NUMERICAL EVALUATION OF THE UNSTEADY SURFACE PRESSURE ATTENUATION DUE TO FINITE SENSOR SIZE

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Motivation

- Sensor size related attenuation function is derived from the autospectrum [Corcos (1964), Hu(2022)]

$$\alpha(f) \longrightarrow \boxed{H(f)} \longrightarrow \beta(f)$$

$\alpha(f)$: wall pressure measured with a sensor of radius $r \rightarrow 0$
$\beta(f)$: wall pressure measured with a sensor of radius r

$$\beta(f) = H(f)\alpha(f)$$

- Autospectrum at x:

$$G_{\beta\beta}^{(x)}(f) = |H(f)|^2 G_{\alpha\alpha}^{(x)}(f)$$

- Wall pressure coherence is also an important property for determining noise generation

- Of 2 sensors separated by ξ:
  - Cross-spectrum:

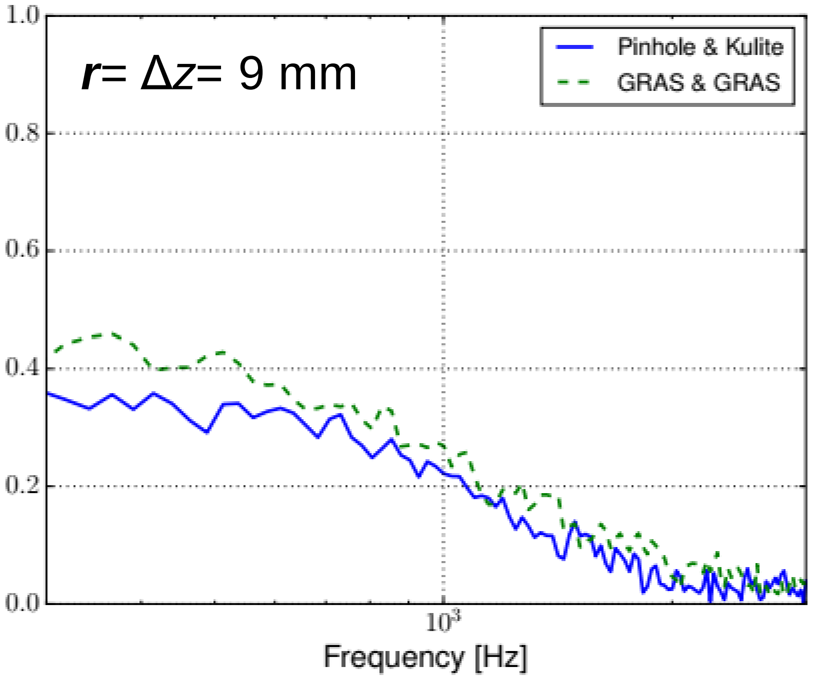
$$\left|G_{\beta\beta}^{(\xi)}(f)\right| = |H(f)|^2 \left|G_{\alpha\alpha}^{(\xi)}(f)\right|$$

  - Coherence:

$$\gamma^2(f) = \frac{\left|G_{\beta\beta}^{(\xi)}(f)\right|^2}{G_{\beta\beta}^{(x)}(f)\, G_{\beta\beta}^{(x+\xi)}(f)} = \frac{\left|G_{\alpha\alpha}^{(\xi)}(f)\right|^2}{G_{\alpha\alpha}^{(x)}(f)\, G_{\alpha\alpha}^{(x+\xi)}(f)}$$

Motivation

$$\Gamma_{pp}(\mathbf{r},\omega) = \frac{|\boldsymbol{\Phi}_{\mathbf{pp}}(\mathbf{r},\omega)|}{\sqrt{|\boldsymbol{\Phi}_{\mathbf{pp}}(\mathbf{x},\omega)\boldsymbol{\Phi}_{\mathbf{pp}}(\mathbf{x}+\mathbf{r},\omega)|}}$$



Pinhole, d= 0.5 mm
Kulite (B screen), d= 1.7 mm
GRAS, d= 1/4''= 6.35 mm

"… larger coherence can be measured when the sensor size is too large."

Hu, Nan. (2024) Effect of Sensor Size on The Wall Pressure Coherence Measurement Beneath Turbulent Boundary Layers, DAGA, Hannover, Germany.

