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Experimental Study and Modeling of the Level-Dependent Acoustical Behavior of Granular Particle Stacks

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Experimental study and modeling of the level-dependent acoustical behavior of granular particle stacks

PURDUE MECHANICAL ENGINEERING

RAY W. HERRICK LABORATORIES

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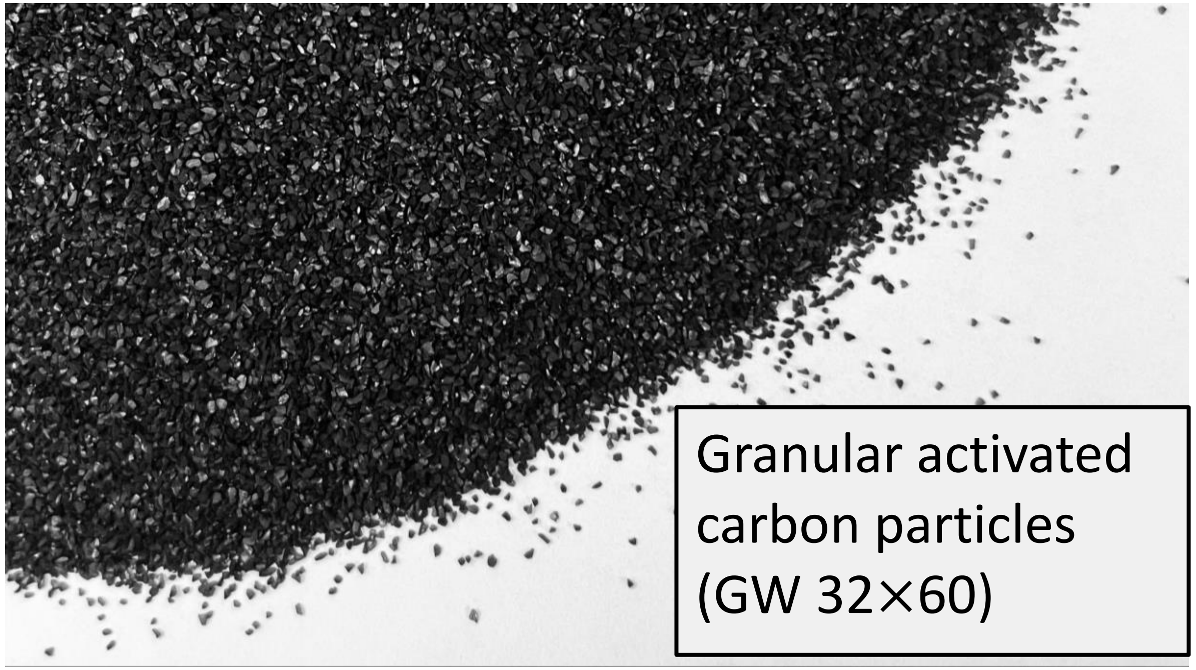
Agenda

- Motivation
- Test setup
- Experimental results
- Preliminary inverse characterization of the granular materials

Motivation (1/2): particle stacks' benefits & applications



Granular activated carbon particles (GW 32×60)

3M™ Flexile Acoustic Material

Benefits of high surface area particles:

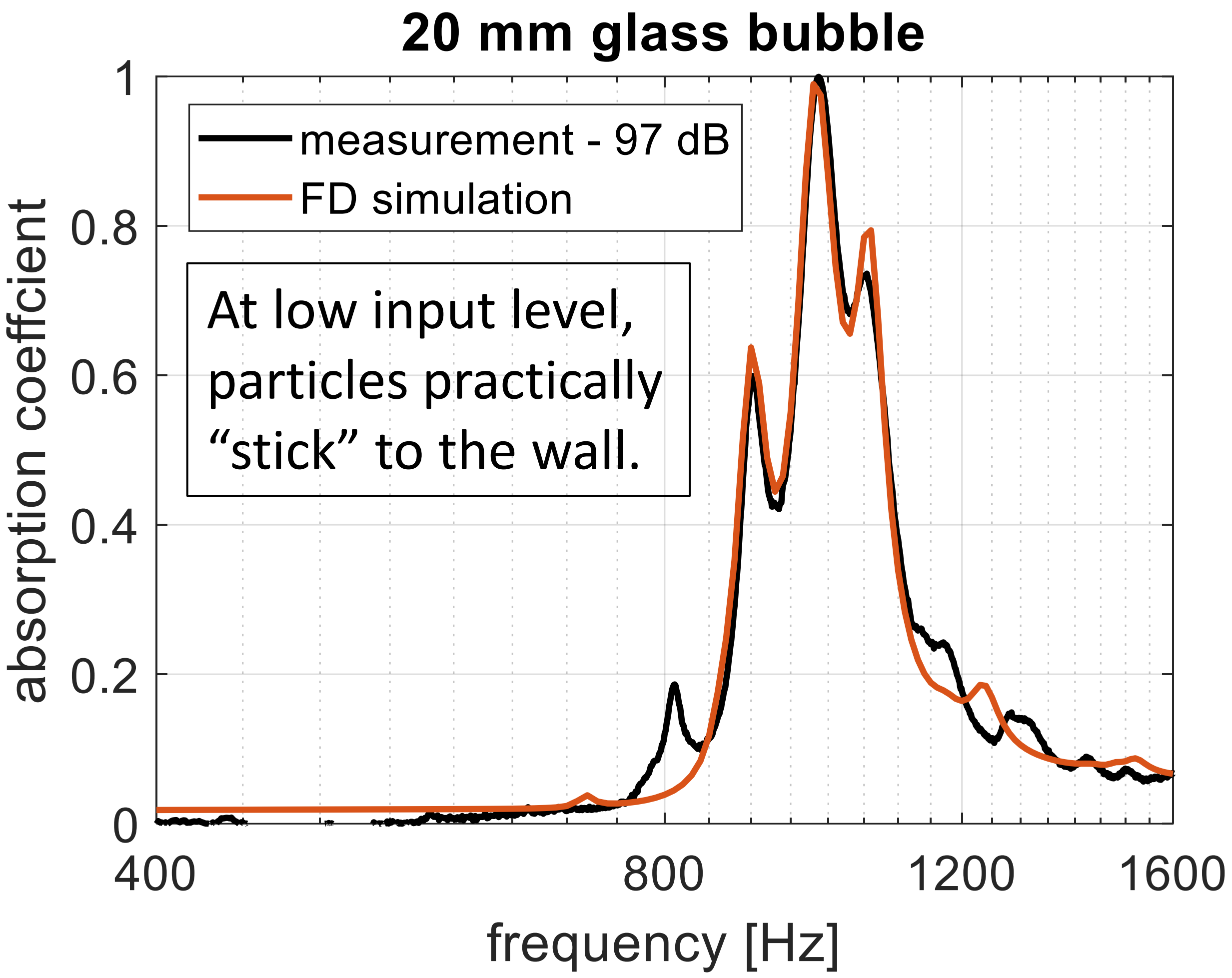
1. Remarkable sorption characteristics
2. Better low frequency sound absorption

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 with the matrix)
3. when the granular particle has already been adopted in various fields (extend it also as an acoustic treatment)

Motivation (2/2): difficulties in modeling particle stacks

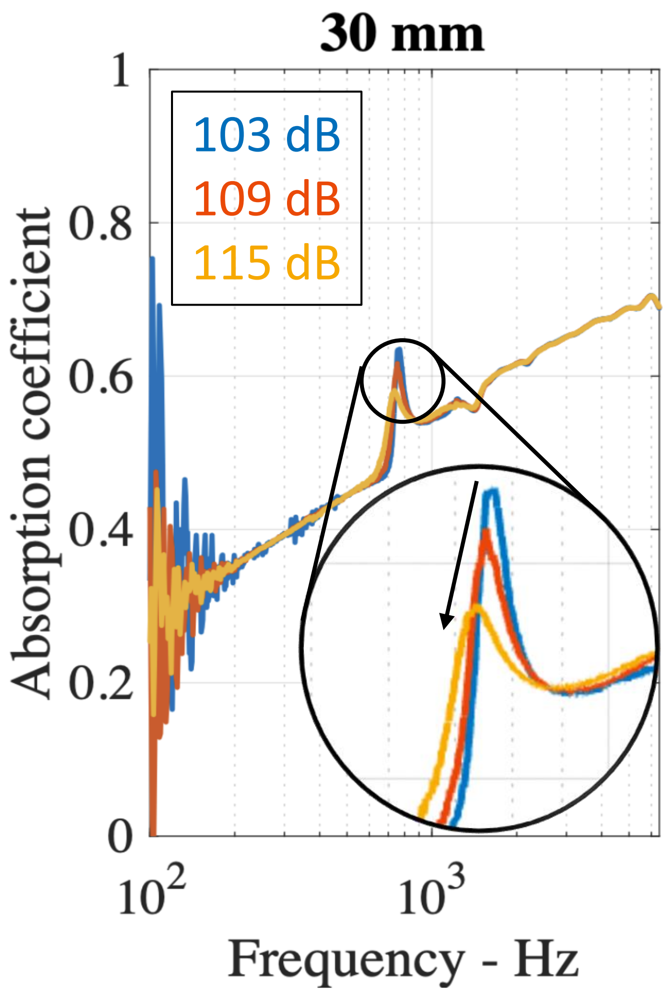
Friction at the impedance tube wall



At low input level, particles practically "stick" to the wall.

