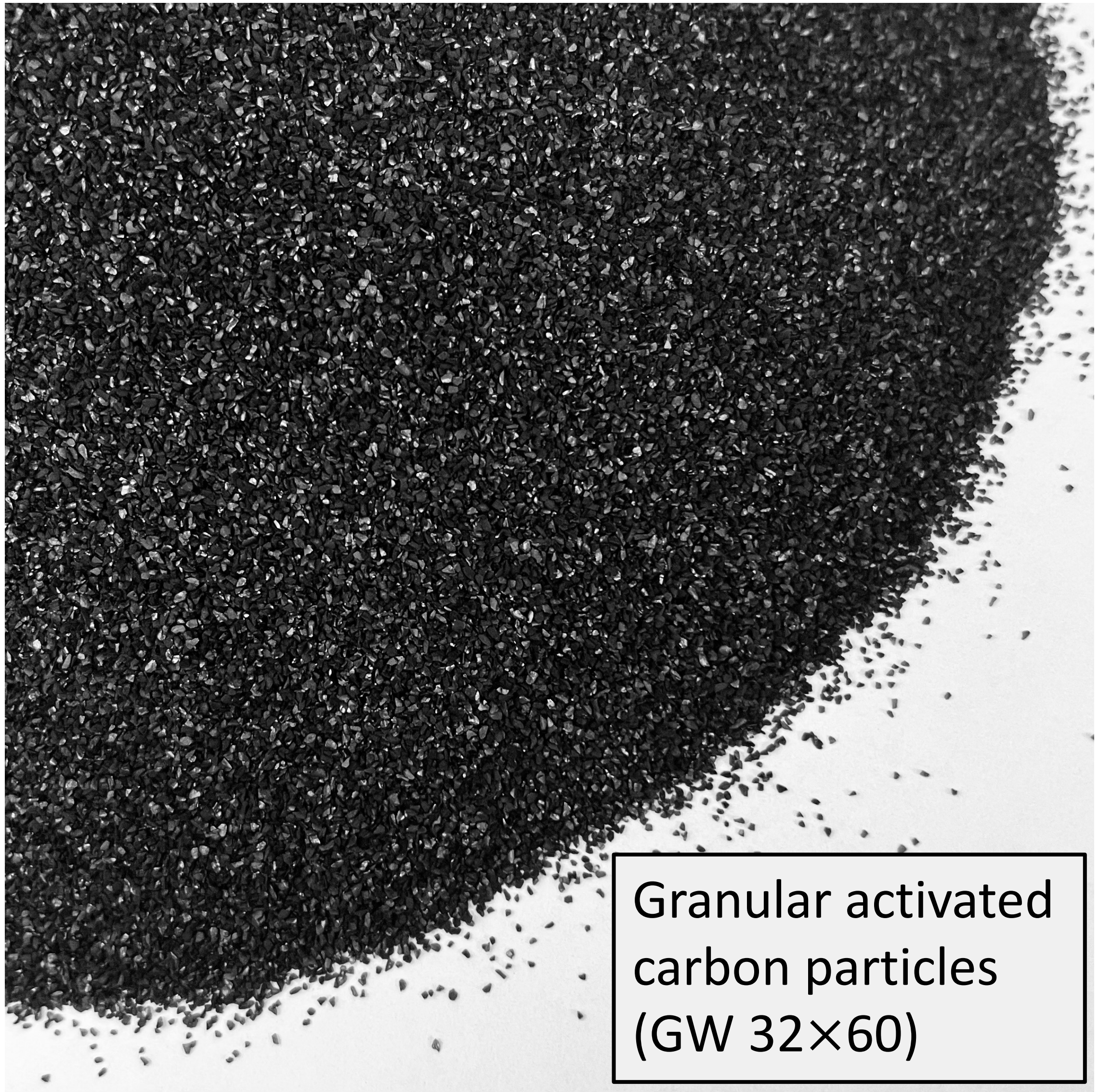
Experimental study of the level-dependent , softening of carbon particle stacks

Guochenhao Song[1], Zhuang Mo[1] and J. Stuart Bolton[1]

[1]Ray W. Herrick Laboratories, Purdue University, West Lafayette, IN, USA ,

Agenda

- Motivation
- Test setup
- Experimental results
- Conclusions



Particle diameter: 250 – 500 µm [9]
Bulk density: 520 kg/m^3

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Motivation

Granular activated carbon particles

- Large surface area
- Remarkable sorption characteristics
- Large low frequency sound absorption ς

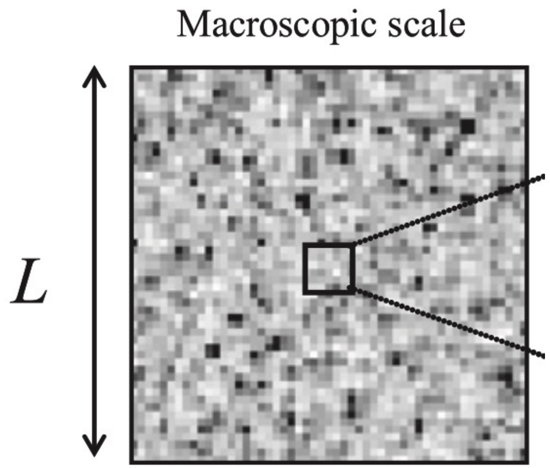

Fig. 1 in Venegas *et al.* (2016)

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Granular activated carbon particles

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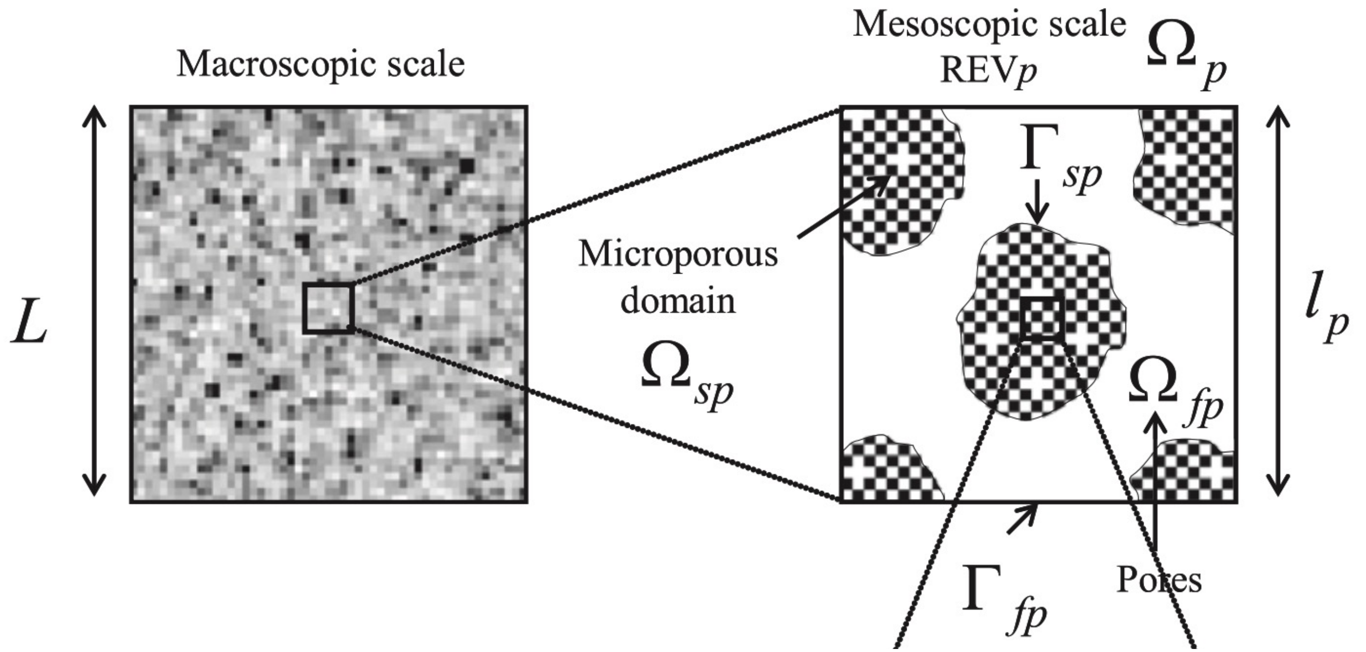

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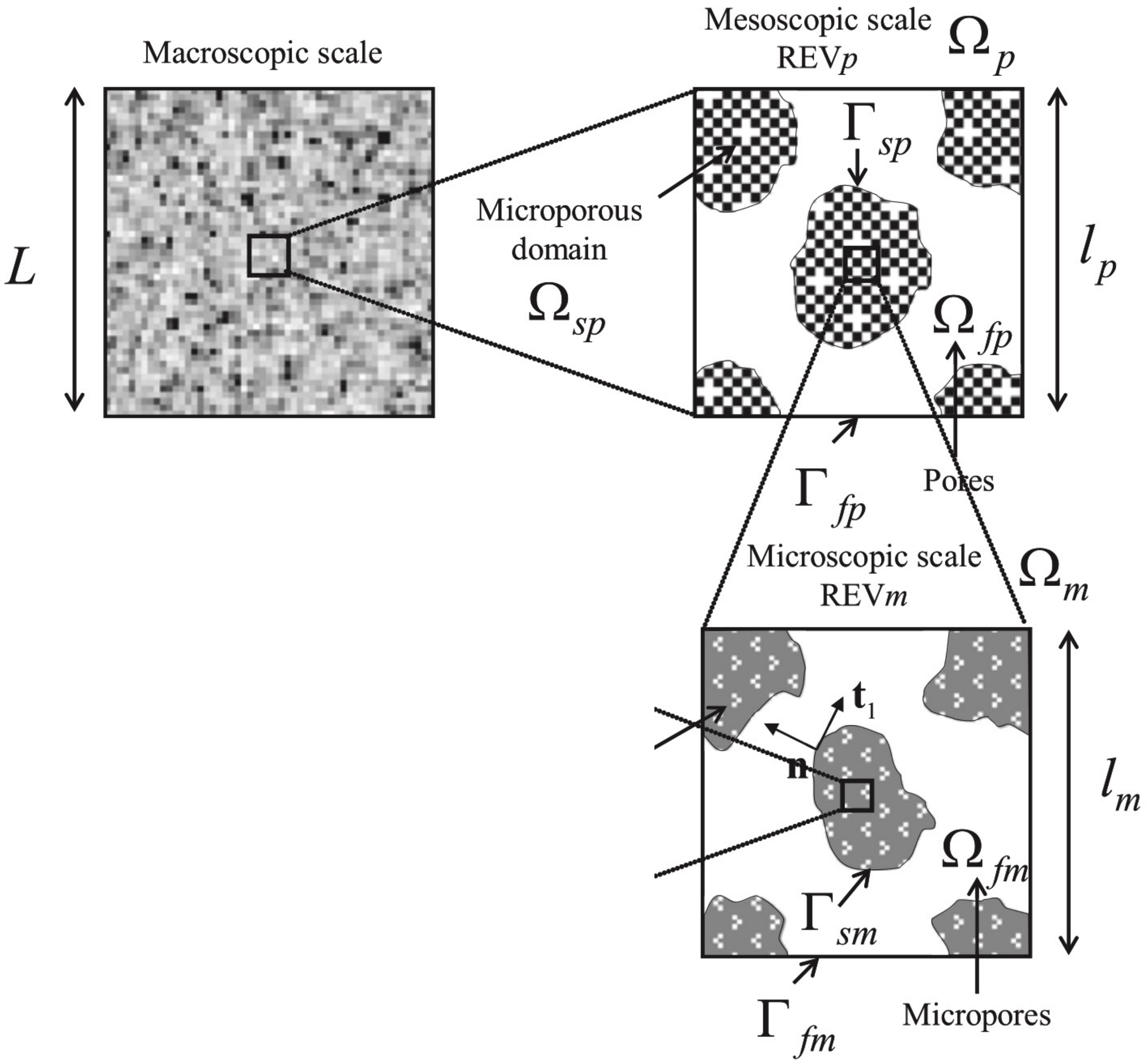

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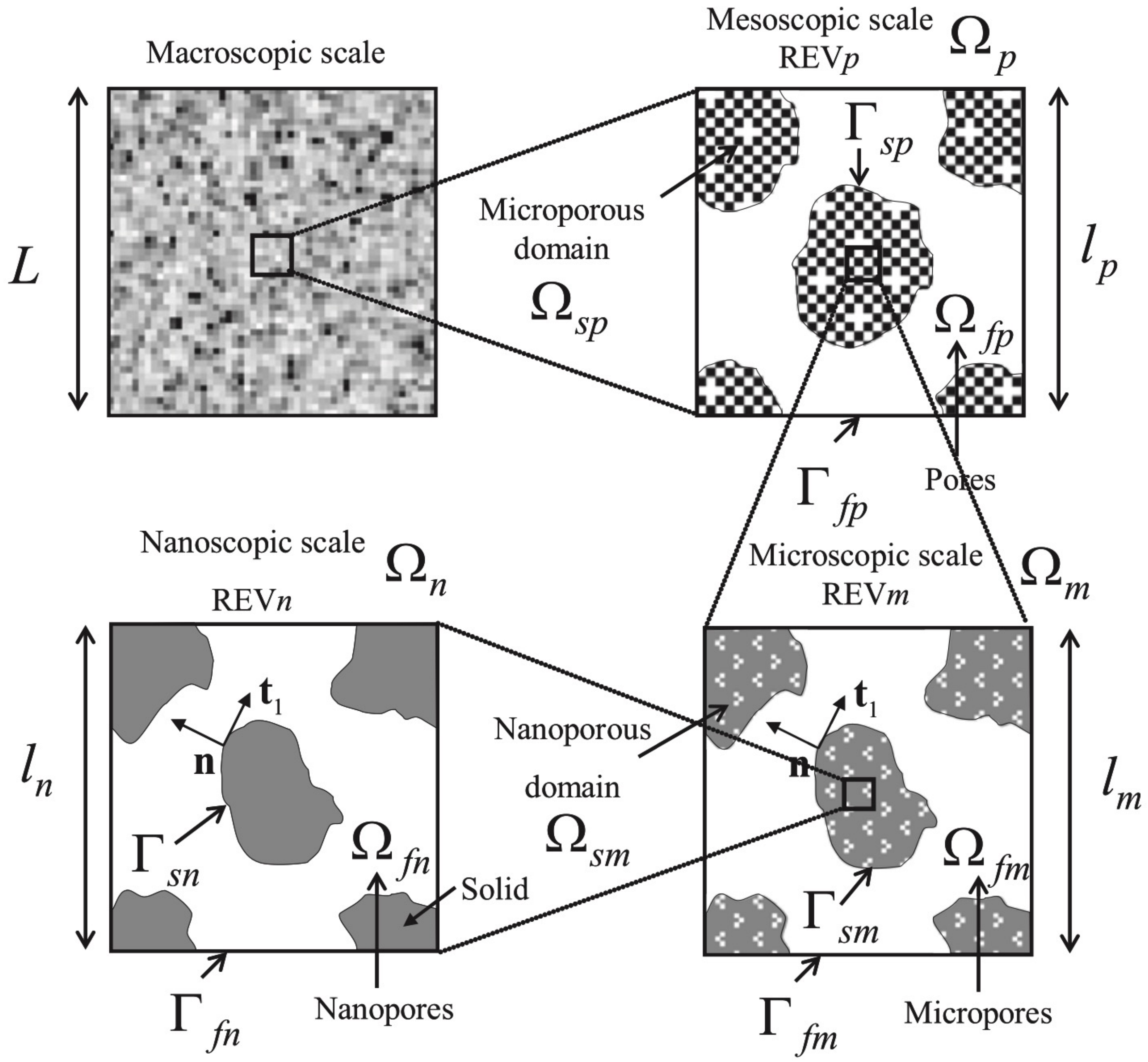