→ Evaluate the wall pressure attenuation using scale resolving simulation and cross-compare with experiment

→ Examine coherence correction by separately examining auto-spectral and cross-spectral corrections

Experimental Setup

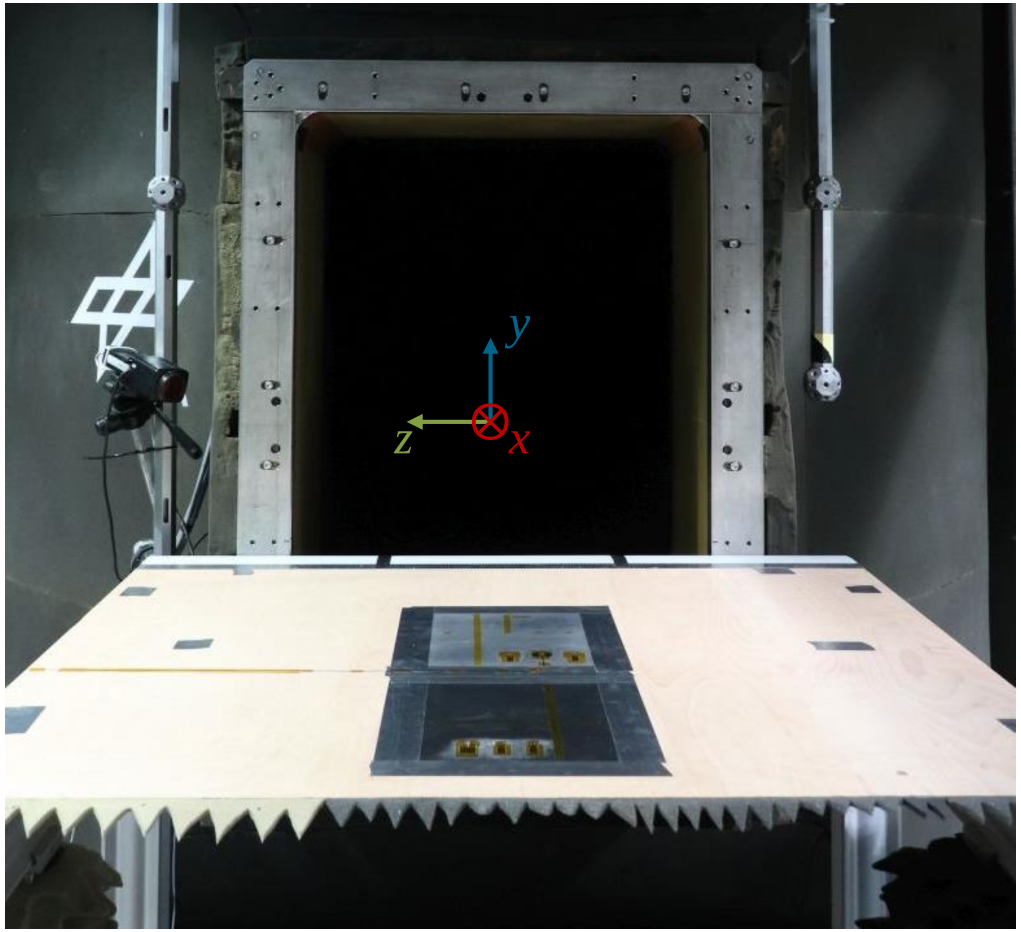
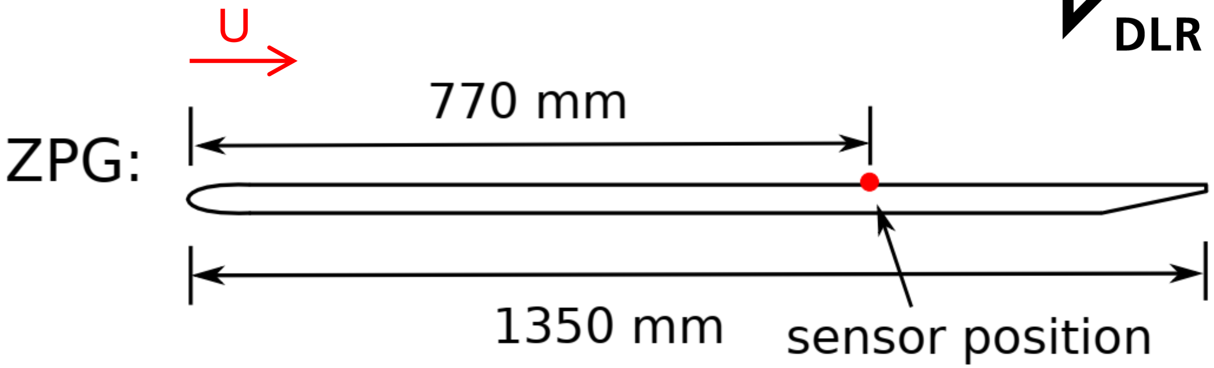