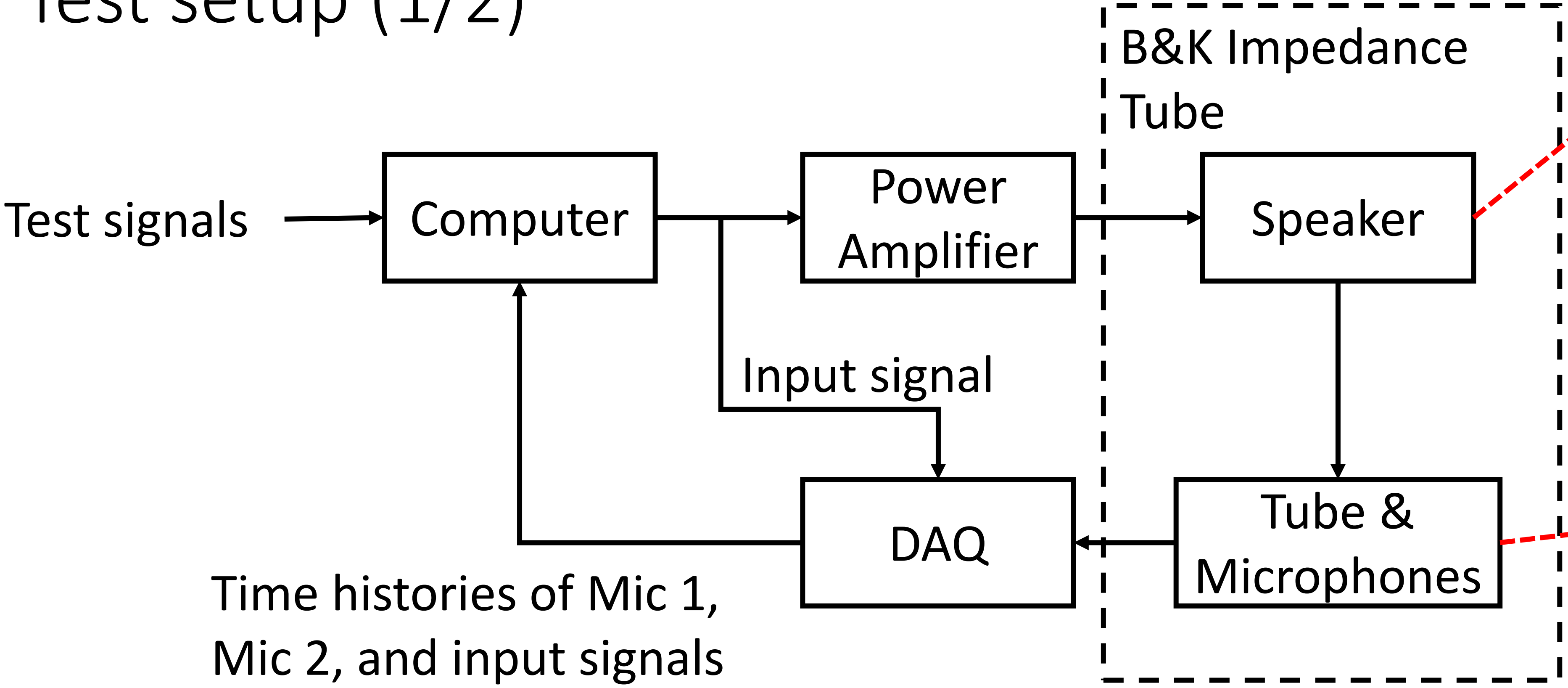
From Mo *et al.* (2022)

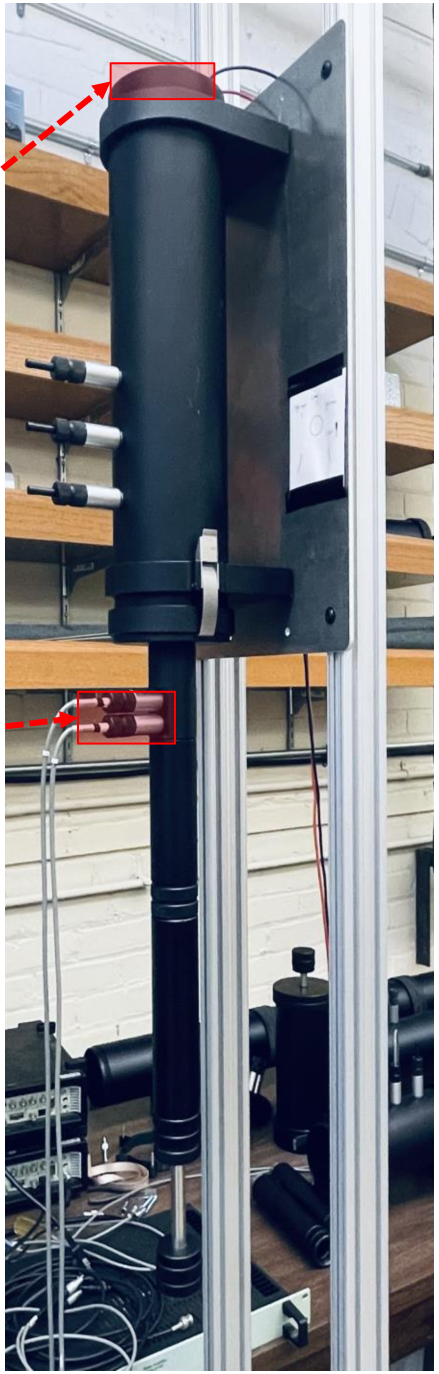
Level-dependent properties



From Song *et al.* (2022)

Test setup (1/2)





Granular material	**Granular activated carbon particles**	**Glass bubbles**	**Glass beads**
Particle diameter [µm]	250-500	60	106-126
Bulk density [kg/m³]	520	135	1494

Test setup (2/2)

Random noise

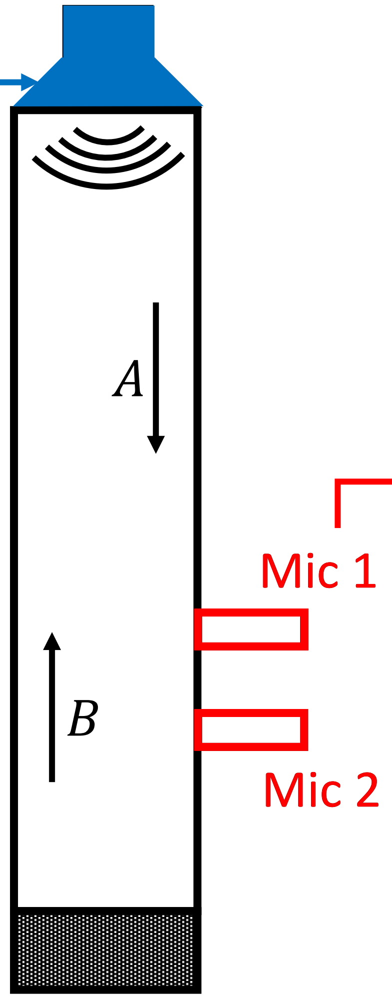
Band-pass filters
[4th order Butterworth]

Scale to 12 levels
[in the step of 2 dB]

In total:
4 bands x 12 levels = 48 signals

Frequency bands:

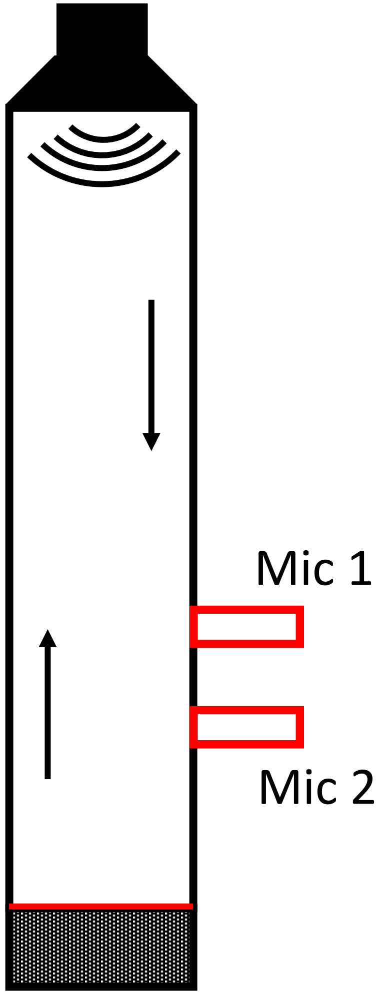
- 500 – 1000 Hz
- 500 – 2000 Hz
- 500 – 4000 Hz
- 500 – 6000 Hz



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

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:

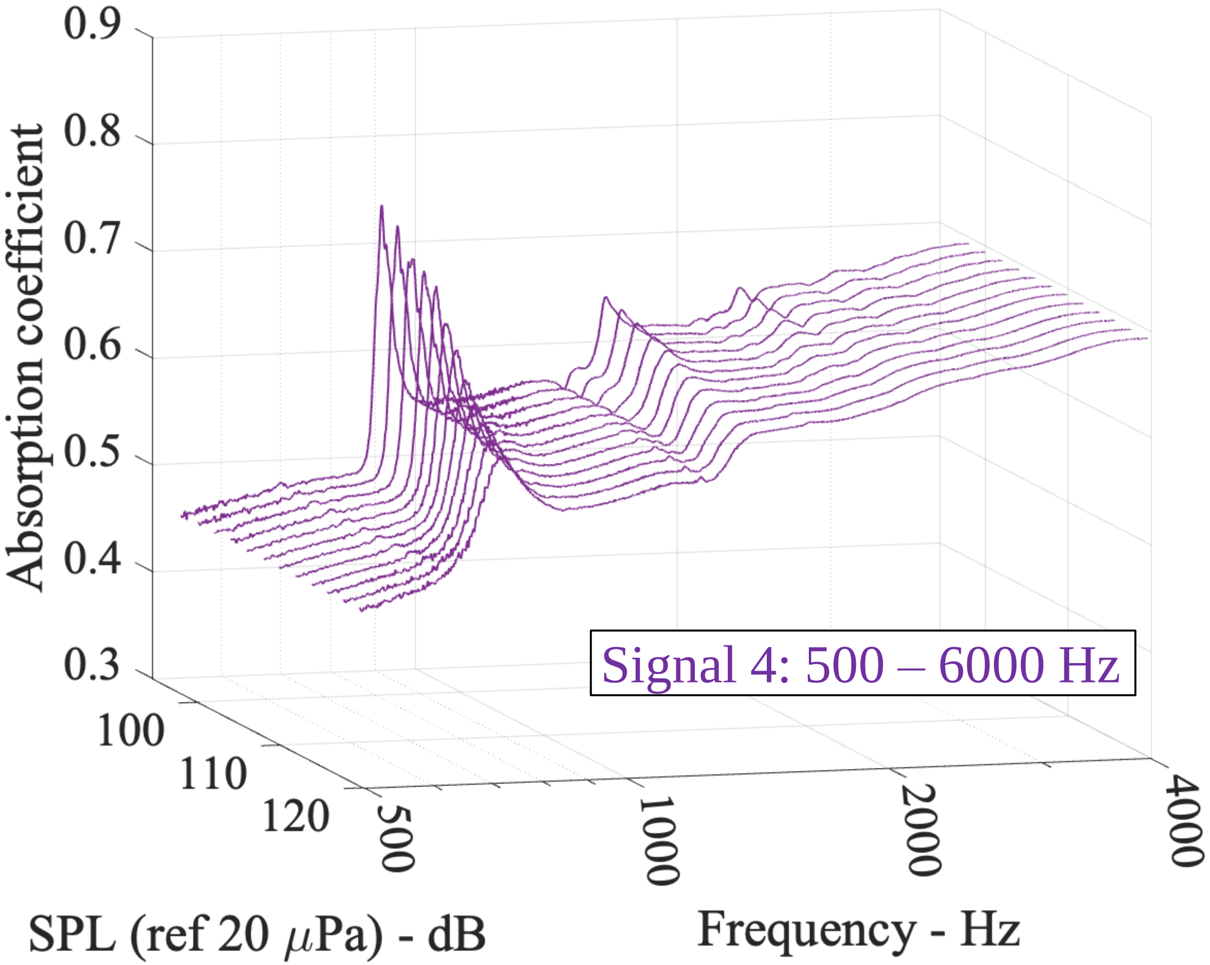
$$S_{P_0P_0} = G_{P_0}\left(S_{P_1P_1}, S_{P_2P_2}, S_{P_1P_2}\right)$$
$$S_{v_0v_0} = G_{v_0}\left(S_{P_1P_1}, S_{P_2P_2}, S_{P_1P_2}\right)$$
$$S_{u_0u_0} = G_{u_0}\left(S_{P_1P_1}, S_{P_2P_2}, S_{P_1P_2}\right)$$

Integrate over frequency:

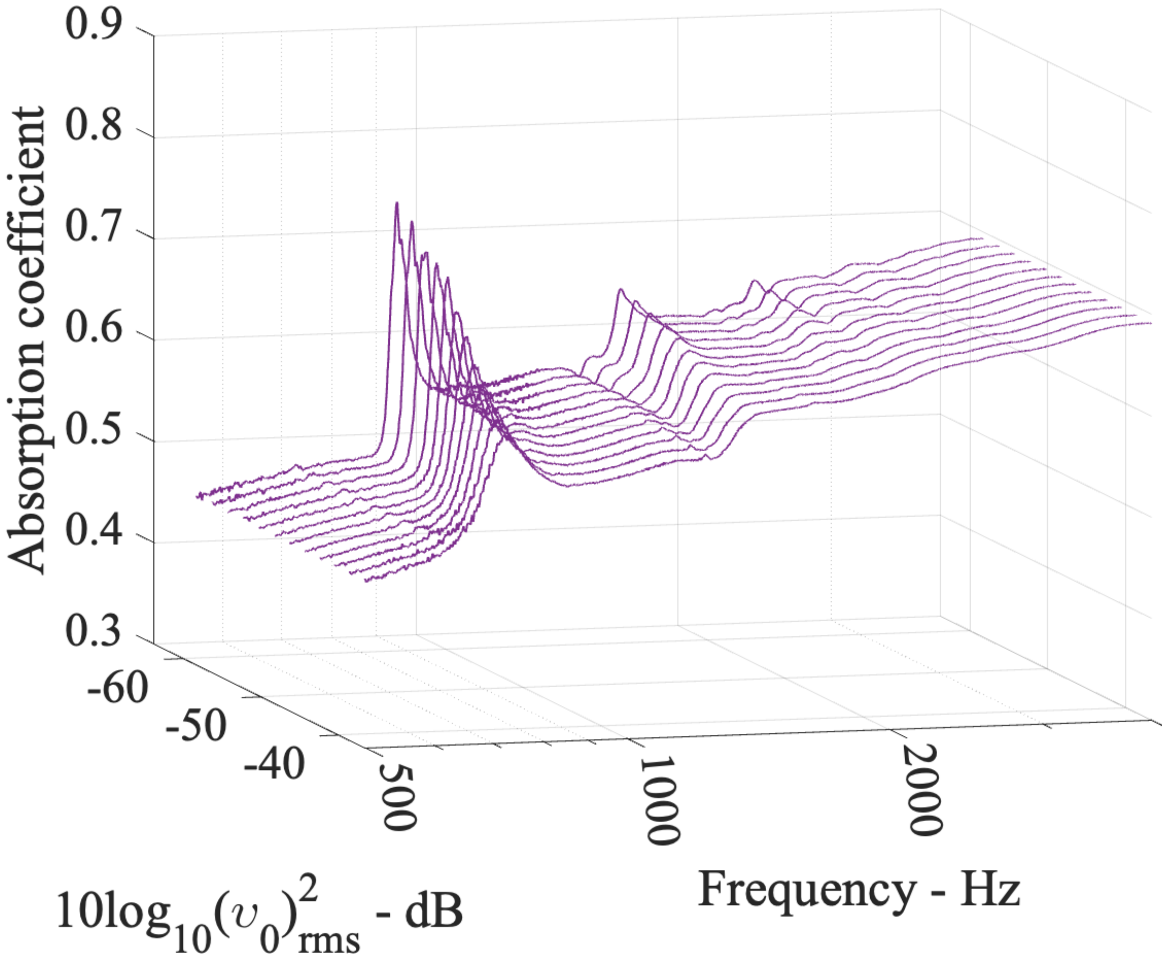
- $(P_0)^2_{rms} = \int S_{P_0P_0}(f)df \quad \rightarrow SPL$
- $(v_0)^2_{rms} = \int S_{v_0v_0}(f)df$ → Integrated RMS fluid velocity
- $(u_0)^2_{rms} = \int S_{u_0u_0}(f)df$ → Integrated RMS fluid displacement