Fig. 1 in Venegas *et al.* (2016)

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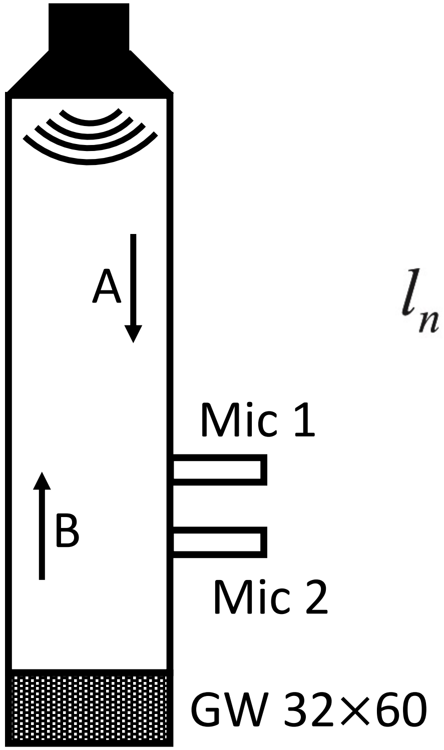
Granular activated carbon particles

- Large surface area
- Remarkable sorption characteristics
- Large low frequency sound absorption

Acoustical properties of GW 32×60 were measured with a vertical standing wave tube:



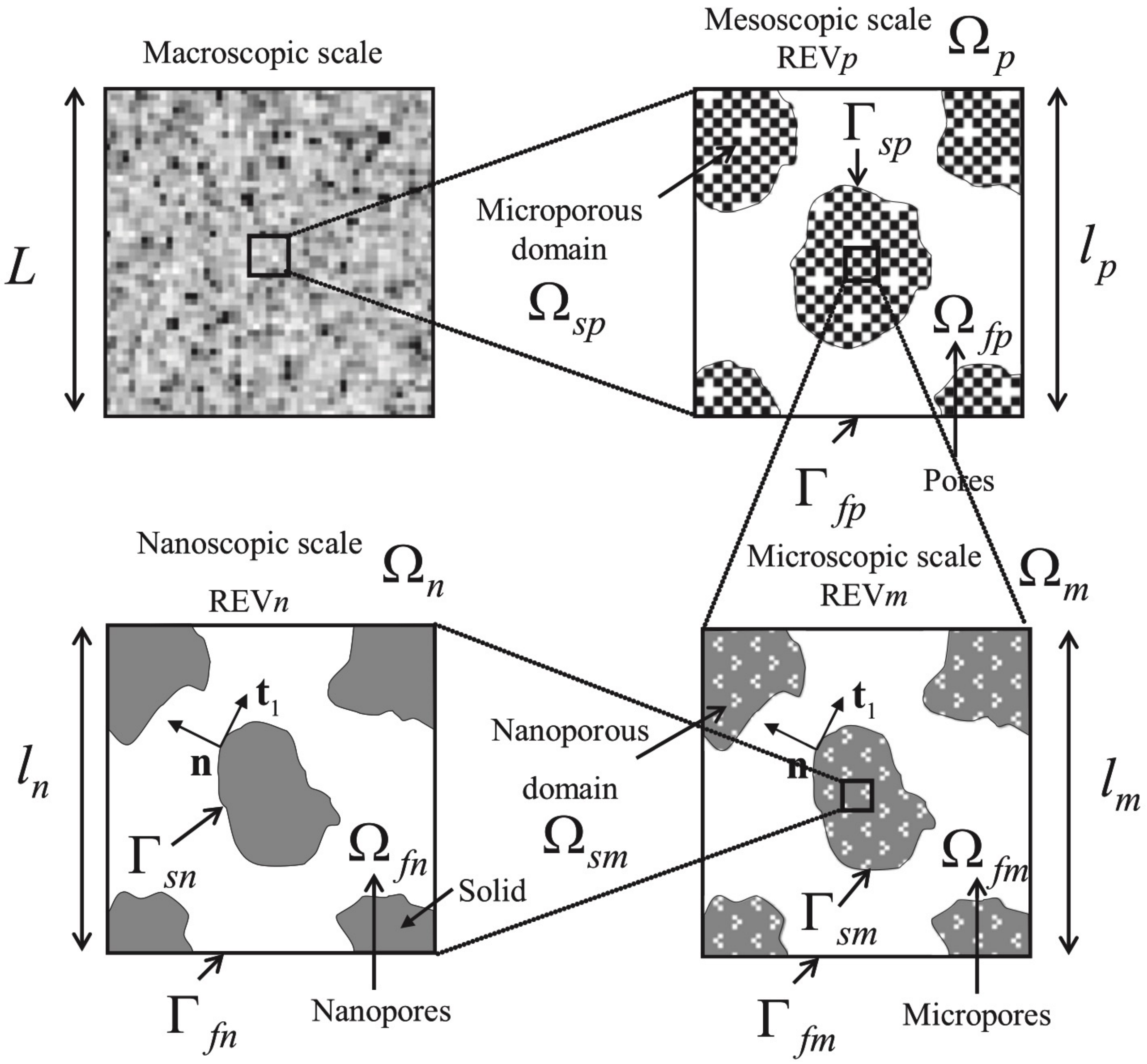
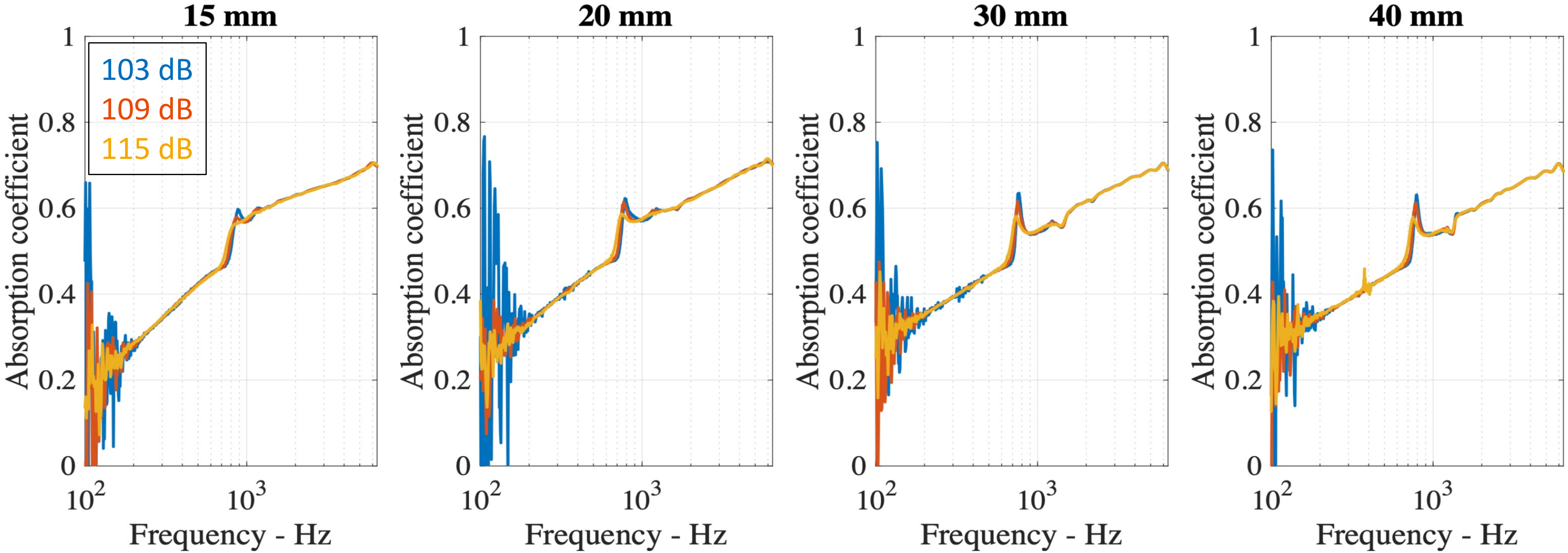


Fig. 1 in Venegas *et al.* (2016)

Level-dependent behavior – GW 32×60

- Stacks of activated carbon are known to be poro-elastic (Mo *et al.,* 2021) ,
- Particle stack shows peak due to resonance of solid phase



With increasing input level:

- The absorption peaks are more damped and shift to a lower frequency.
- Solid phase appears to soften as sound level increases. (Mo *et al.,* 2021)

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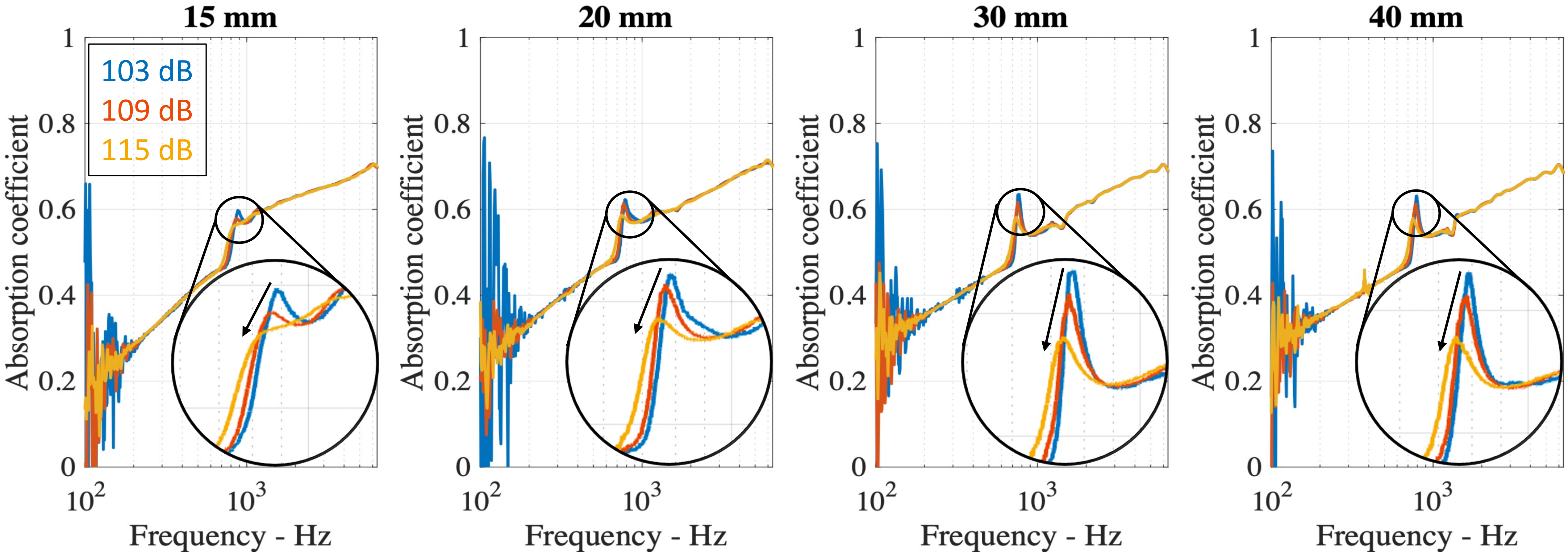

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Level-dependent behavior – glass bubbles

- Stacks of low density, small diameter particles also appear to “soften” as incident , sound pressure level increases ,

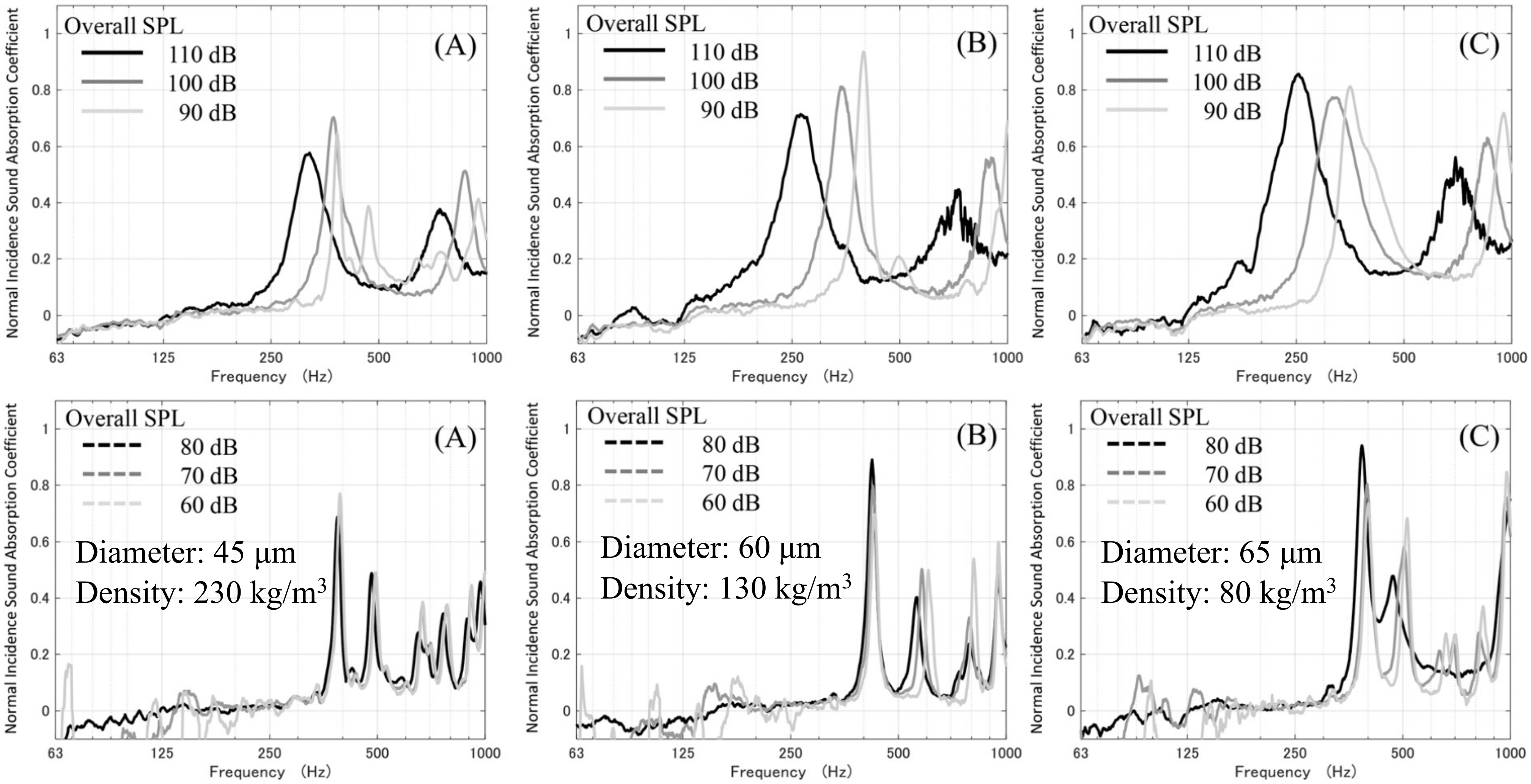

Fig. 4 in Tsuruha *et al.* "Effect of acoustically-induced elastic softening on sound absorption coefficient of hollow glass beads with inner closed cavities." *The Journal of the Acoustical Society of America*150, no. 2 (2021): 841-850.