Photo: Nan Hu



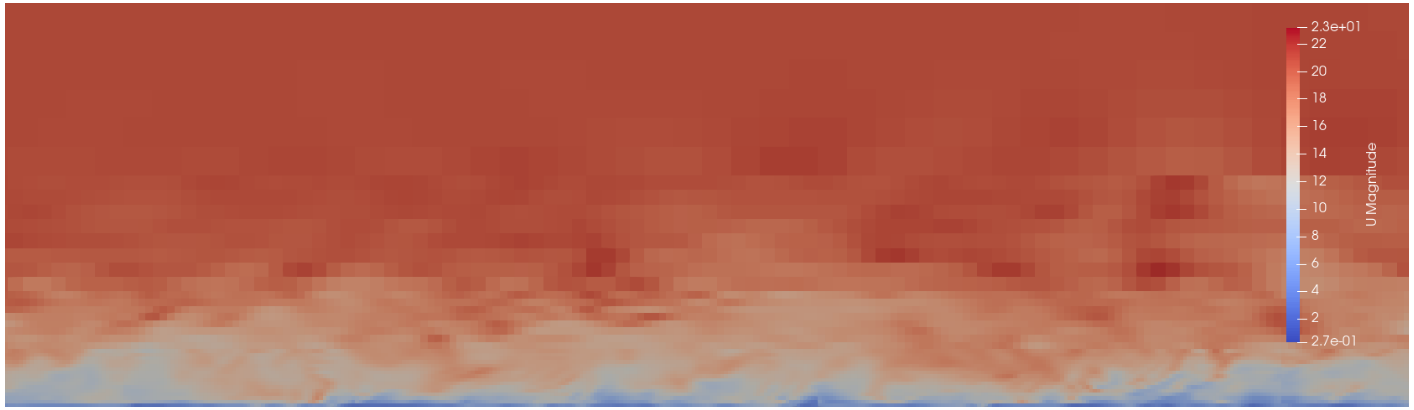
Sensor	U=20 m/s	U=30 m/s	U=40 m/s
Ue, m/s	19.8	29.6	39.5
δ, mm	13.90	13.20	12.50
δ*, mm	2.40	2.18	2.03
Θ, mm	1.69	1.56	1.47
U_τ	0.830	1.210	1.570
Re_τ	769.6	1062.9	1297.6
d (d+), mm *	0.7 (38.8)	0.5 (40.3)	0.5 (51.9)

* Sensor is under a pinhole of diameter d

Numerical Setup, MGLET Solver

	U=20 m/s	U=30 m/s	U=40 m/s
LES Model	WALE		
Wall model	Werner-Wengle		
Tripping	Roughness, Δ=0.3 mm, X=[-0.0384m, 0]		
Domain	X=[-0.2m, 1.0288m], Y=±0.0384m, Z=0.0768m	X=[-0.2288m, 1.m], Y=±0.0256m, Z=0.0512m	X=[-0.2288m, 1.m], Y=±0.0256m, Z=0.0512m
Grid cells	76 424 320	221 165 056	221 165 056
Wall cells (viscous unit, δx^+)	0.15 mm (8.31)	0.1 mm (8.05)	0.1 mm (10.38)
Sim. time (Sampling time)	0.55s (0.4 s)	0.2 s (0.14 s)	0.2s (0.14 s)
Computational time (CPUh)	19159.3	66495.3*	75313.7*