Test results: 40 mm granular activated carbon stack

Sound pressure level



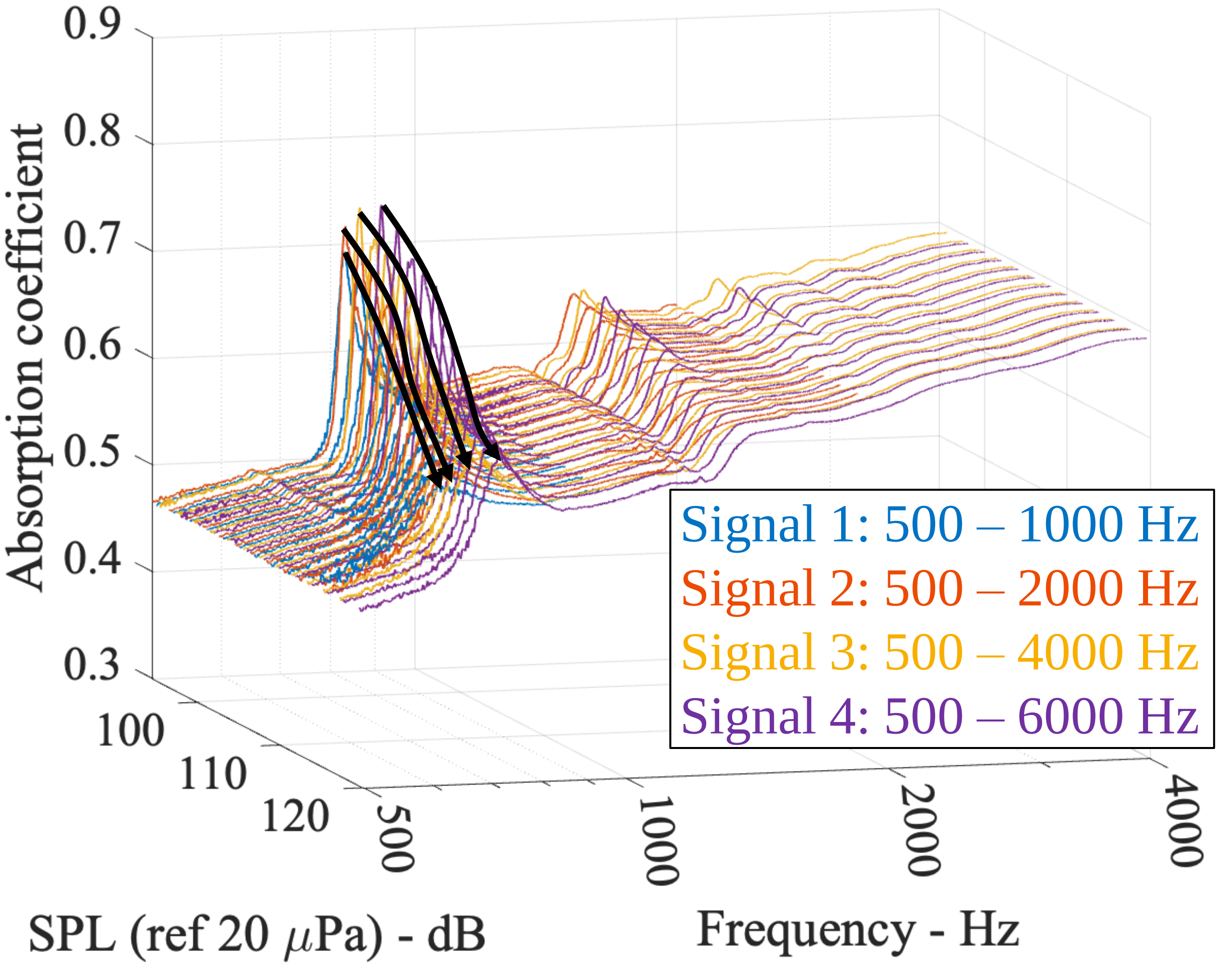
Integrated fluid RMS velocity



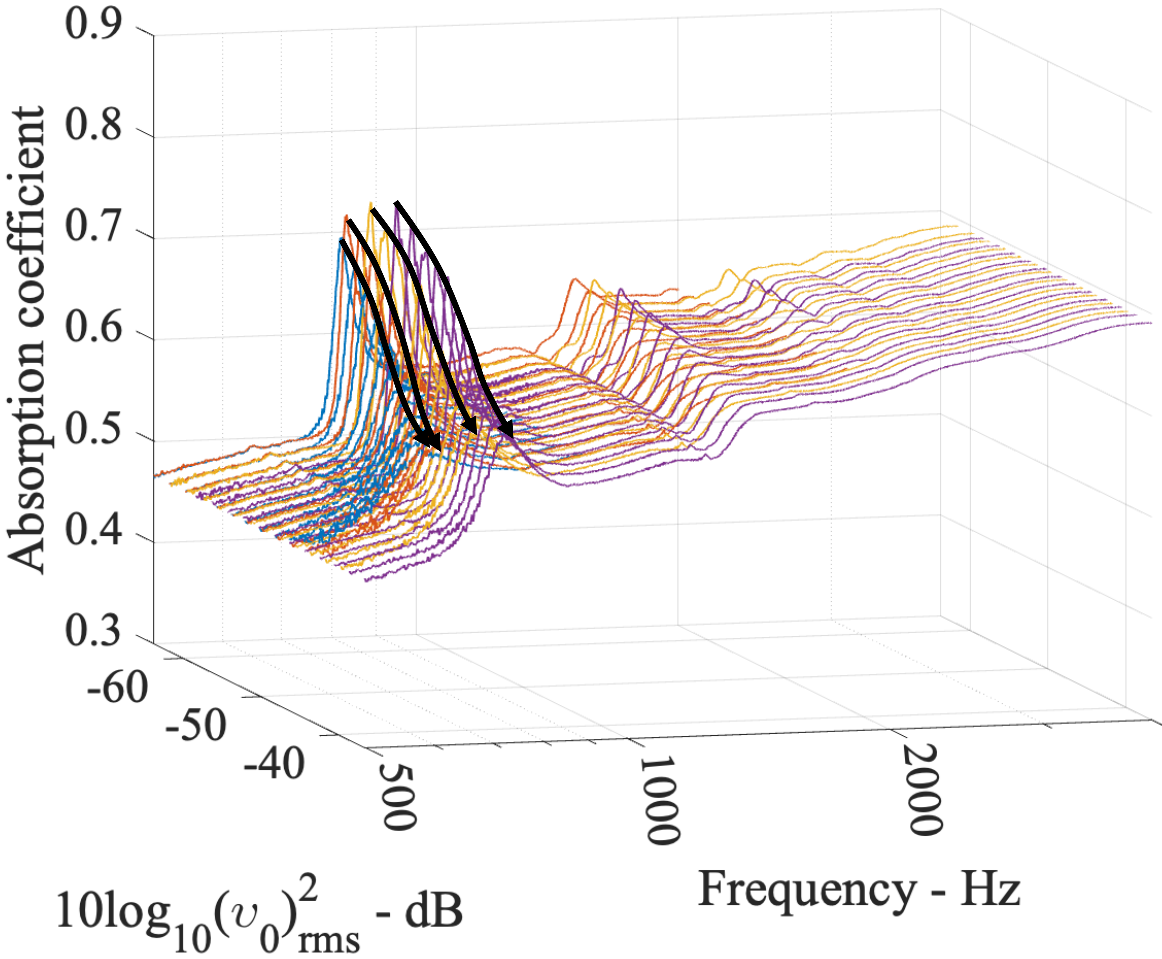
Test results: 40 mm granular activated carbon stack