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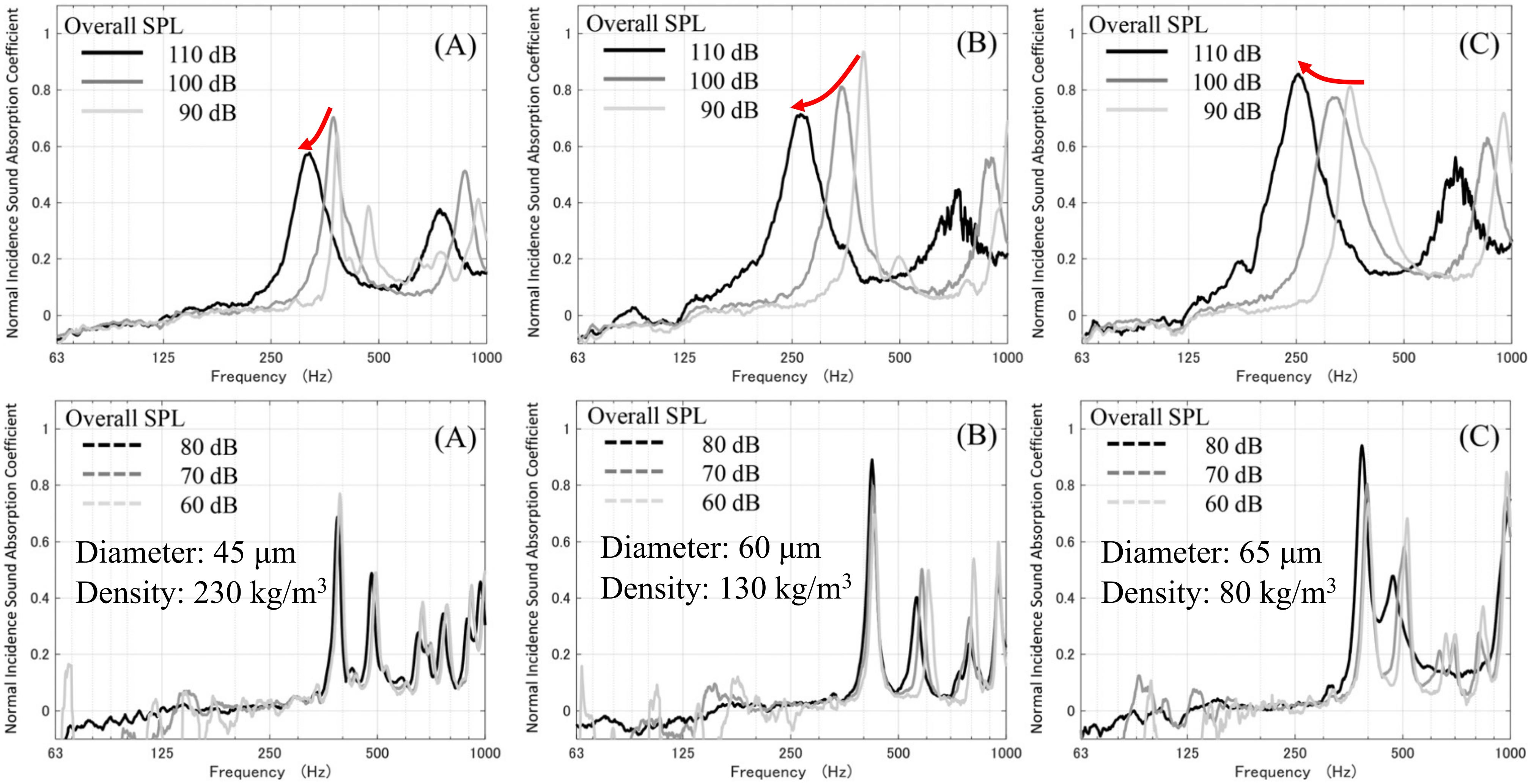

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Previous models for particle level-dependent behavior @

Velocity-dependent modulus ,
[Glass bubbles] ,

$$E/E_{sg} = \frac{1}{1+(v/v_{0g})^{ag}}$$

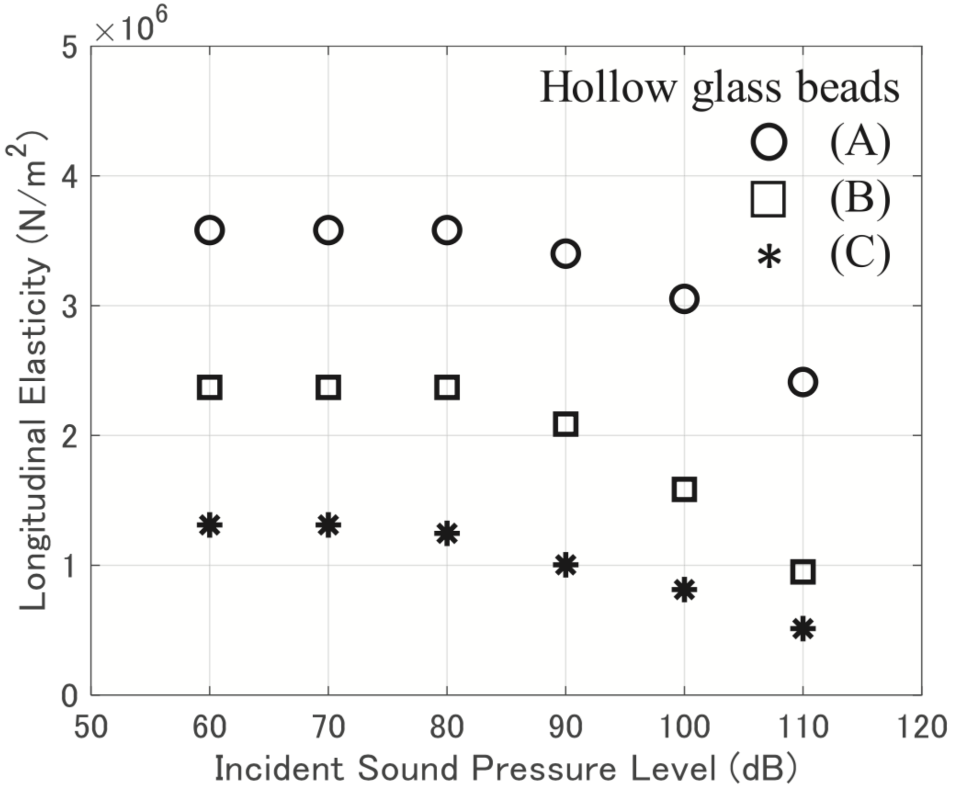

Fig. 6 in Tsuruha *et al.* (2021)

Previous models for particle level-dependent behavior

Velocity-dependent modulus
[Glass bubbles]

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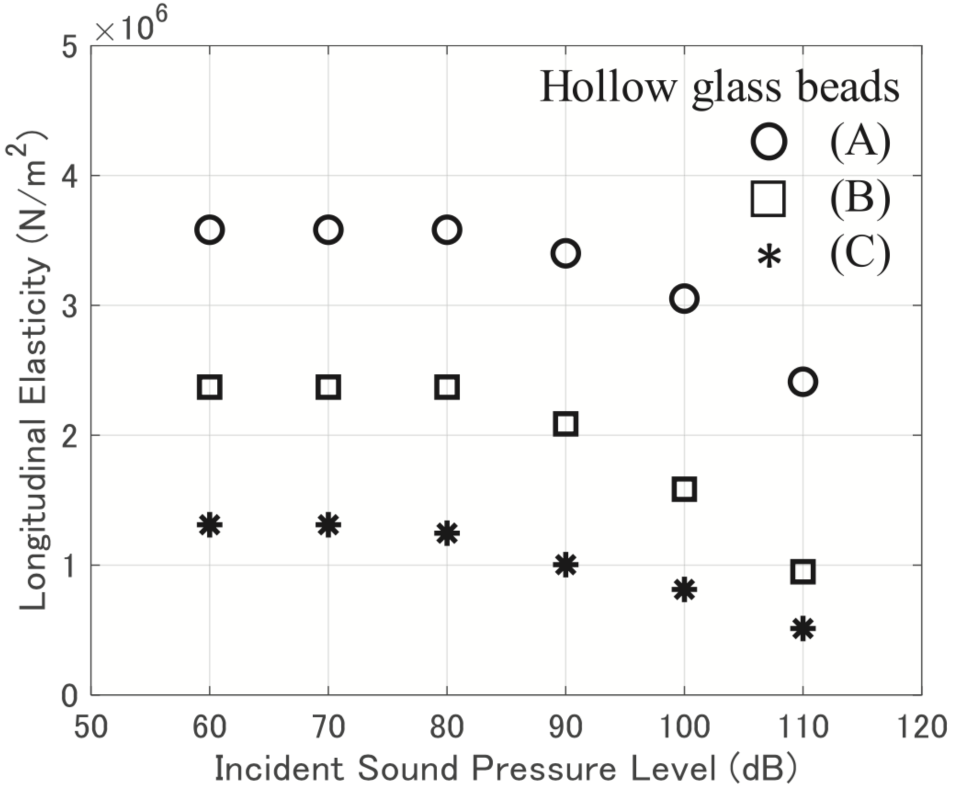


Fig. 6 in Tsuruha *et al.* (2021) 6

Strain-dependent modulus & damping
[Clayey sand]

$$G/G_0'^{g} = \frac{1}{1+b\ \gamma}$$

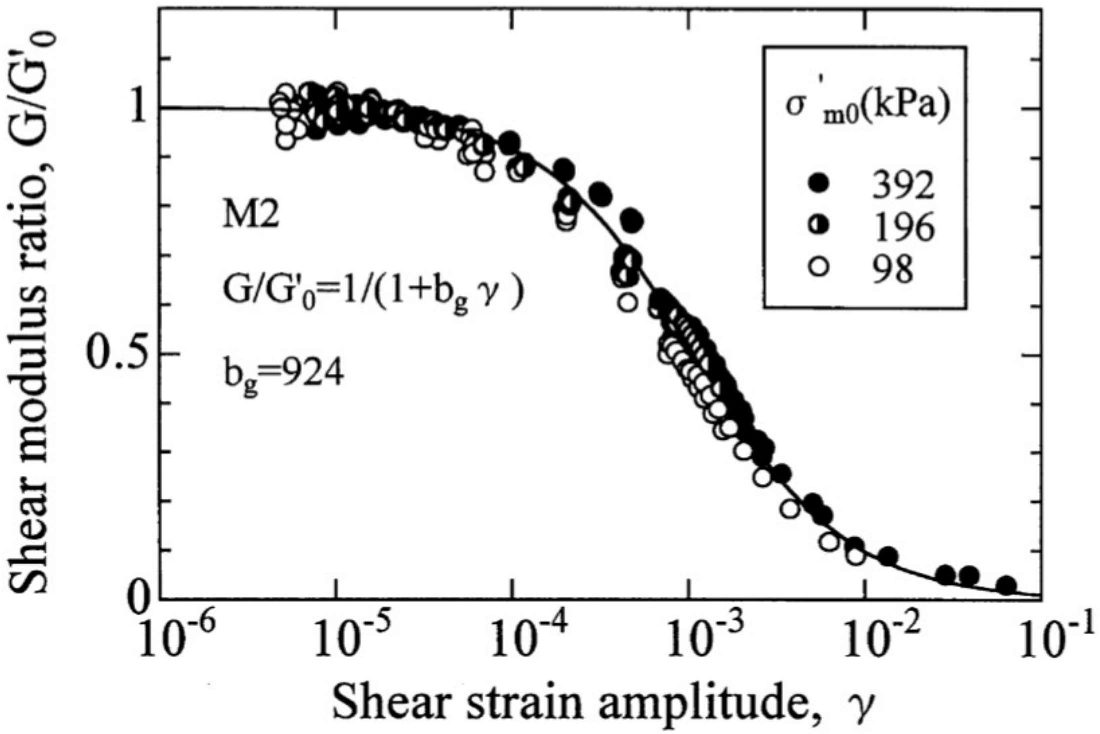
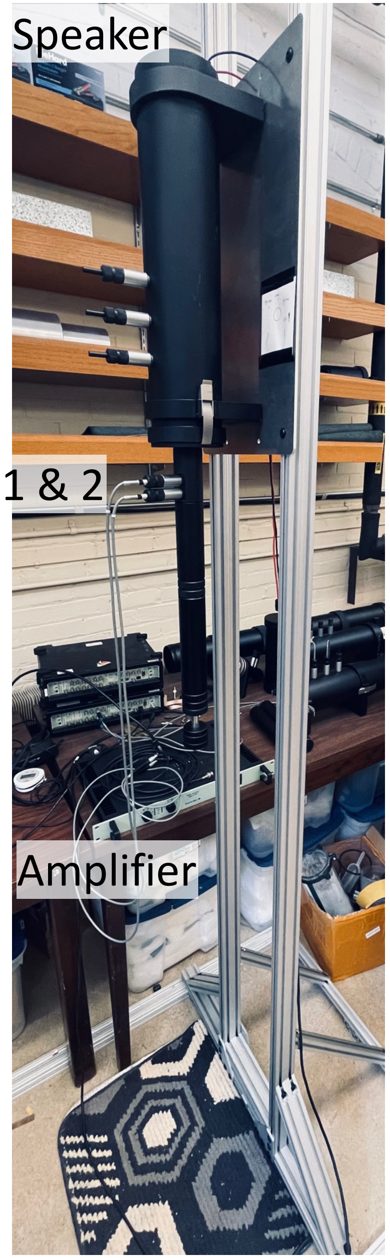


Fig. 12 in Wang & Kuwano (1999) 6

Test setup

Test setup

4 pre-generated input signals



30 mm carbon particles

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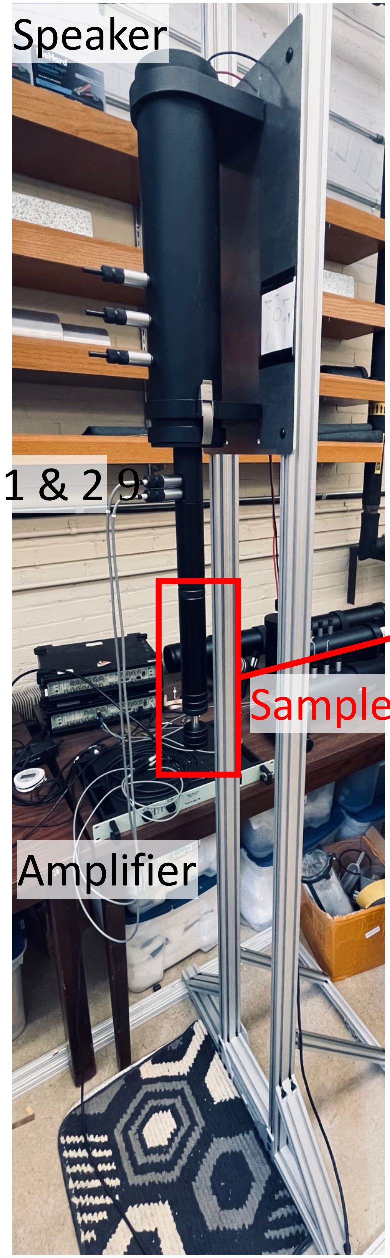
Test setup