* parallelization unoptimized



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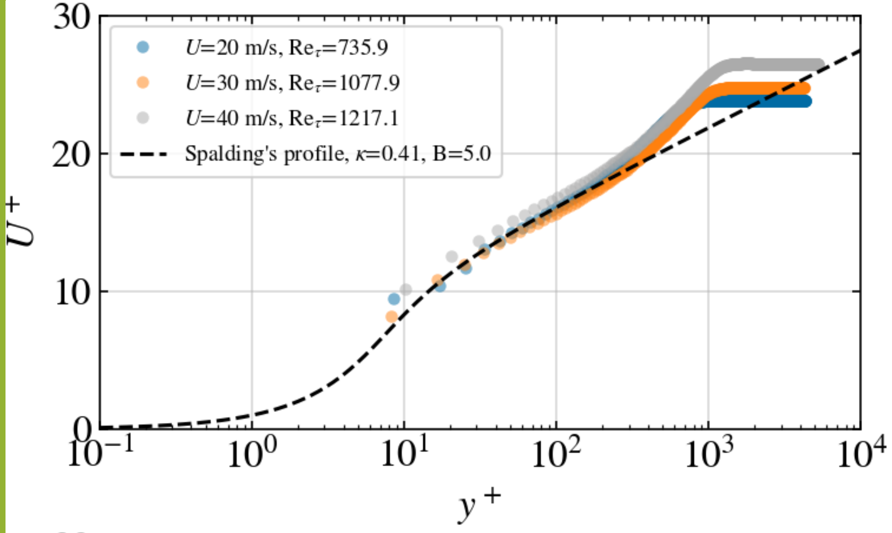
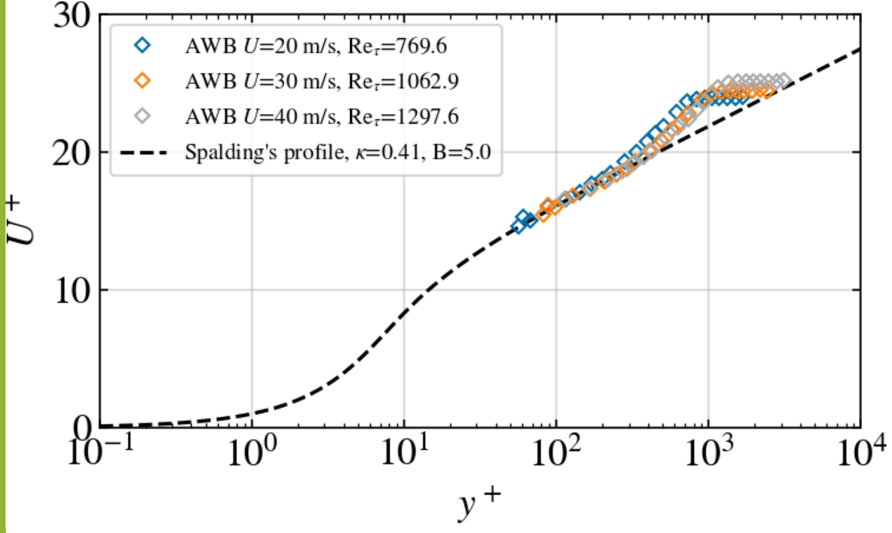