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

Sound pressure level

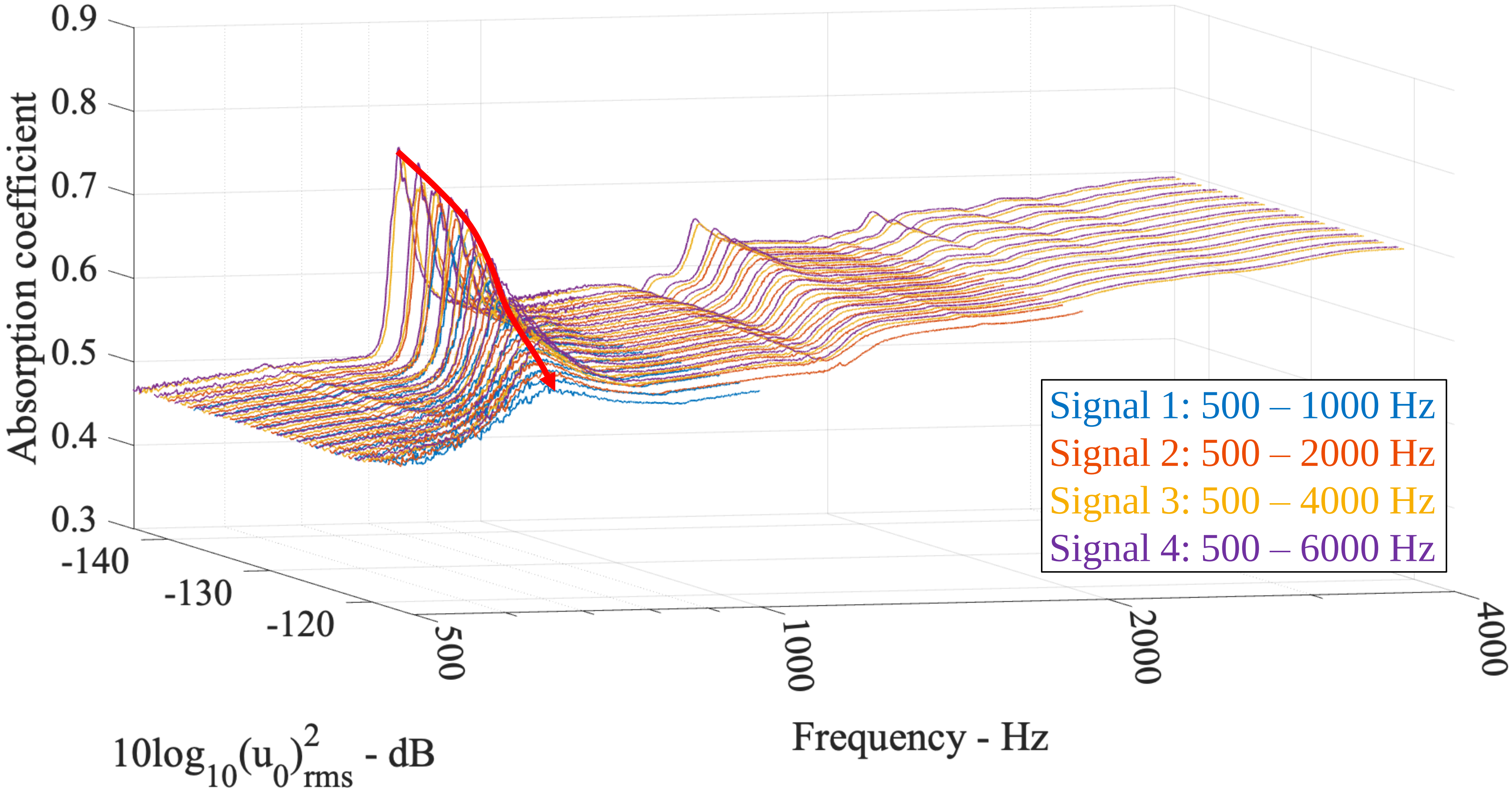


Integrated fluid RMS velocity



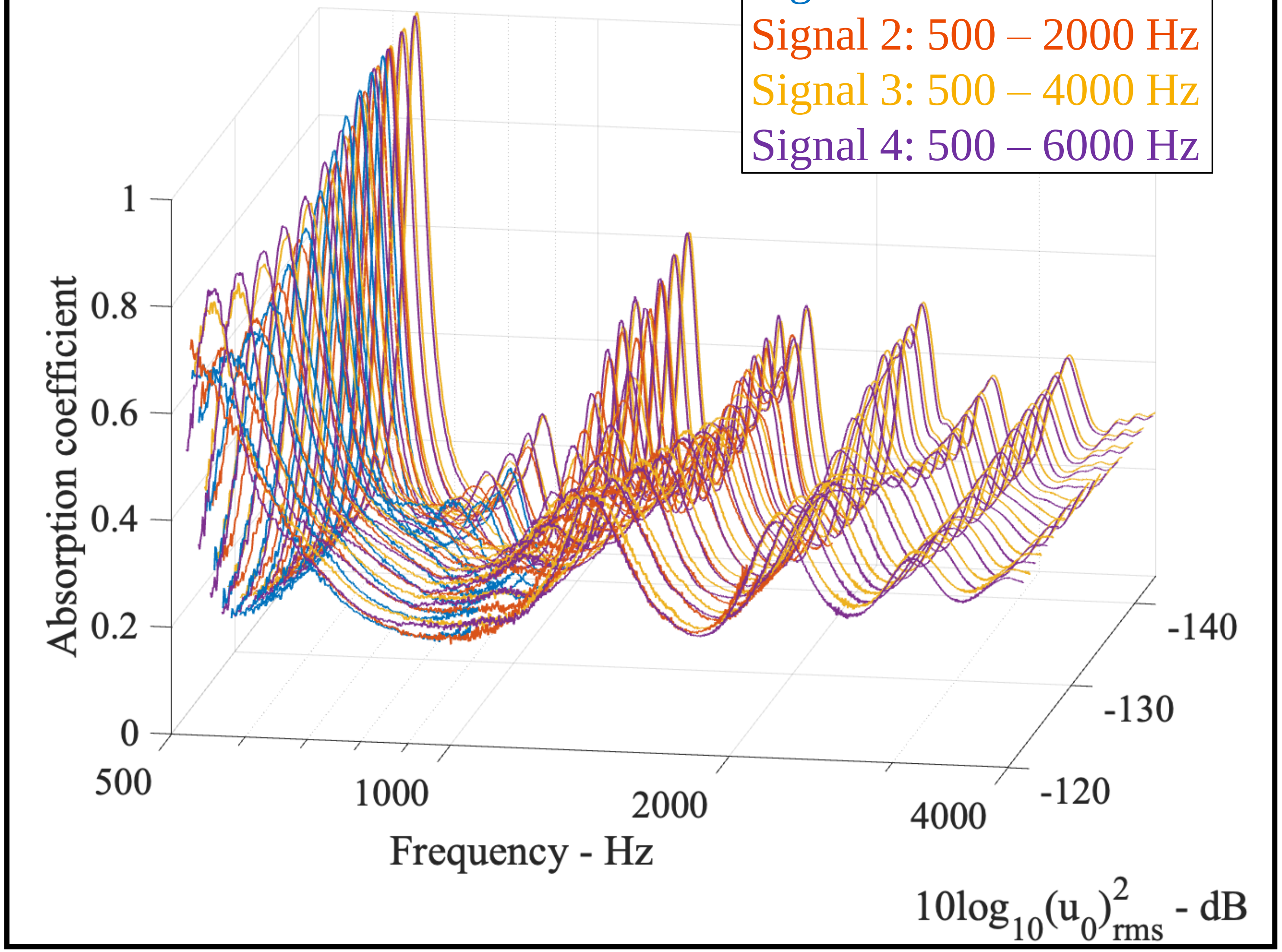
Test results: 40 mm granular activated carbon