4 pre-generated input signals



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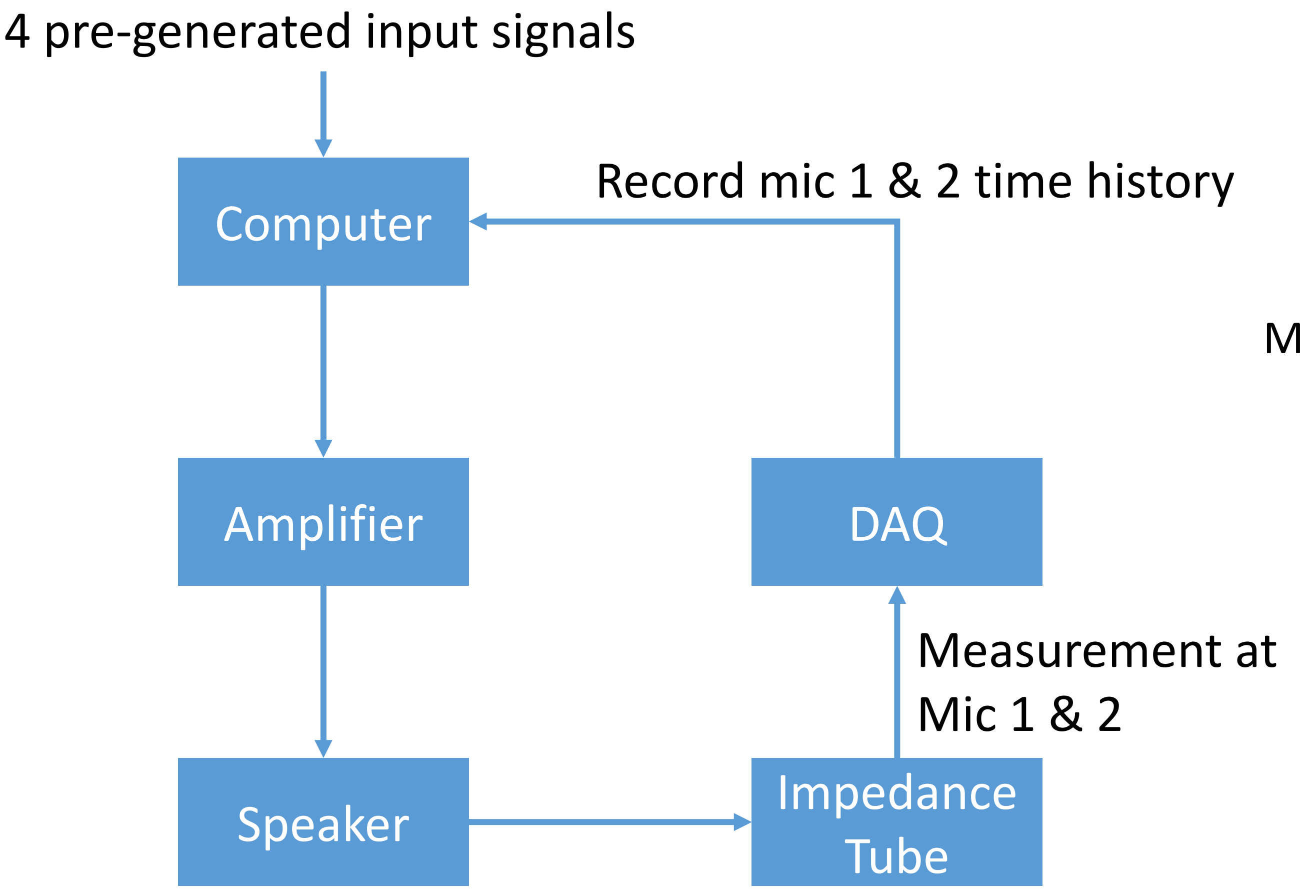

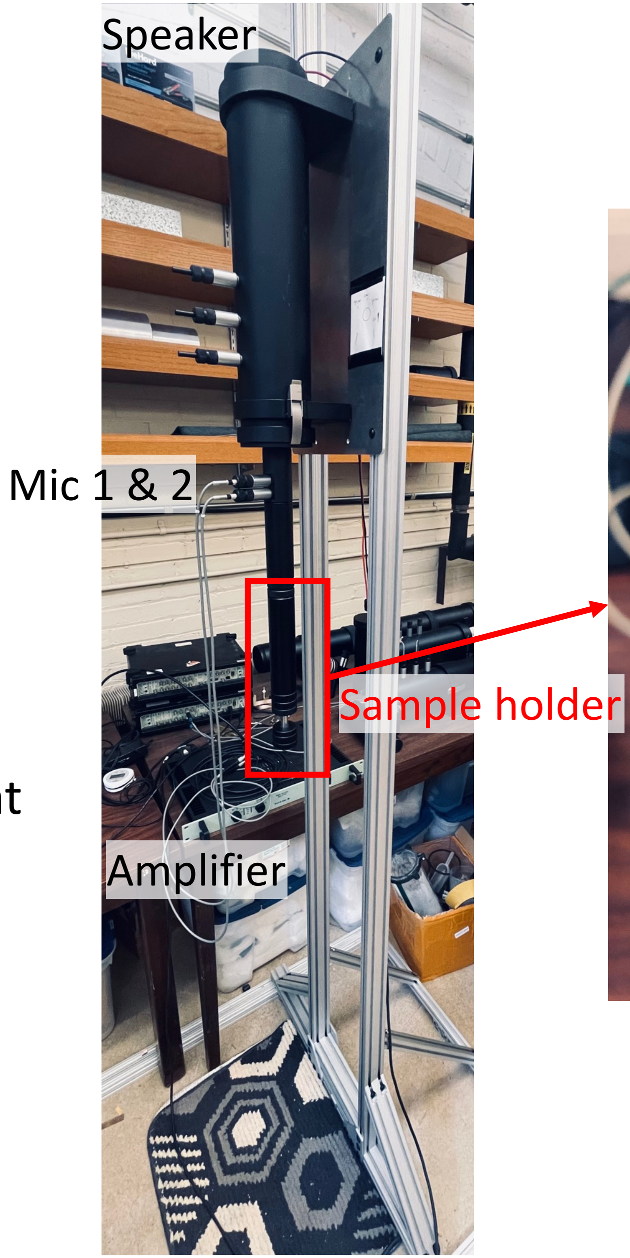

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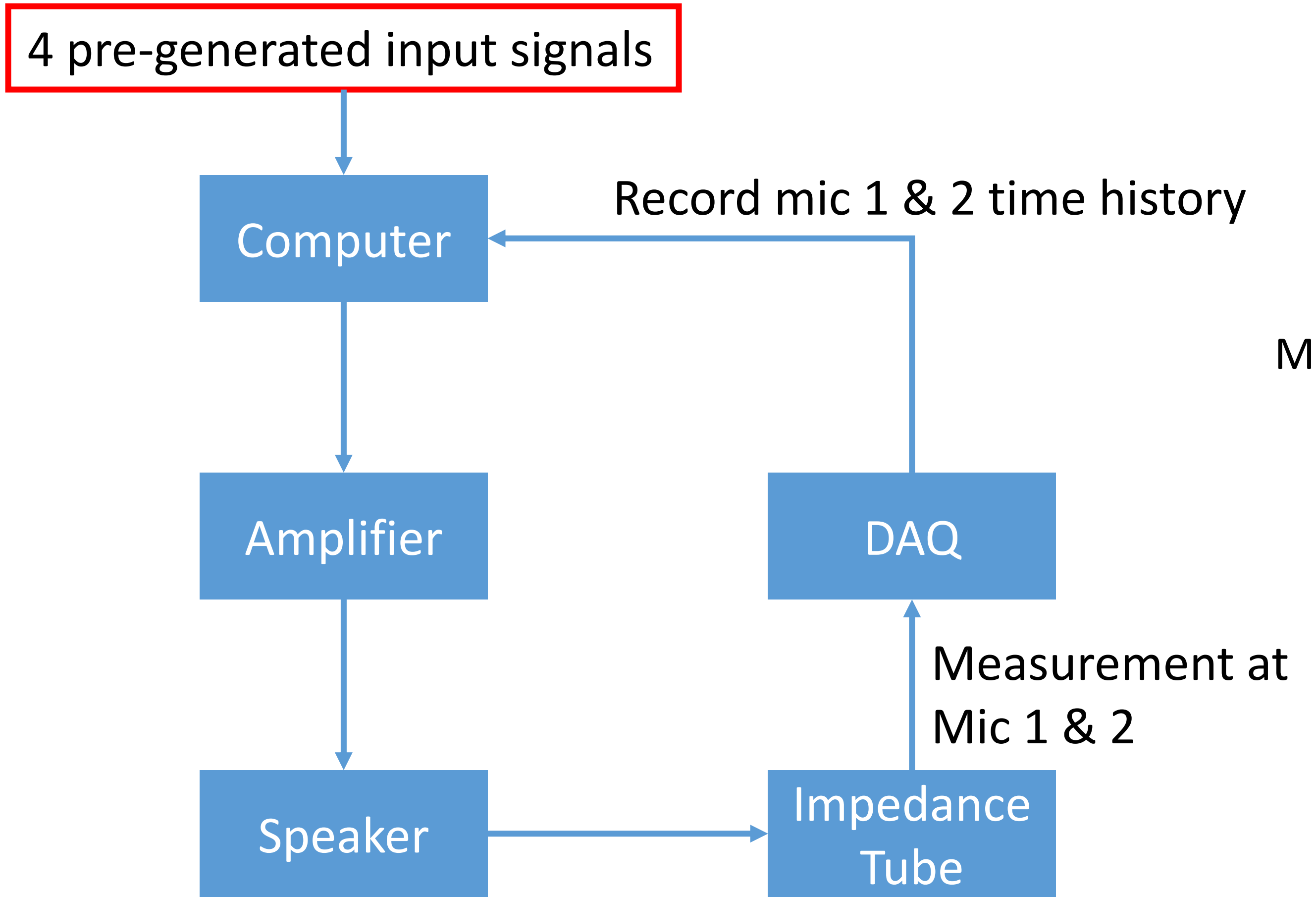
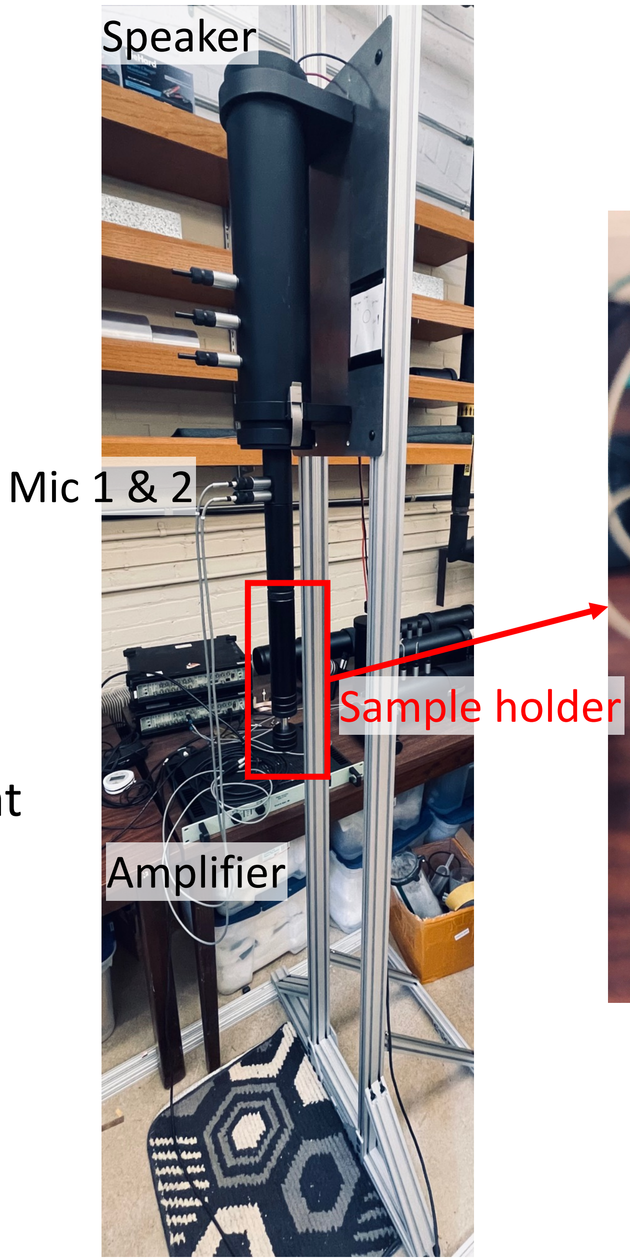
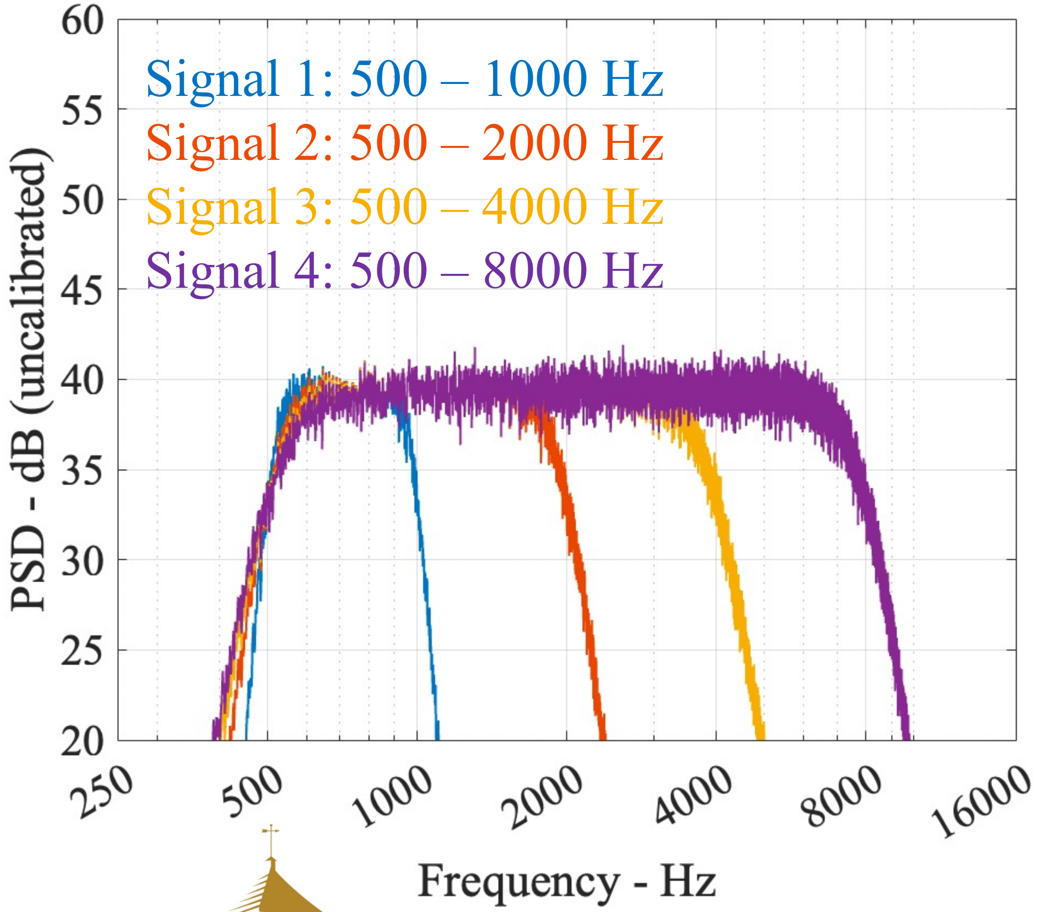




30 mm carbon particles

Pre-generated input signals @

- 4 signals, each with 15 levels in steps of 1 dB.
- In total 4 x 15 = 60 measurements