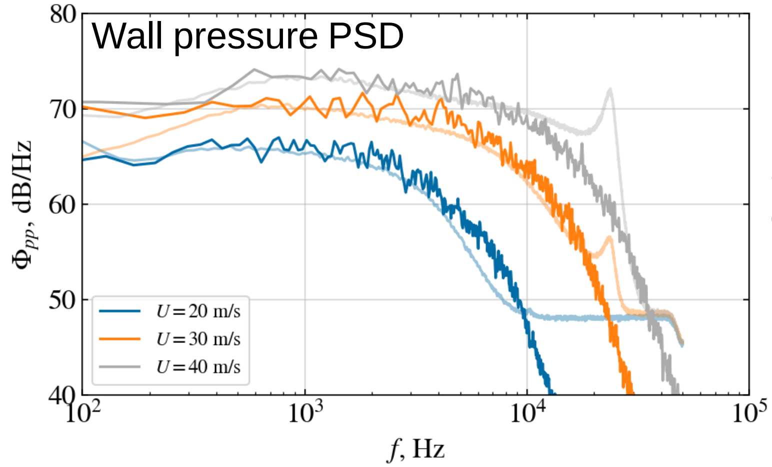
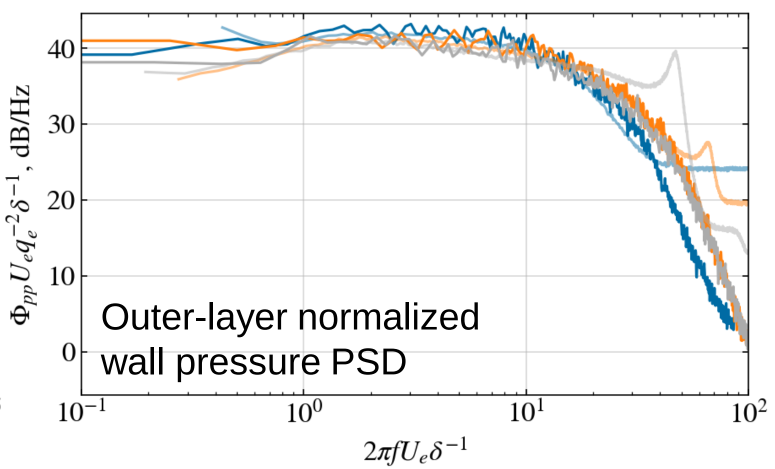
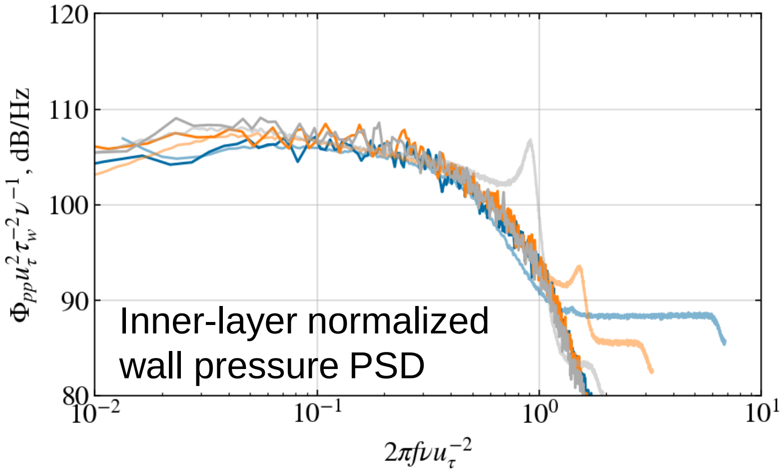
ZPG Boundary Layer