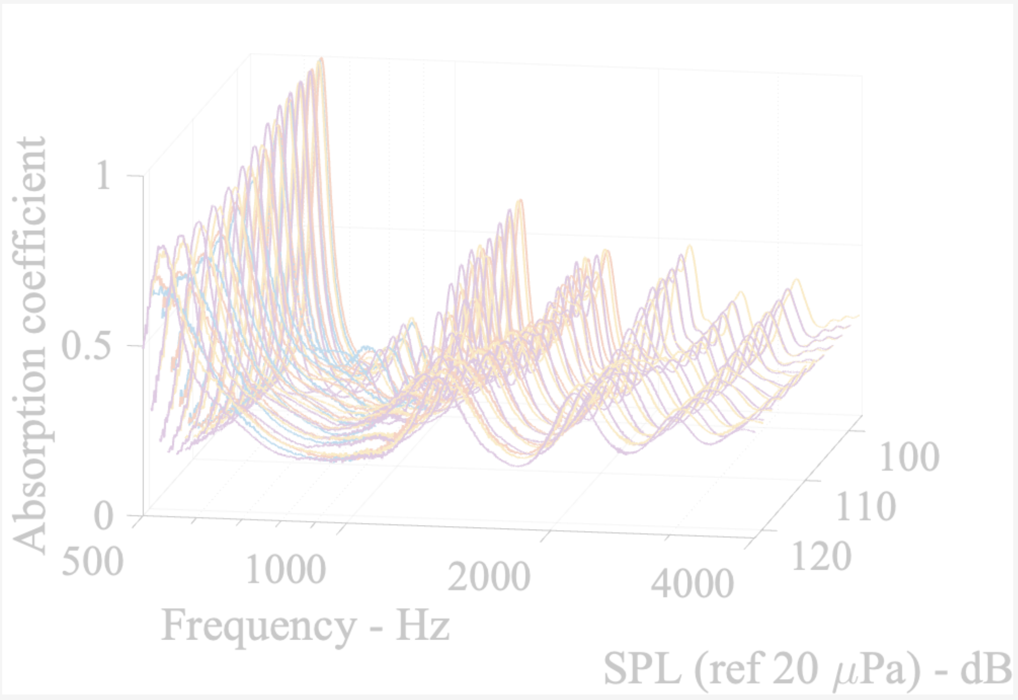
- All the peaks collapse to one single line when plotting against integrated RMS displacement at surface of particle stack, independent of signal bandwidth