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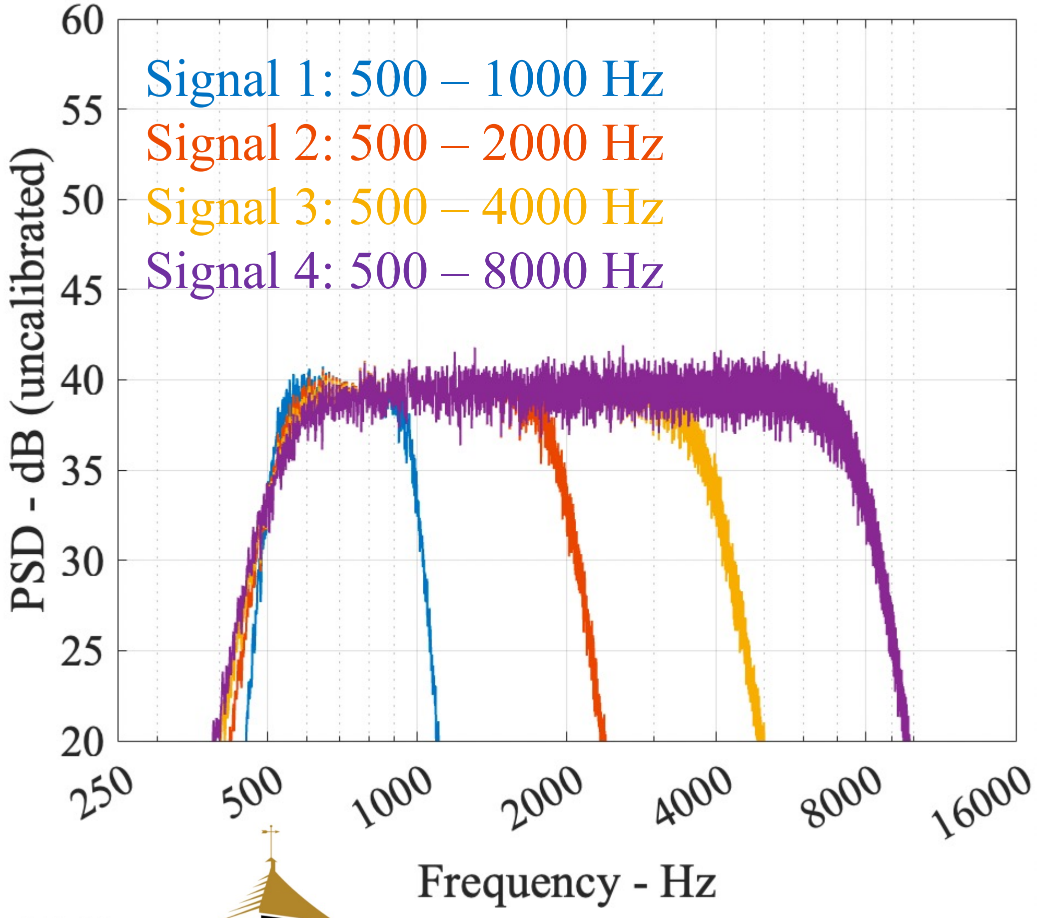

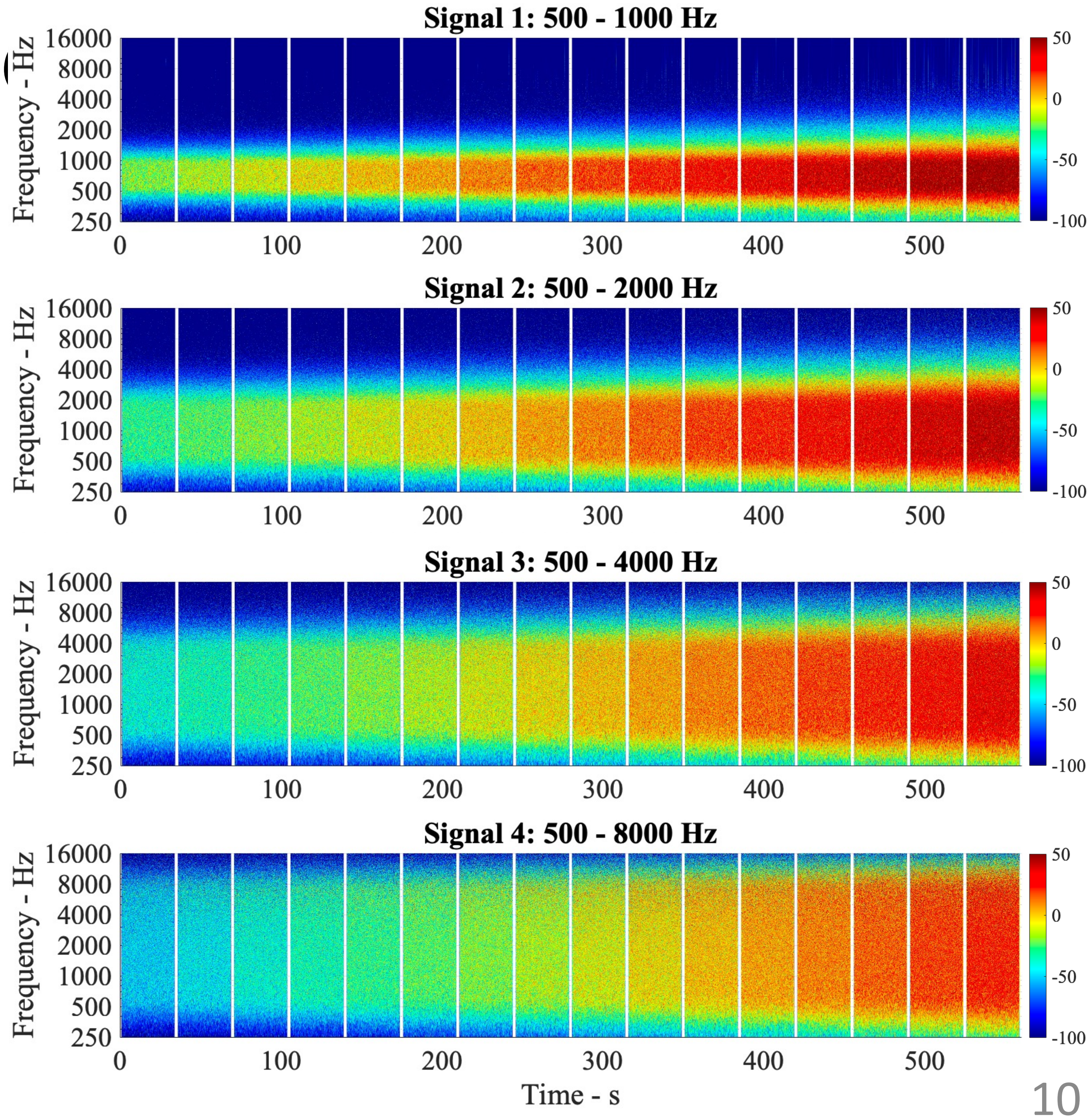

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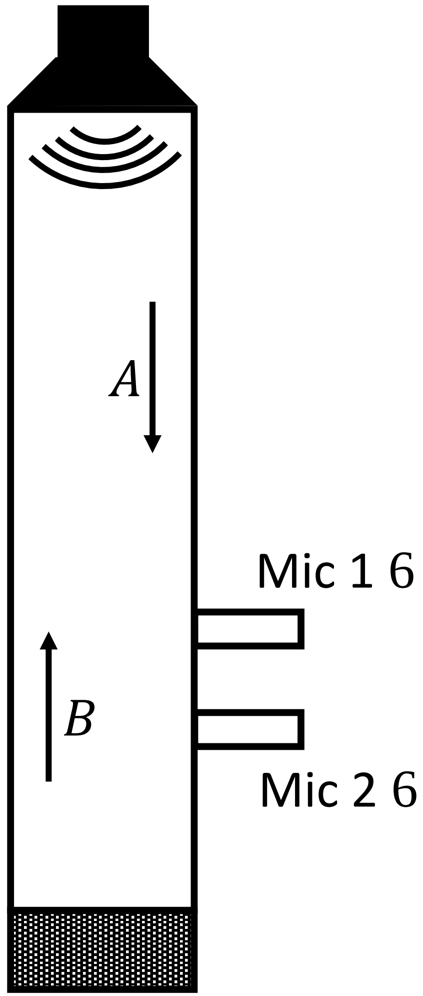
Experimental results

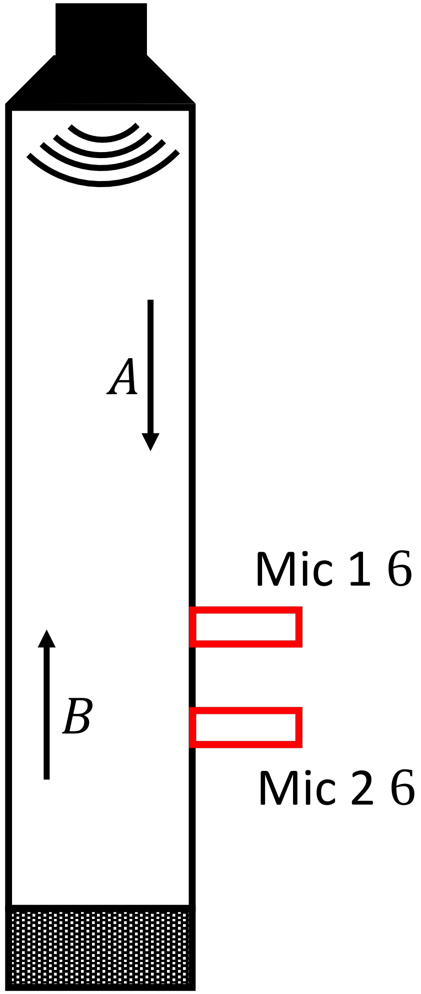
- Absorption coefficients against SPL, integrated RMS velocity, integrated RMS displacement

Integrated RMS pressure, velocity, displacement @

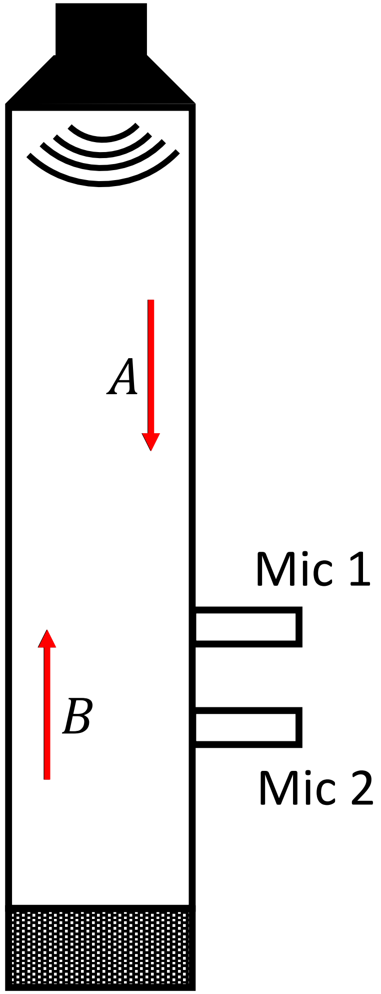


Integrated RMS pressure, velocity, displacement @

Measurements at Mic 1 & 2 ,



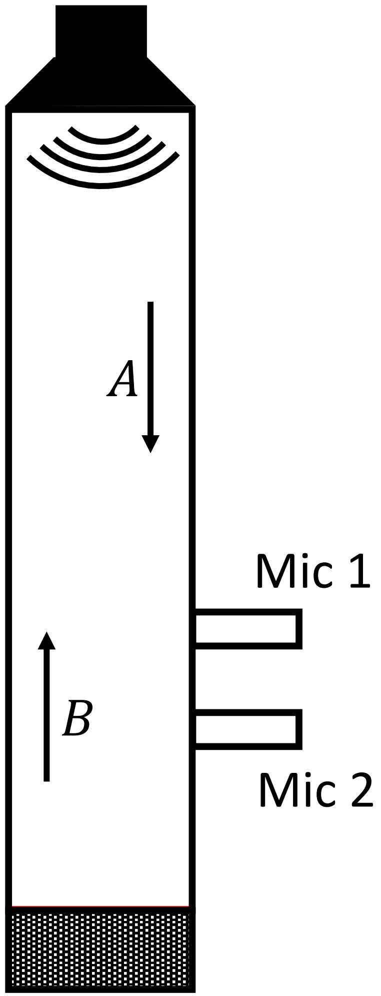
Integrated RMS pressure, velocity, displacement @



Measurements at Mic 1 & 2 ,

Complex amplitudes of forward and backward propagating waves: $A(f), B(f)$

Integrated RMS pressure, velocity, displacement @



Measurements at Mic 1 & 2 ,

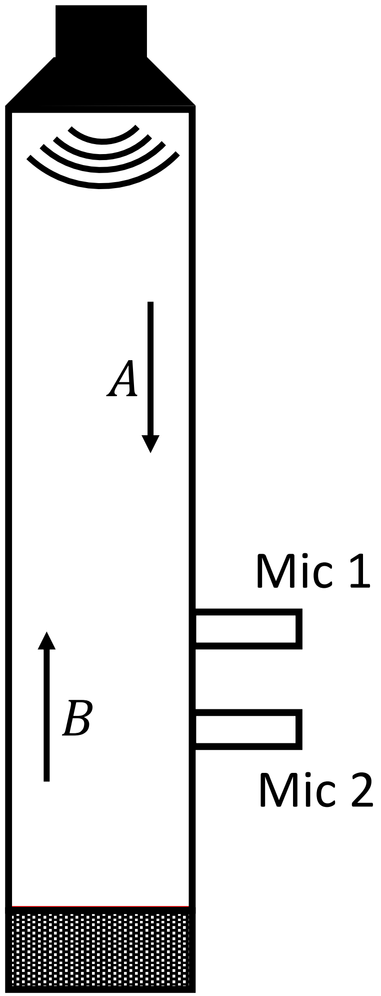
↓

Complex amplitudes of forward and backward propagating waves: $A(f), B(f)$

↓

RMS pressure, velocity, displacement at the front surface of the material: $(P_0(f))^2_{rms},\ (v_0(f))^2_{rms},\ (u_0(f))^2_{rms}$

Integrated RMS pressure, velocity, displacement @



Measurements at Mic 1 & 2 ,

↓

Complex amplitudes of forward and backward propagating waves: $A(f), B(f)$

↓

RMS pressure, velocity, displacement at the front surface , of the material: $(P_0(f))^2_{rms},\ (v_0(f))^2_{rms},\ (u_0(f))^2_{rms}$