- $\delta x^+ \approx d^+/5$
  - d^+ (20 m/s) = 38.8
  - δx^+ (20 m/s) = 8.3, ($5\delta x^+$ = 41.5)
- Perfectly flush-mounted sensor avoids the Helmholtz resonance and installation artifacts

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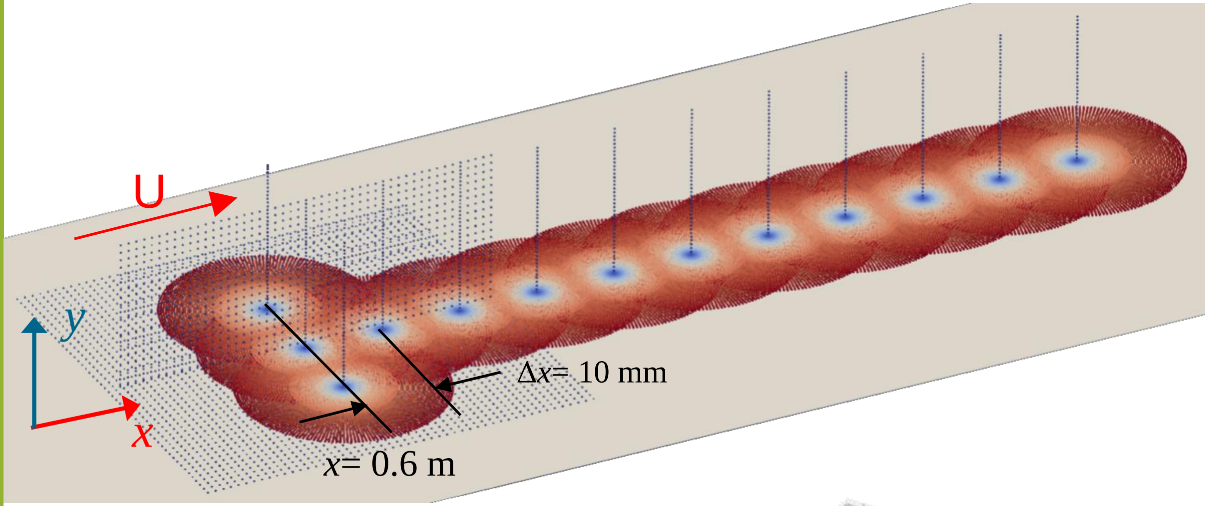
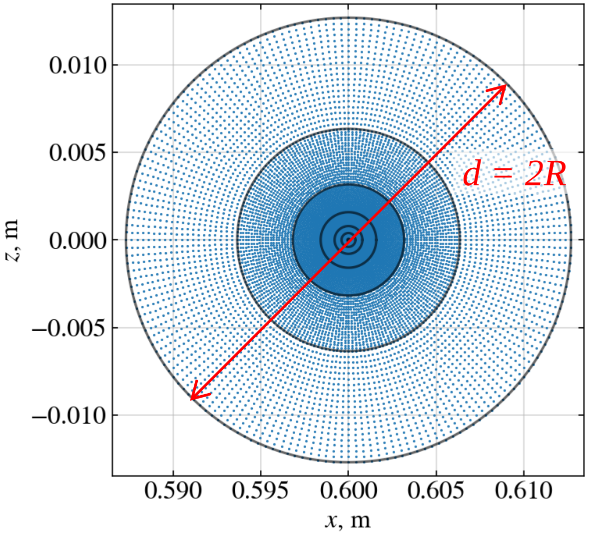
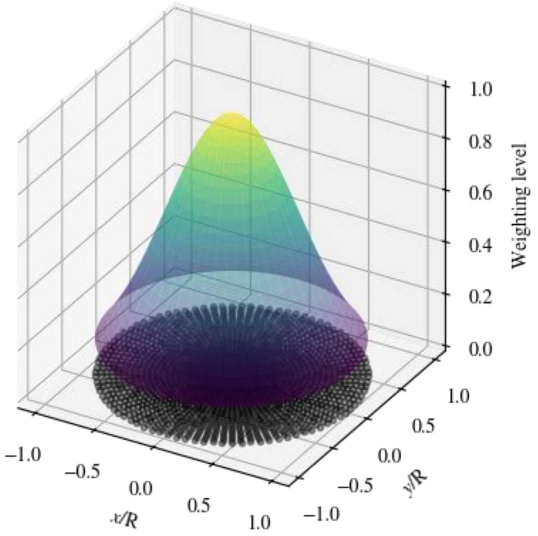
Simulated Microphones