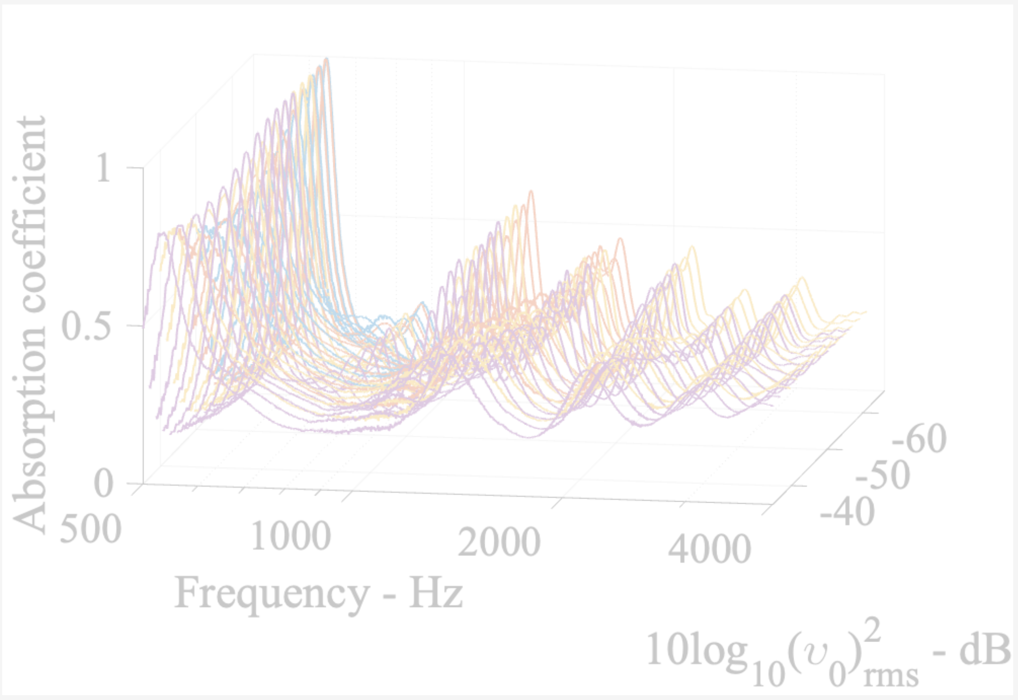


Test results: 40 mm glass bubbles

Particle diameter [µm]	60
Bulk density [kg/m³]	135

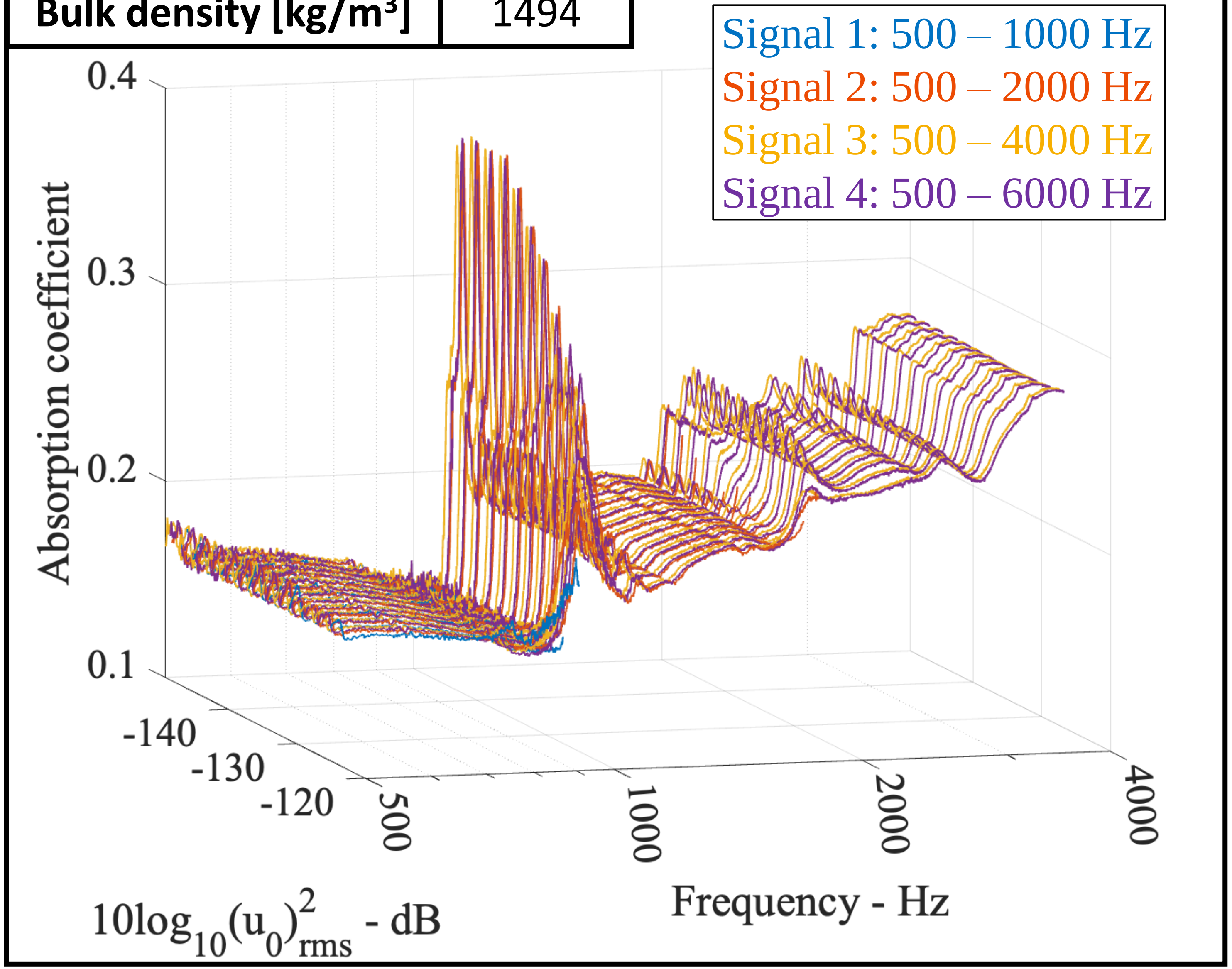


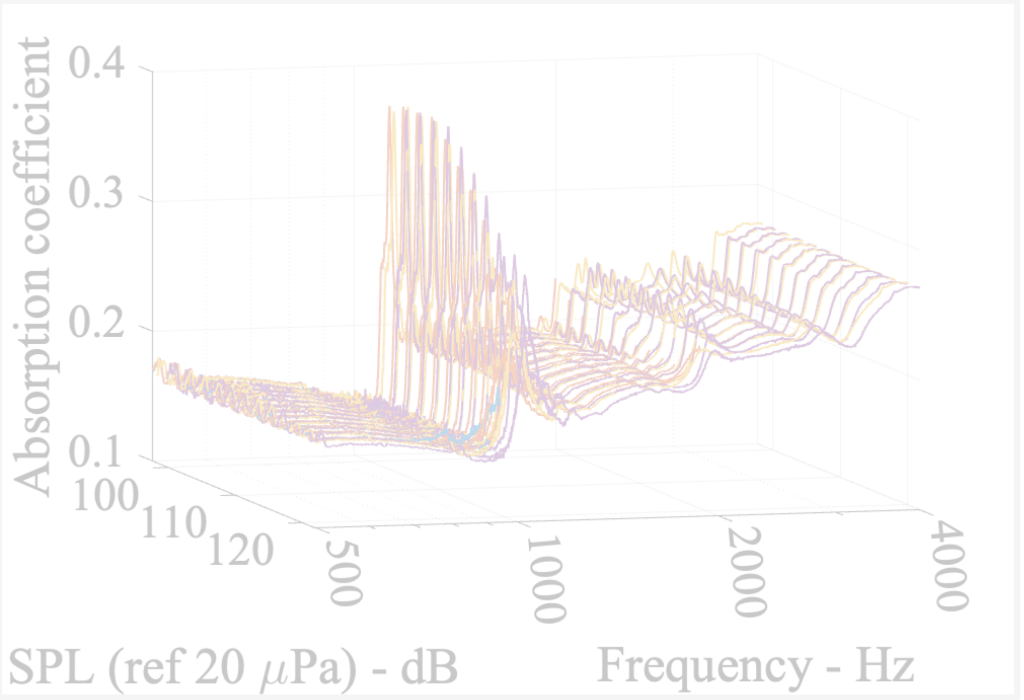


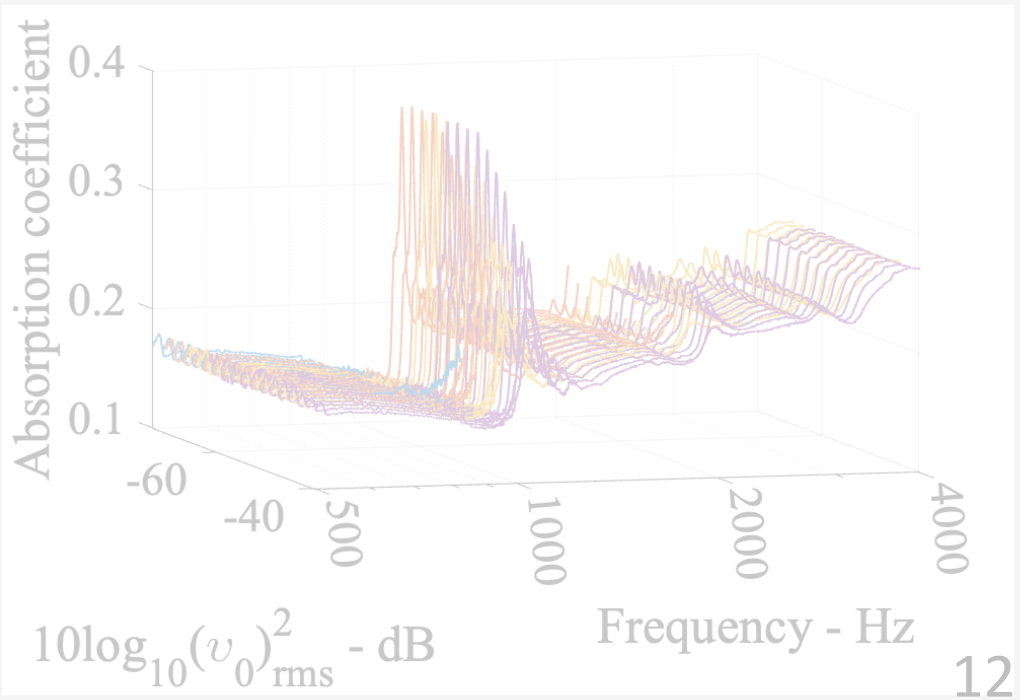


Test results: 40 mm glass beads

Particle diameter [μm]	106-126
Bulk density [kg/m³]	1494







Preliminary fitting results: glass beads

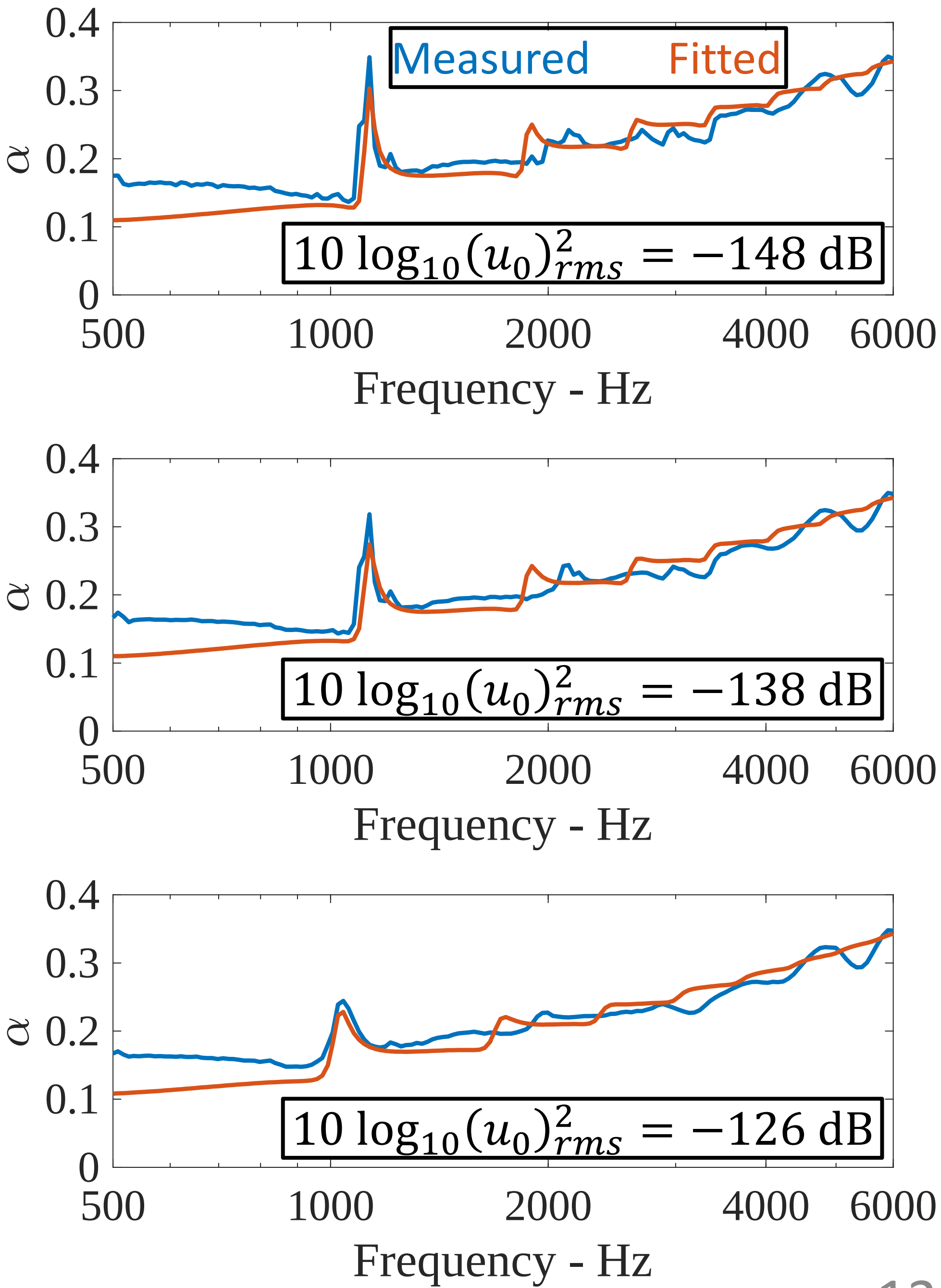
A poro-elastic model:

h [mm]	40	Assumed
ν	0.35	
ρ_b [kg/m^3]	1494	Measured
ϕ	0.402	Calculated from ρ_b
α_∞	1.743	Calculated under spherical shape assumptions. (Tsuruha *et al.* 2020)
σ [Rayls/m]	1.336×10^6	
Λ [μm]	17.89	
Λ' [μm]	19.92	