↓

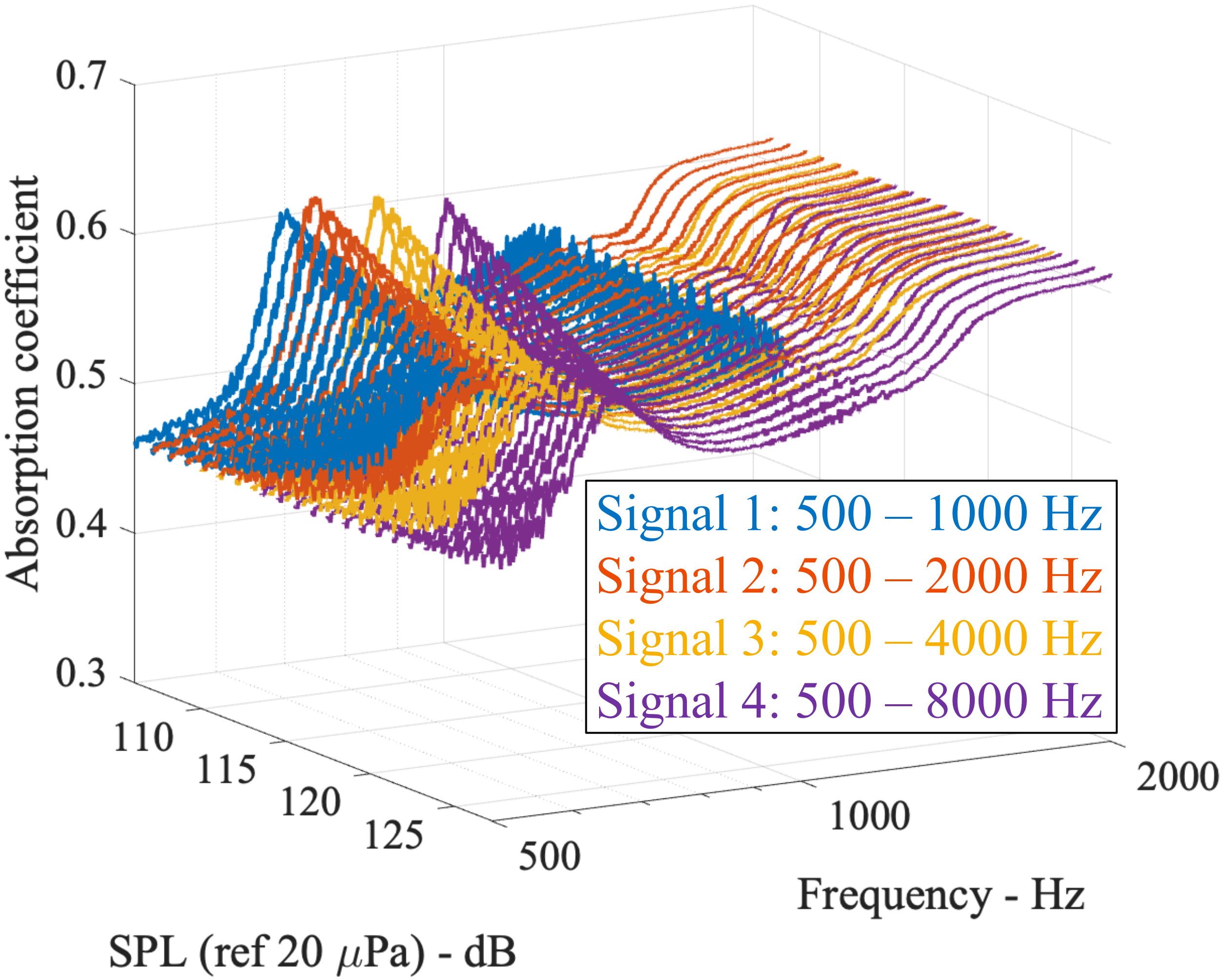
Integrate over frequency:

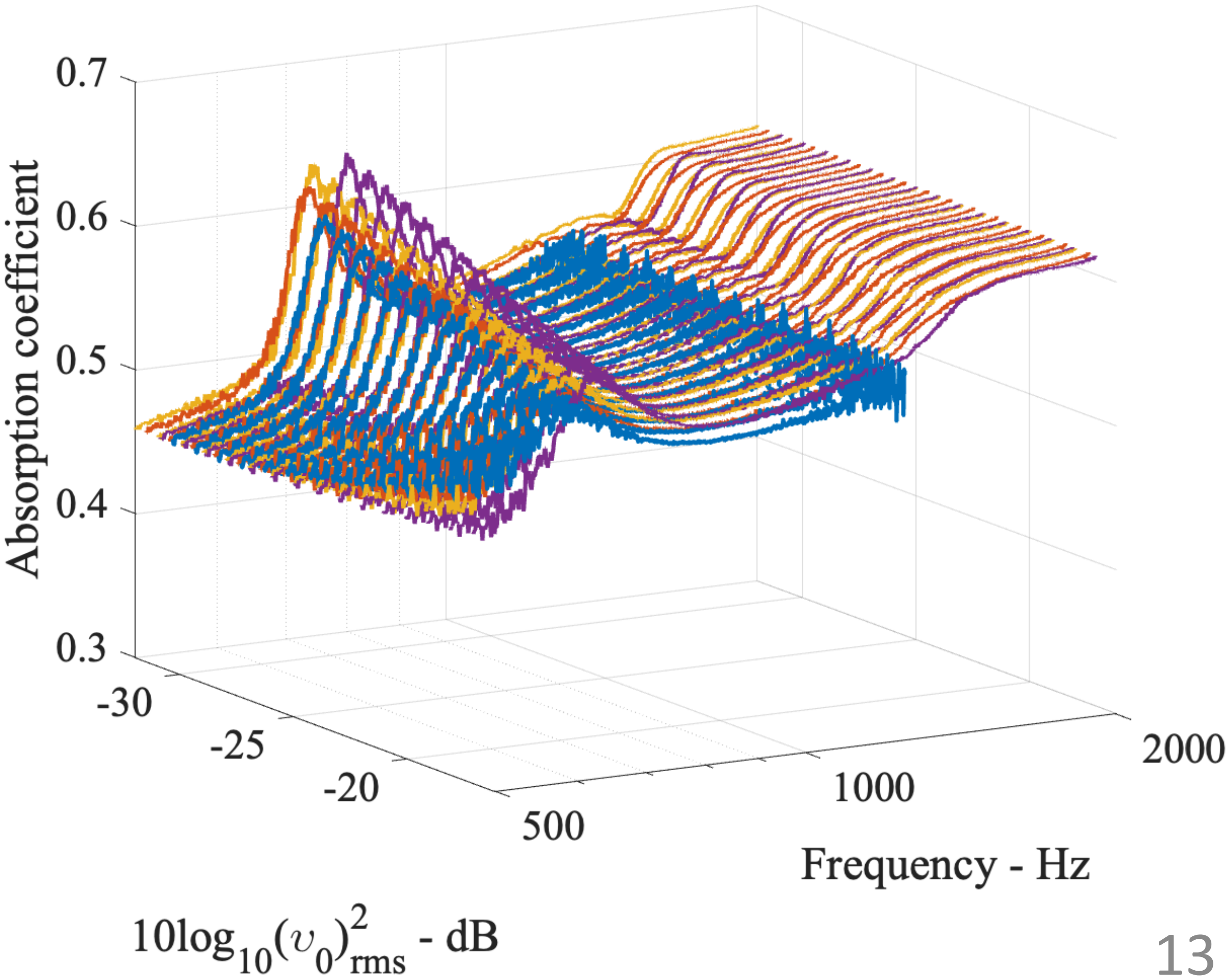
- $(P_0)^2_{rms} = \int \left(P_0(f)\right)^2_{rms} df \ \rightarrow SPL$
- $(v_0)^2_{rms} = \int \left(v_0(f)\right)^2_{rms} df$
- $(u_0)^2_{rms} = \int \left(u_0(f)\right)^2_{rms} df$

Absorption coefficient against SPL and integrated RMS velocity @

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

Sound pressure level





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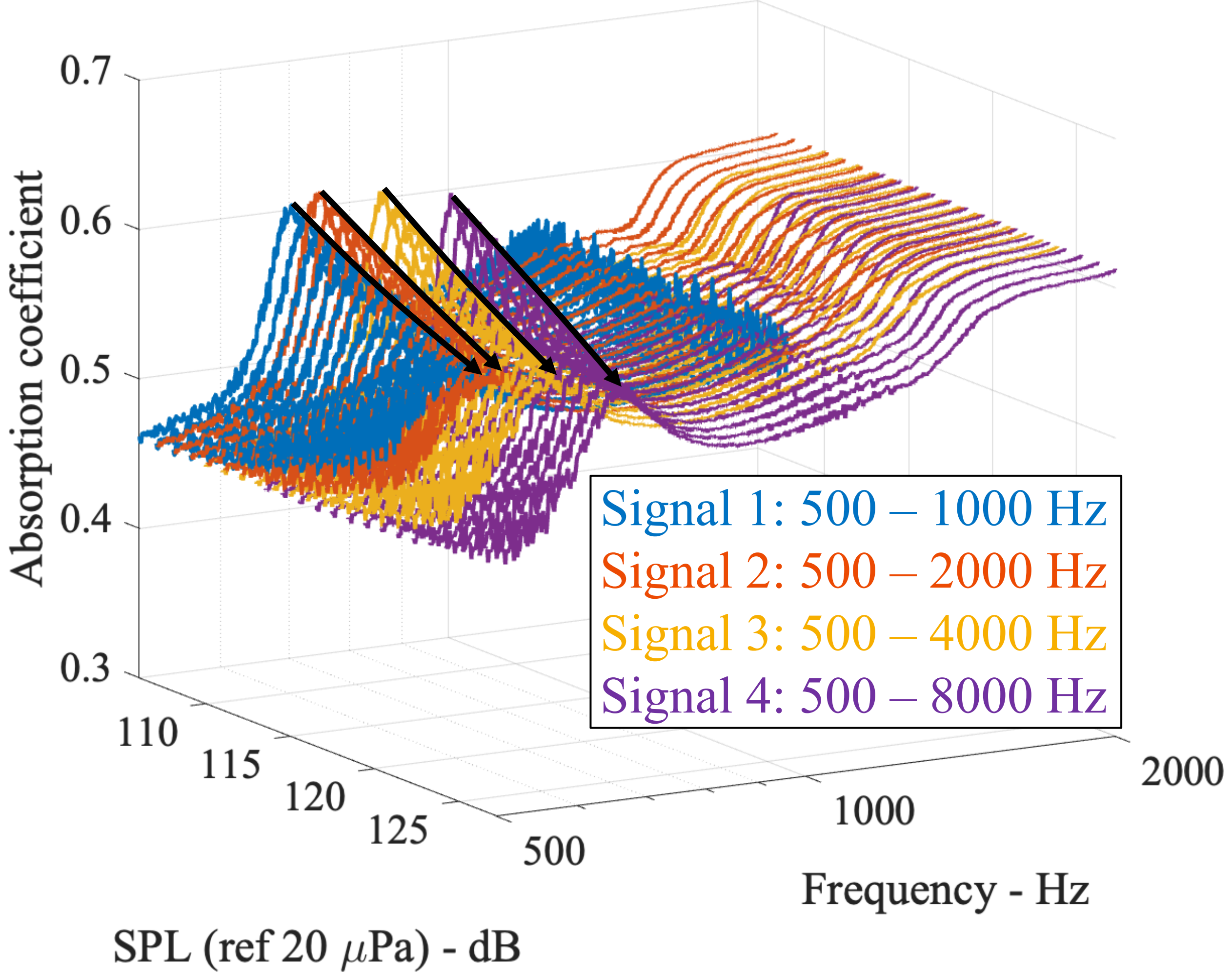