- Point sensors along the wall-normal direction and center plane inside the boundary layer
- Distributed point sensors on the wall, inside an expanding circle up to *d*=1"
- 10 mm separations between *circles*
- $\overline{p_w}(R) = \frac{1}{N}\sum_{i,j=1}^{i=N,j=M} G(r_i; \sigma = R/2) p_w(r_i, \theta_j)$

  where $r_i \leq 2\sigma$, G = Gaussian kernel

  The Gaussian function merely simulates a finite sensor response, and not to represent any brand of wall pressure sensors

- Multiple diameter-varying-mics. at 1 position measuring the same instance of turbulence

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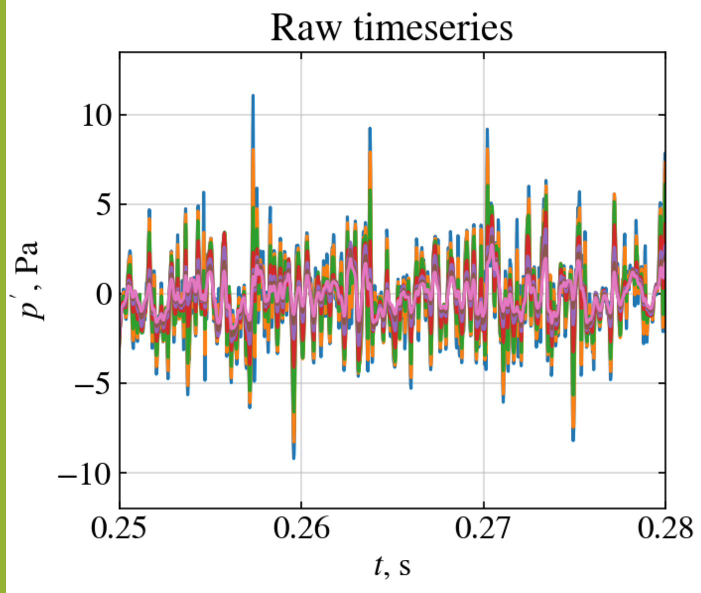
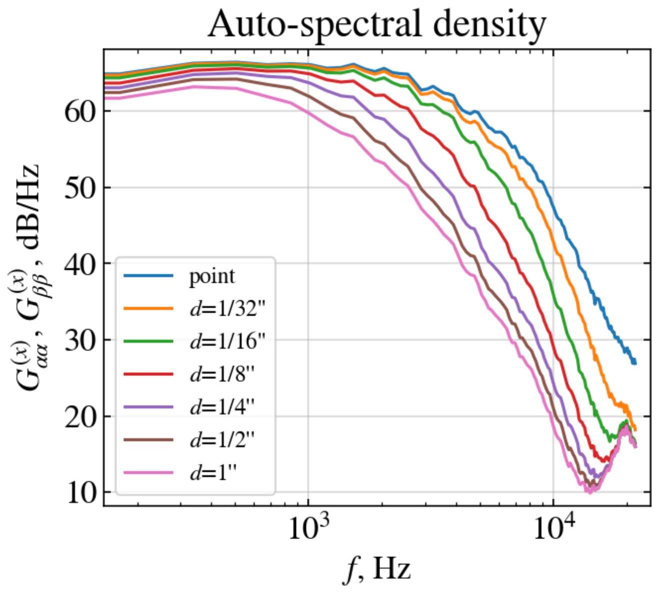
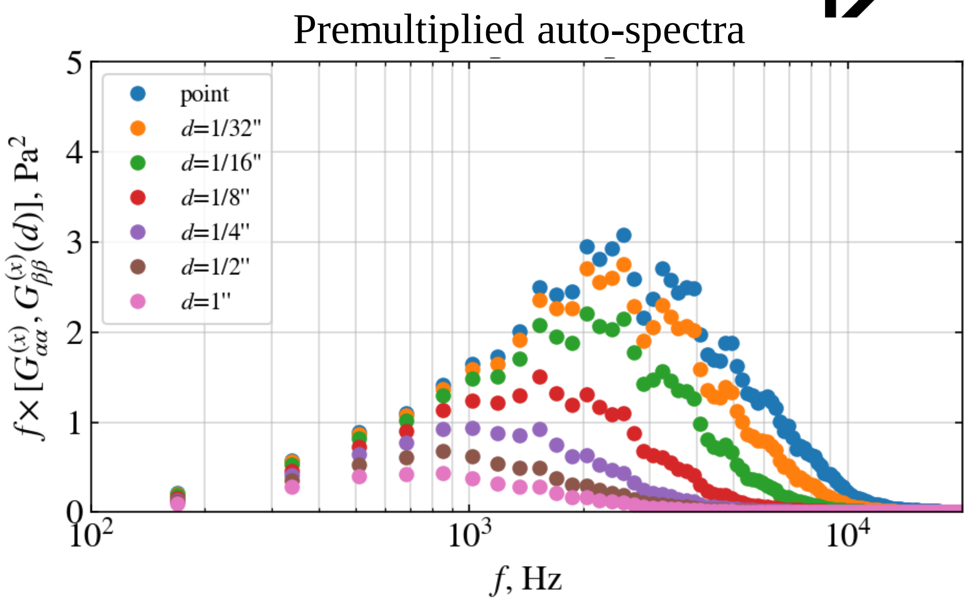
Data Survey at x= 0.6 mm







Sensor size attenuates the higher, most *energetic,* frequencies first. Then to the lower frequencies as the size increases.