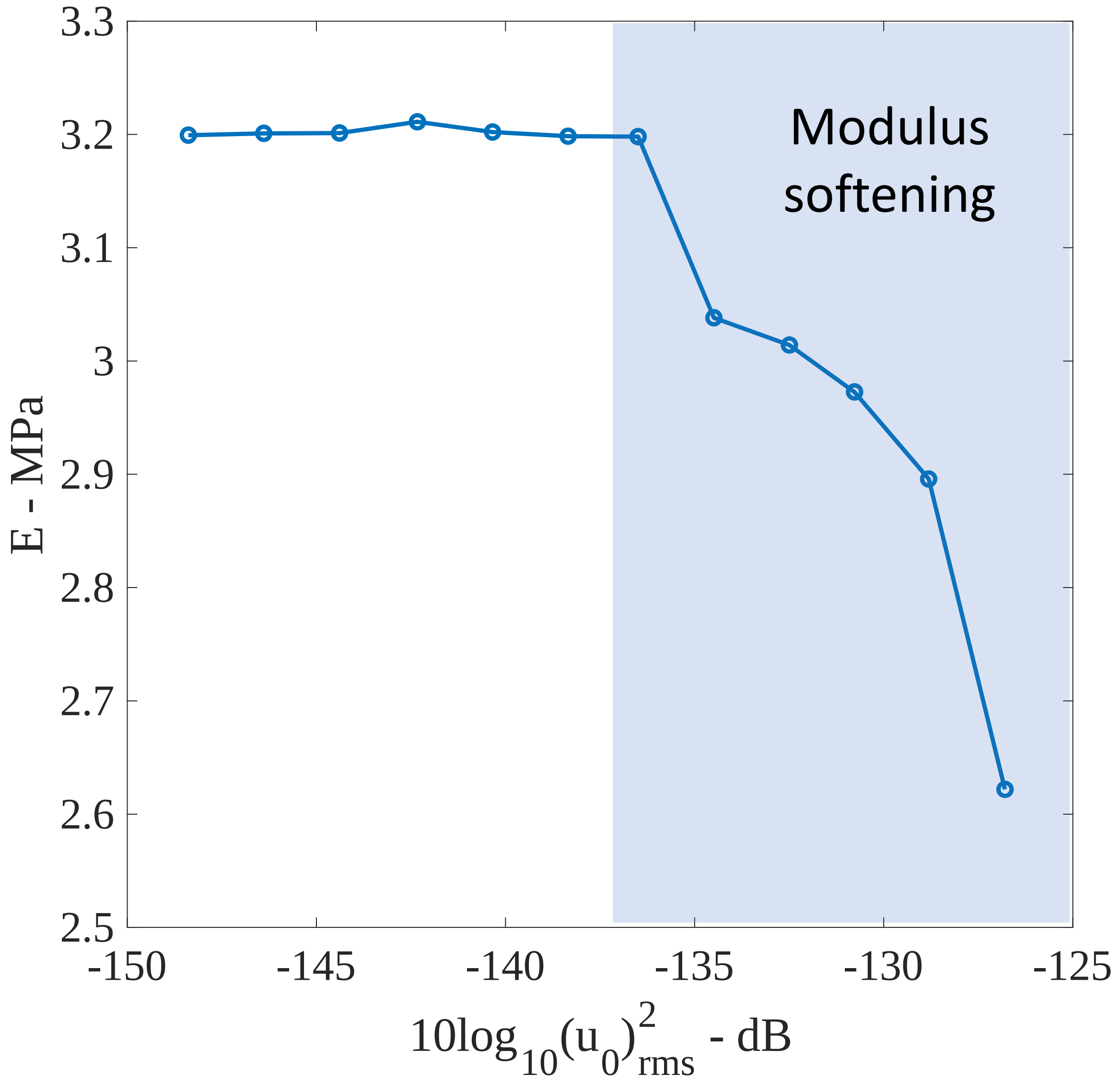
Particle swarm optimization:

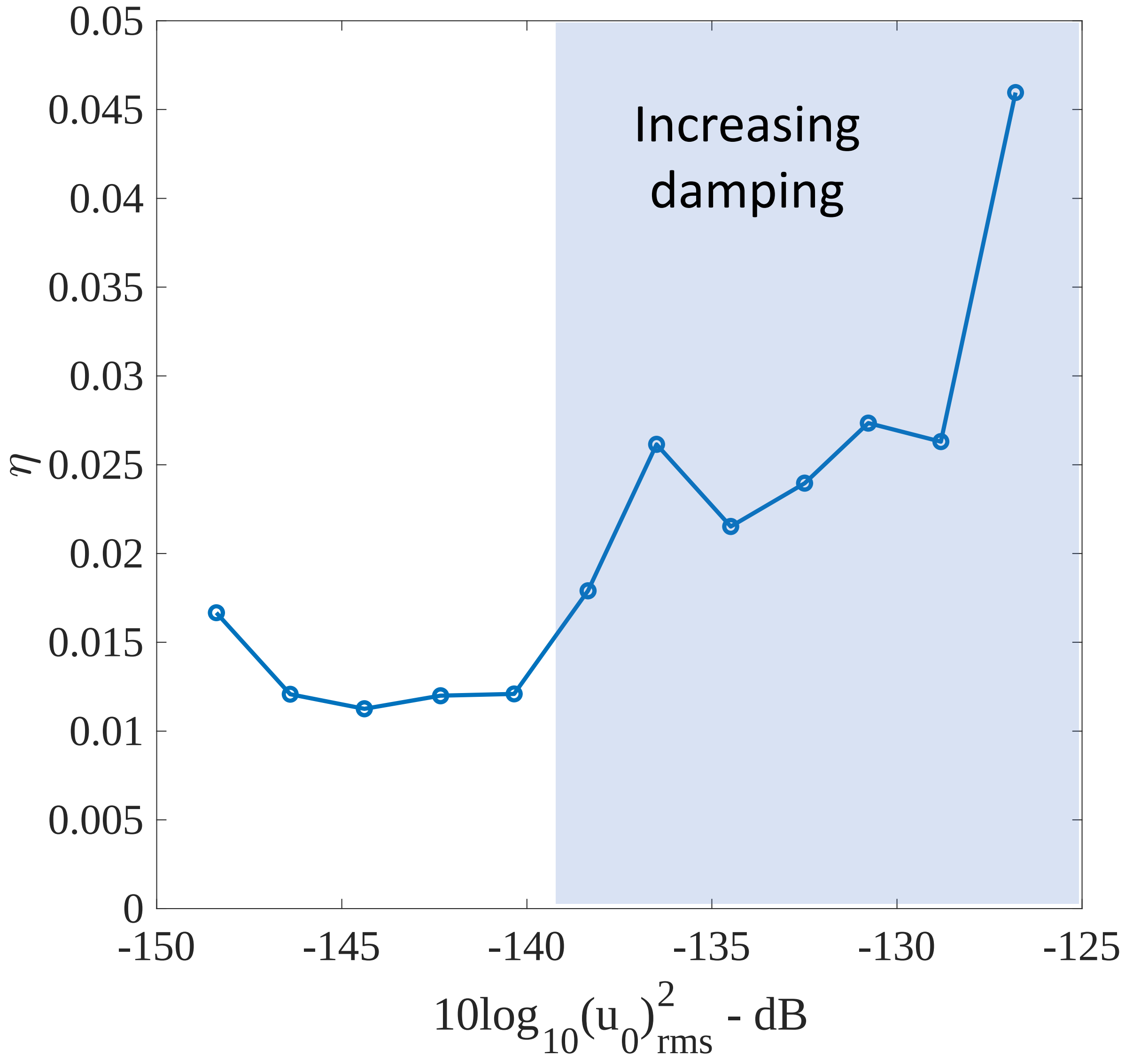
[Based on absorption coefficients, α]

	Lower bound	Higher bound
E [Pa]	10^3	10^{12}
η	0	1



Preliminary fitting results: glass beads





Conclusions

- 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., integrated fluid RMS displacement at the particle stack surface
- By introducing this fluid-strain-dependent modulus and damping, it is still possible to model the granular particle stack with just one set of parameters
- In future, introduce a multi-layer model to account for granular particle stacks' inhomogeneous properties (i.e., depth-dependent modulus)

References

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[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.

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Thanks

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