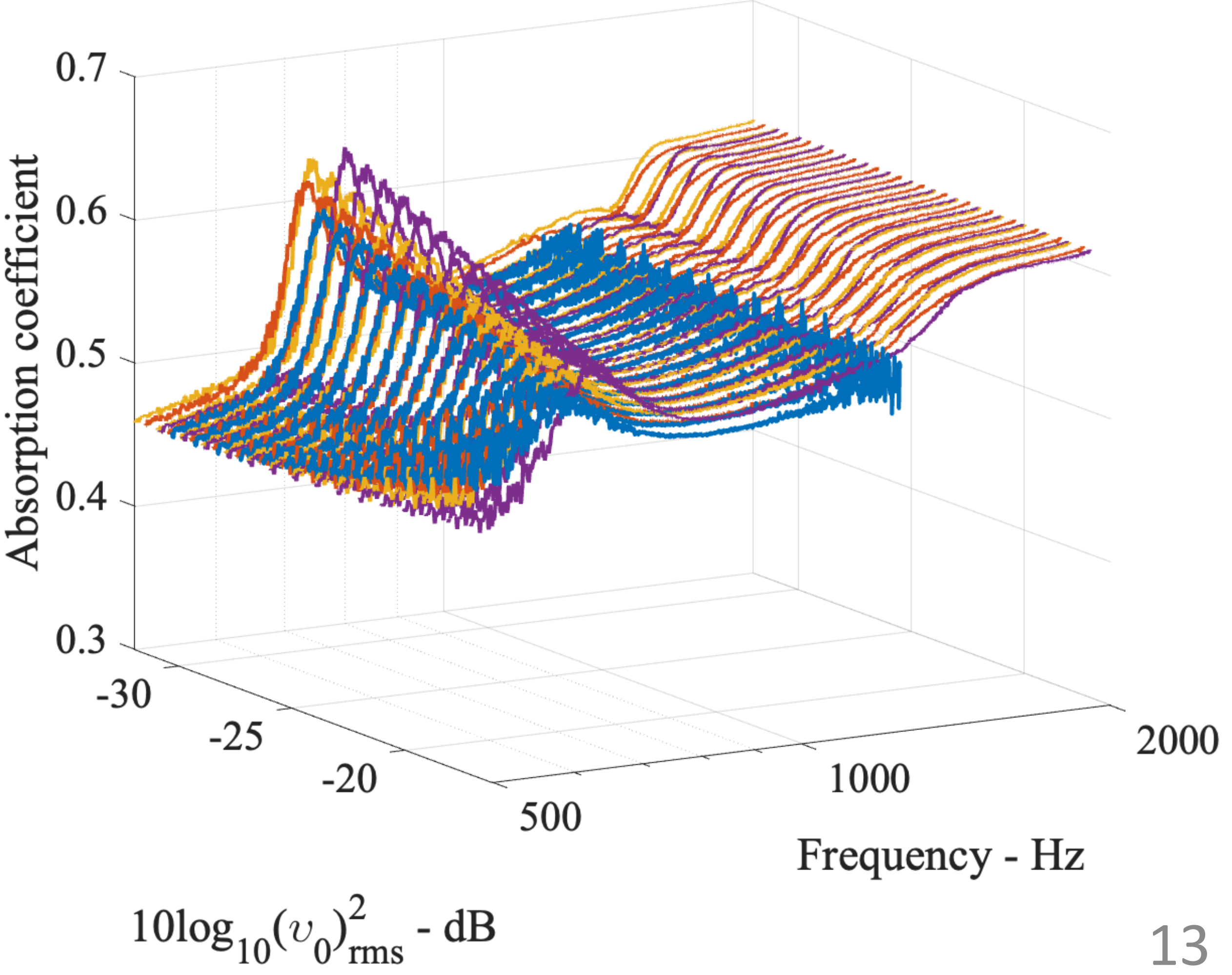

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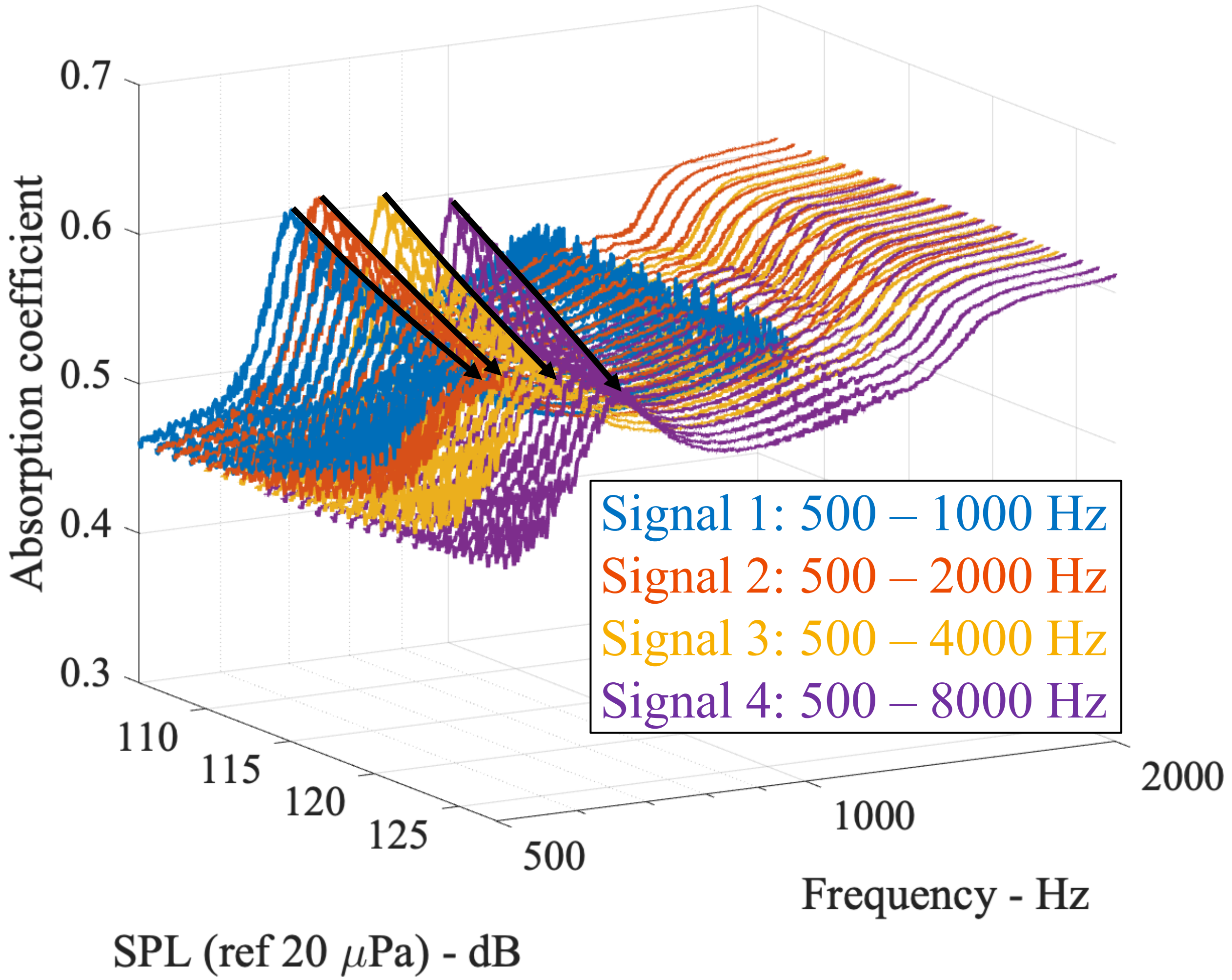
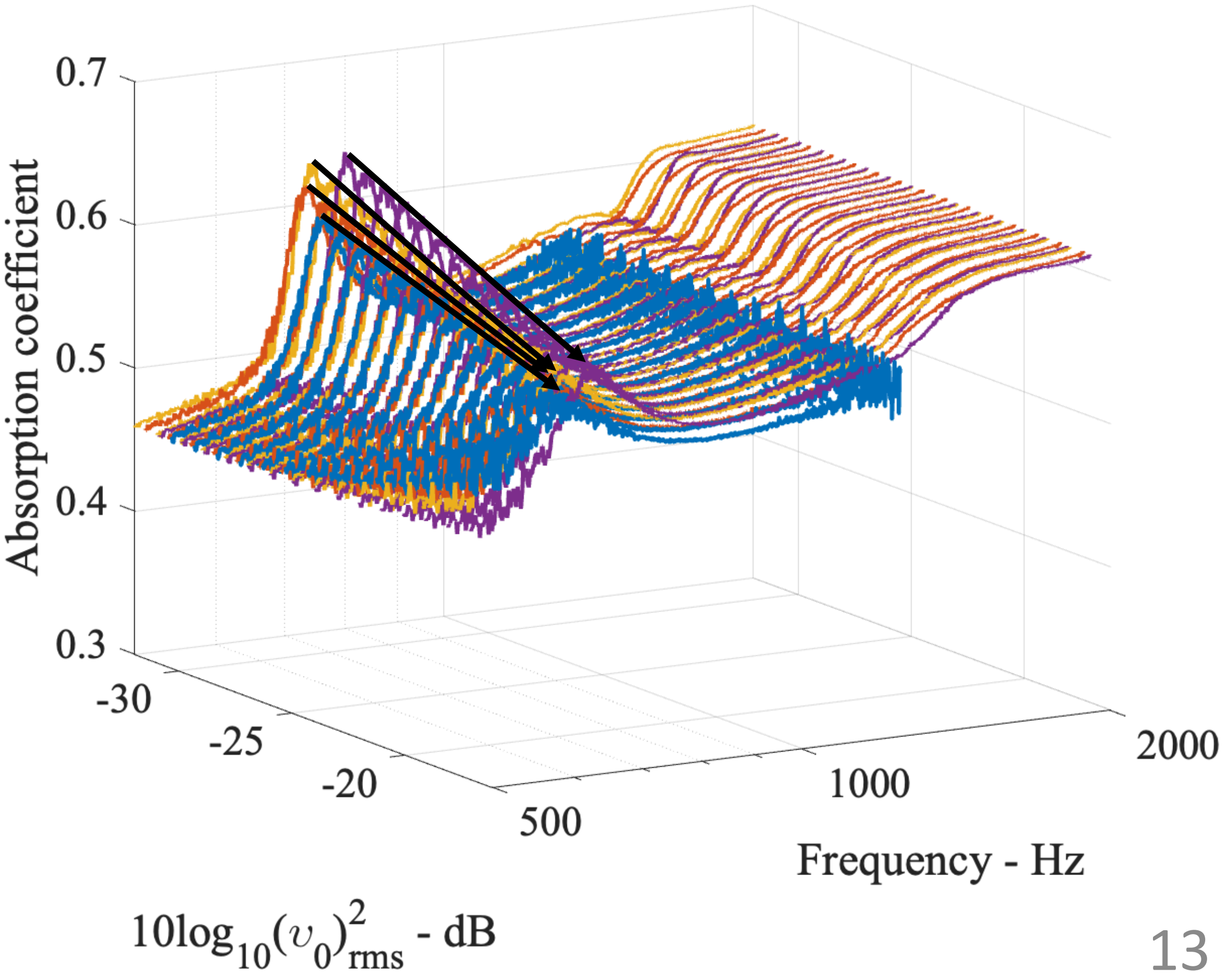
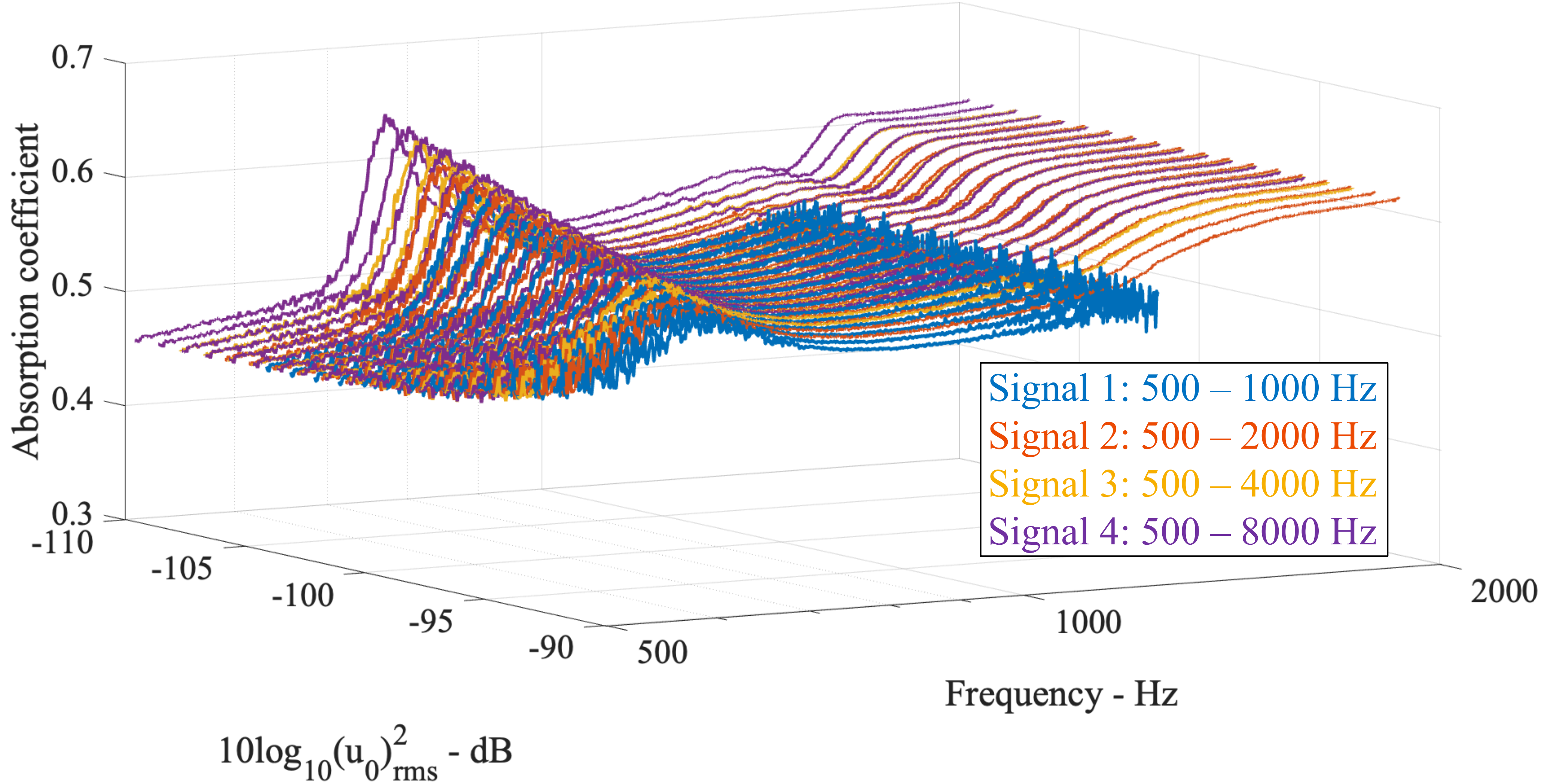




Absorption coefficients against integrated RMS displacement @

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



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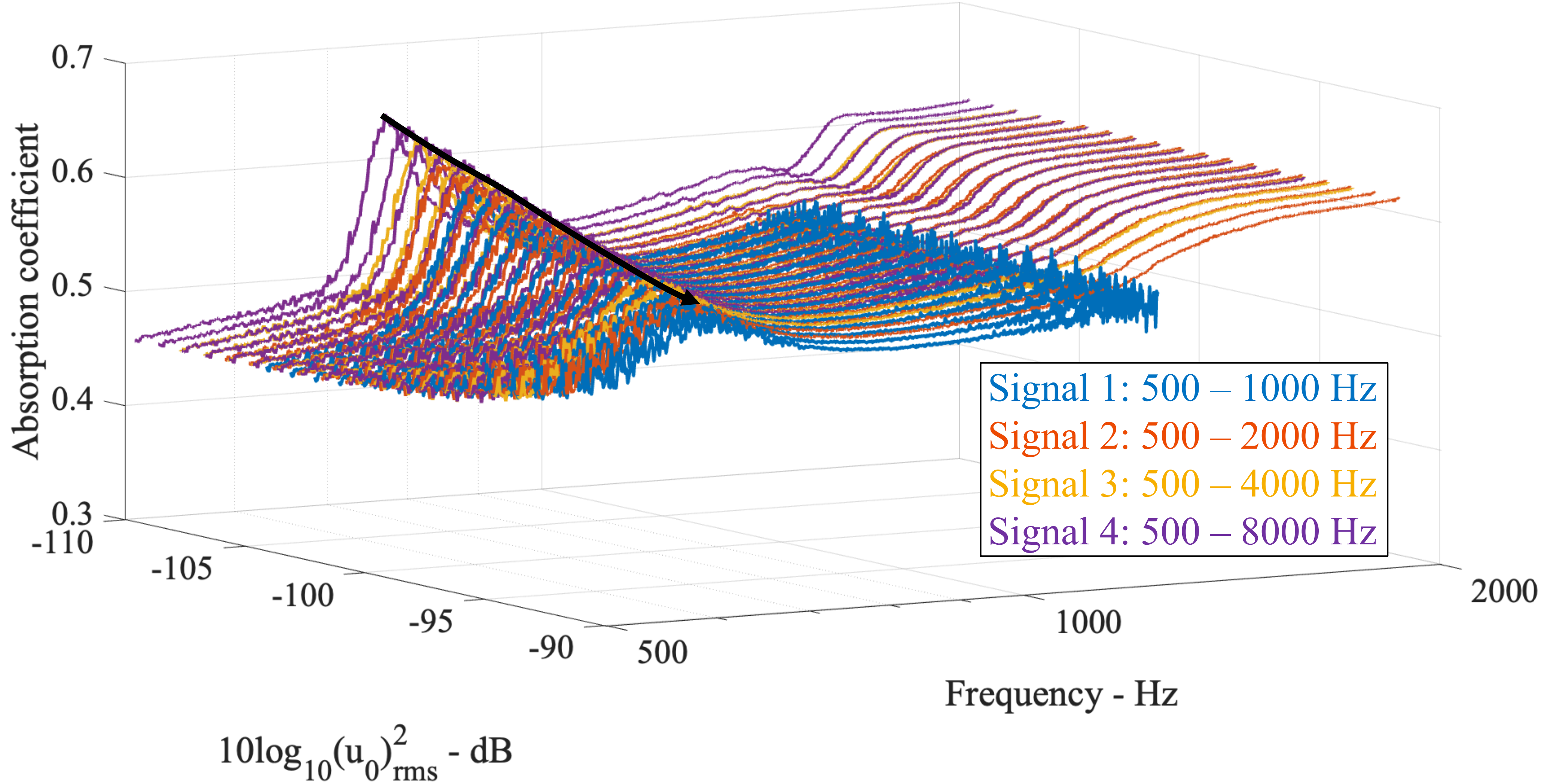
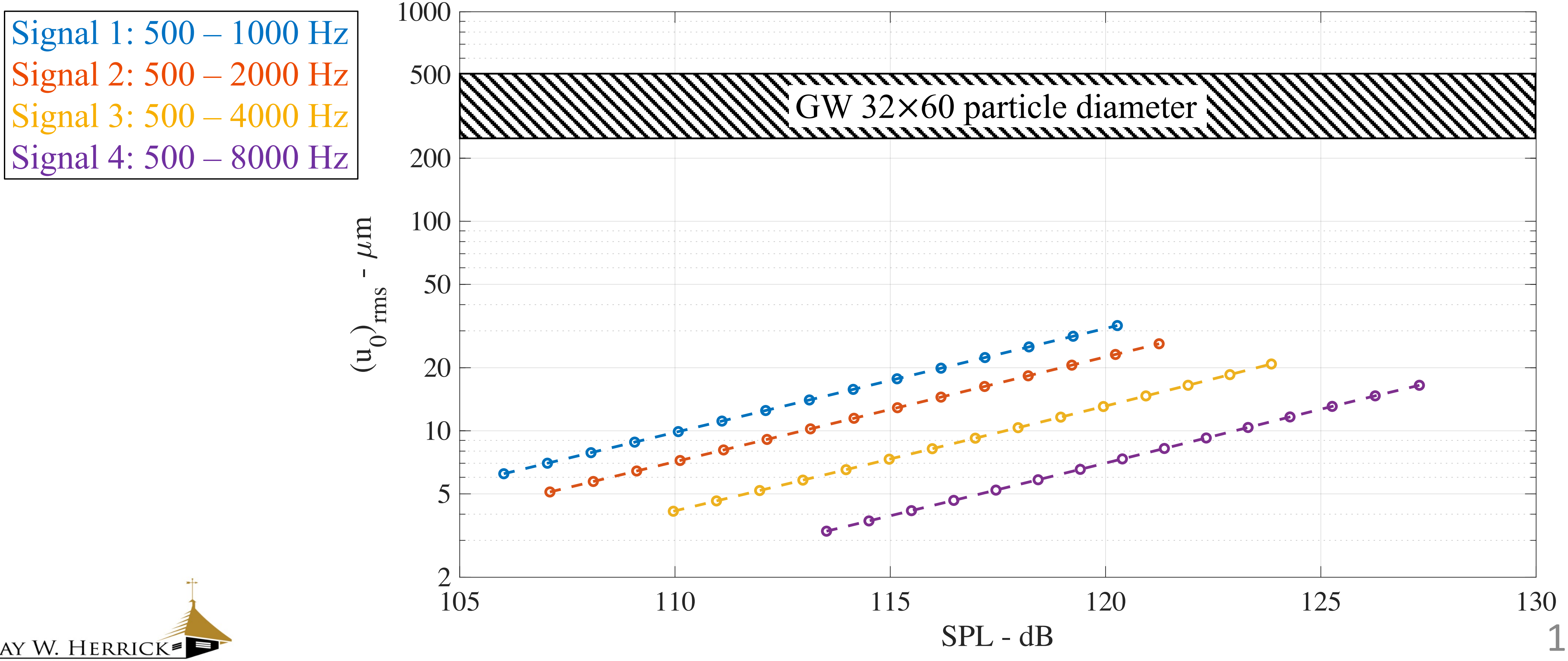


RMS displacement

- The effect becomes significant when RMS displacement at the surface of the stack is a small fraction of the particle diameter.



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Conclusions

Conclusion @

- For relatively low-density 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 effect becomes significant when the RMS displacement at the surface of the stack is a small fraction of the particle diameter

- The modulus softening and the increasing damping can be characterized by the integrated RMS displacement (which can be related to strain) at the carbon particle stack surface

References @

[1] Venegas, Rodolfo, and Olga Umnova. "Influence of sorption on sound propagation in granular activated carbon." *The Journal of the Acoustical Society of America* 140, no. 2 (2016): 755-766.

[2] Zhuang Mo, Tongyang Shi, Seunkyu Lee, Yongbeom Seo and J. Stuart Bolton, "A Poro-Elastic Model for Activated Carbon Stacks," 6th Symposium on the Acoustics fo Poro-Elastic Materials (SAPEM 2020+1), West Lafayette, IN, 20 March to April 2 2021. Extended Abstract available at: https://sapem2021.matelys.com/proceedings/07-06_Mo_etal.pdf. Presentation video available at: https://sapem2021.matelys.com/proceedings/07-06_Mo_etal.mp4.

[3] Tsuruha, Takumasa, Makoto Otani, and Yasushi Takano. "Effect of acoustically-induced elastic softening on sound absorption coefficient of hollow glass beads with inner closed cavities." *The Journal of the Acoustical Society of America* 150, no. 2 (2021): 841-850.

[4] Begum, H., Y. Xue, J. S. Bolton, and K. V. Horoshenkov. "The acoustical absorption by air-saturated aerogel powders." *The Journal of the Acoustical Society of America* 151, no. 3 (2022): 1502-1515.

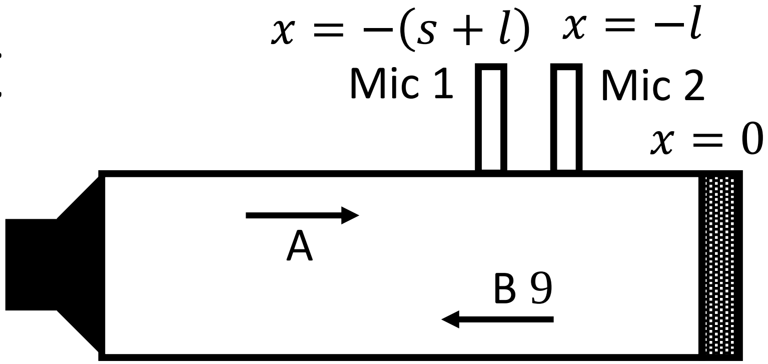
[5] Wang, G. X., and J. Kuwano. "Modeling of strain dependency of shear modulus and damping of clayey sand." *Soil Dynamics and Earthquake Engineering* 18, no. 6 (1999): 463-471.

[6] ASTM, 2019, "Standard Test Method for Normal Incidence Determination of Porous Material Acoustical Properties Based on the Transfer Matrix Method E2611," *American Society for Testing of Materials*, pp. 1–14.

Thanks

Appendix

RMS pressure, velocity, and displacement



Sound pressure at sample surface, mic 1 and mic 2:

$@\ x = 0$ [Sample surface] 9

$$P_{02} = A + B$$

$@\ x = -(s+l)$ [Mic 1] 9

$$P_1 = Ae^{jk(s+l)2} + Be^{-jk(s+l)2}$$

$@\ x = -l$ [Mic 2]

$$P = Ae^{jkl2} + Be^{-jkl2}$$

Solve for $A(f), B(f)$

$$A = j\frac{P\ e^{-jkl} - P_2 e^{-jk(l+s)}}{\sin(ks)2} = j\frac{e^{-jkl} - H_{2,}^{c1} e^{-jk(l+s)}}{\sin(ks)+} P_{12}$$

$$B = j\frac{P_2 e^{+jk(l+s)} - P\ e^{+jkl1}}{\sin(ks)2} = j\frac{H_{2,}^{c1} e^{+jk(l+s)} - e^{+jkl}"}{\sin(ks)2} P_{12}$$

$$P_{02} = A + B$$

$$= \left[j\frac{e^{-jkl} - H_{2,}^{c}\ e^{-jk(l+s)}}{2\sin(ks)1} + j\frac{H_{2,}^{c}\ e^{+jk(l+s)} - e^{+jkl1}}{2\sin(ks)}\right] P$$

$$v_{02} = \frac{A2}{\rho_0 c2} - \frac{B}{\rho_0 c2}$$

$$= \frac{}{\rho_0 c1}\left[j\frac{e^{-jkl} - H_{2,}^{c1} e^{-jk(l+s)}}{2\sin(ks)1} - j\frac{H_{2,}^{c1} e^{+jk(l+s)} - e^{+jkl1}}{2\sin(ks)1}\right] P$$

$$u_{02} = \frac{v_{01}}{j\omega 2}$$

$$= \frac{}{\rho_0 c\cdot j\omega 1}\left[j\frac{e^{-jkl} - H_{2,}^{c1} e^{-jk(l+s)}}{2\sin(ks)1} - j\frac{H_{2,}^{c1} e^{+jk(l+s)} - e^{+jkl1}}{2\sin(ks)1}\right] P$$

Therefore,

$$(P_{01})^2_{rms} = \left|j\frac{e^{-jkl} - H_{2,}^{c1} e^{-jk(l+s)}}{2\sin(ks)1} + j\frac{H_{2,}^{c1} e^{+jk(l+s)} - e^{+jkl1}}{2\sin(ks)1}\right|^{21} (P\ )^{21}_{rms}$$

$$(v_{01})^{21}_{rms} = \frac{}{(\rho_0 c)^{21}}\left|j\frac{e^{-jkl} - H_{2,}^{c1} e^{-jk(l+s)}}{2\sin(ks)1} - j\frac{H_{2,}^{c1} e^{+jk(l+s)} - e^{+jkl1}}{2\sin(ks)1}\right|^{2} (P\ )^{21}_{rms}$$

$$(u_{01})^{21}_{rms} = \frac{}{(\rho_0 c)^{12}\omega^{21}}\left|j\frac{e^{-jkl} - H_{2,}^{c1} e^{-jk(l+s)}}{2\sin(ks)1} - j\frac{H_{2,}^{c1} e^{+jk(l+s)} - e^{+jkl1}}{2\sin(ks)1}\right|^{21} (P\ )^{21}_{rms}$$

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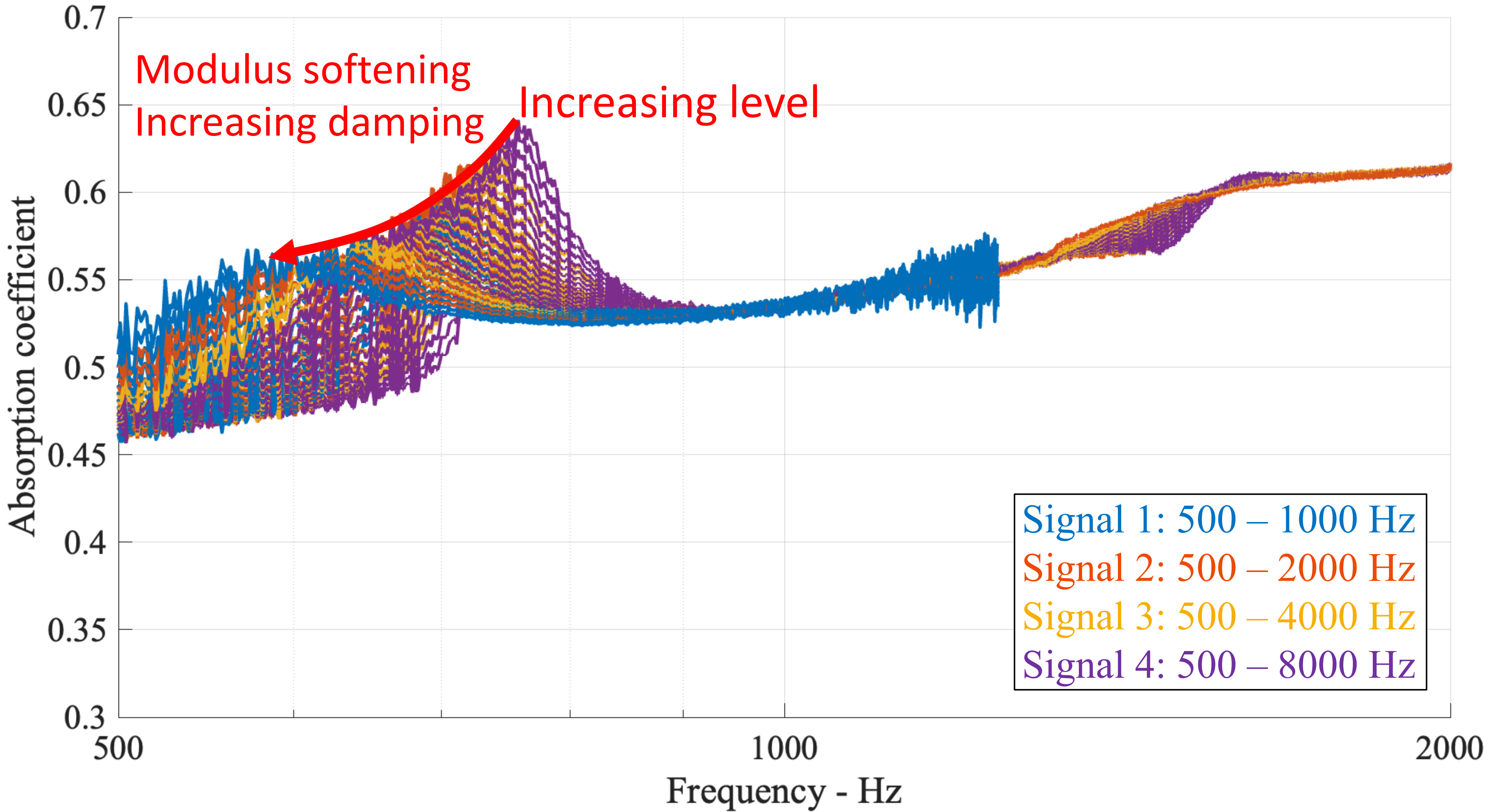
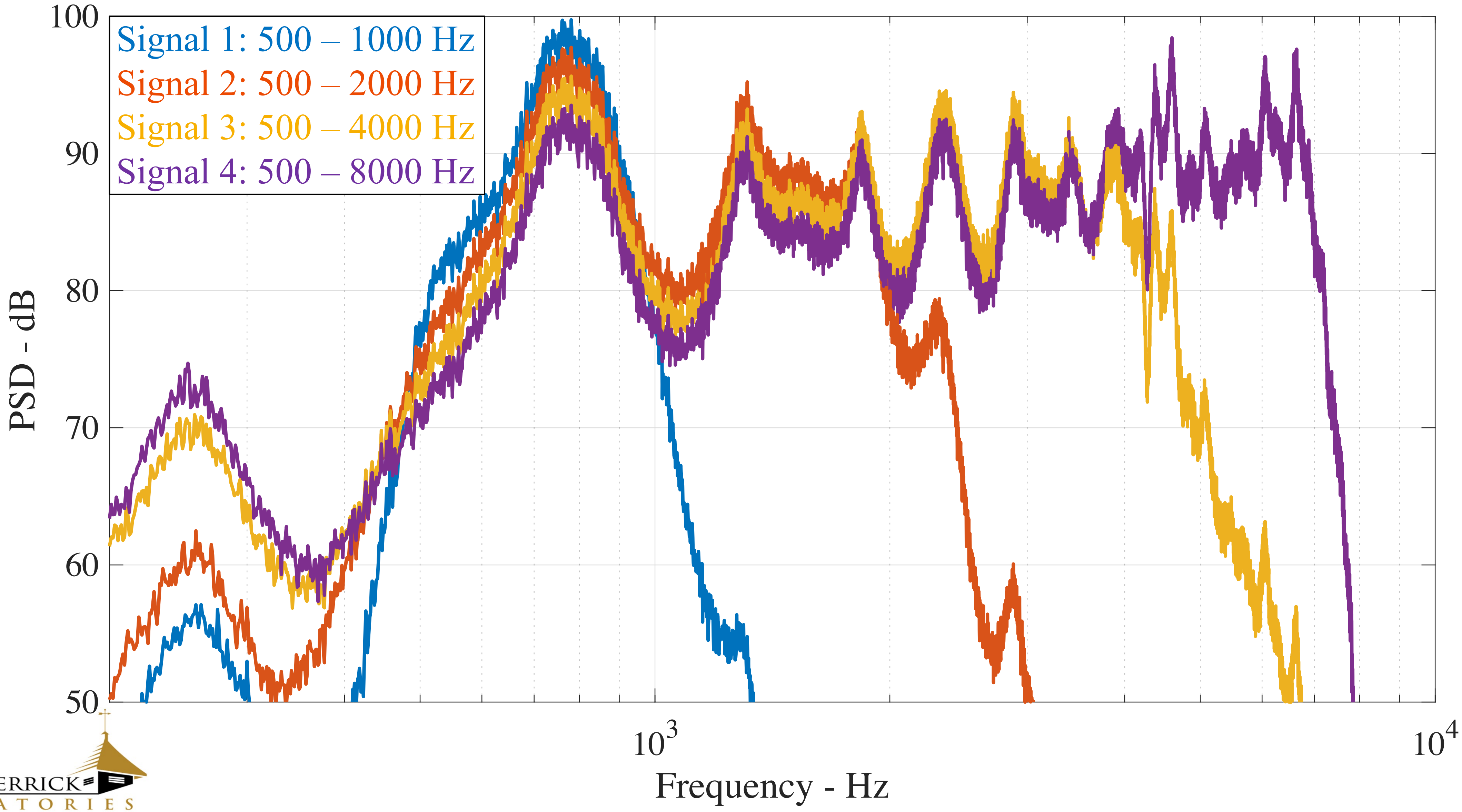
Absorption coefficients against integrated RMS displacement @

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



PSD of the pressure at the front surface of the material (calculated based on the highest-level segment in each signal)



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