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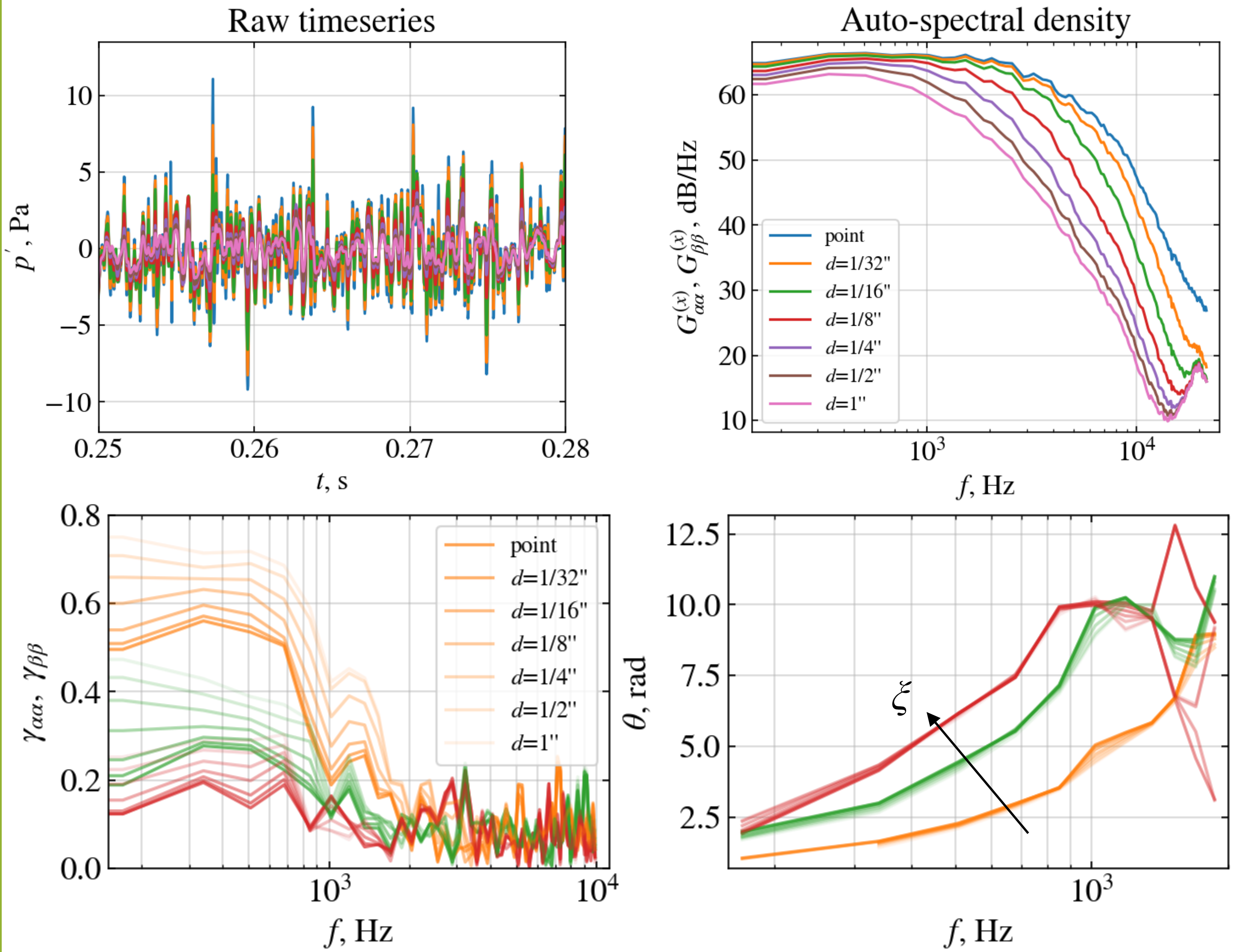
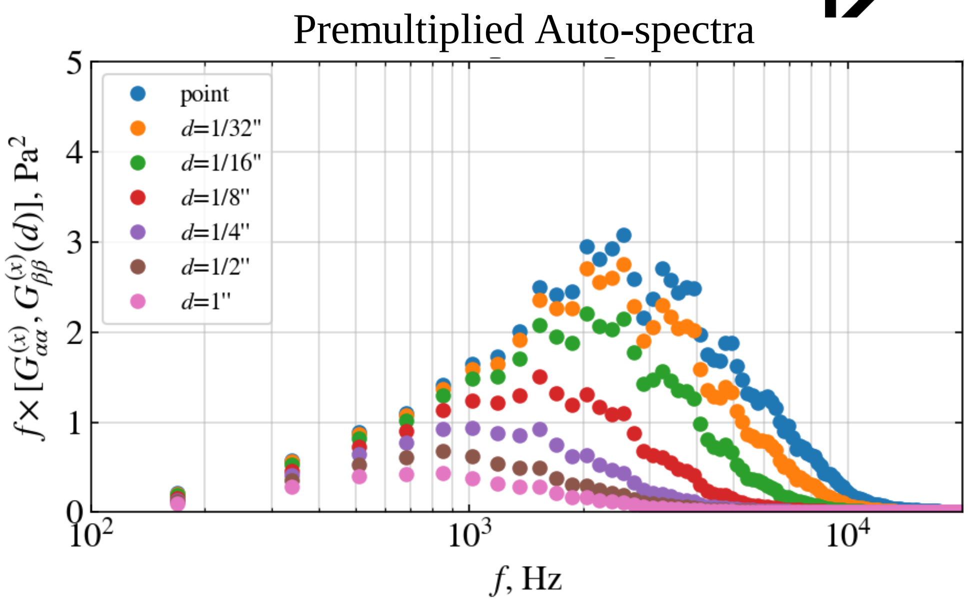


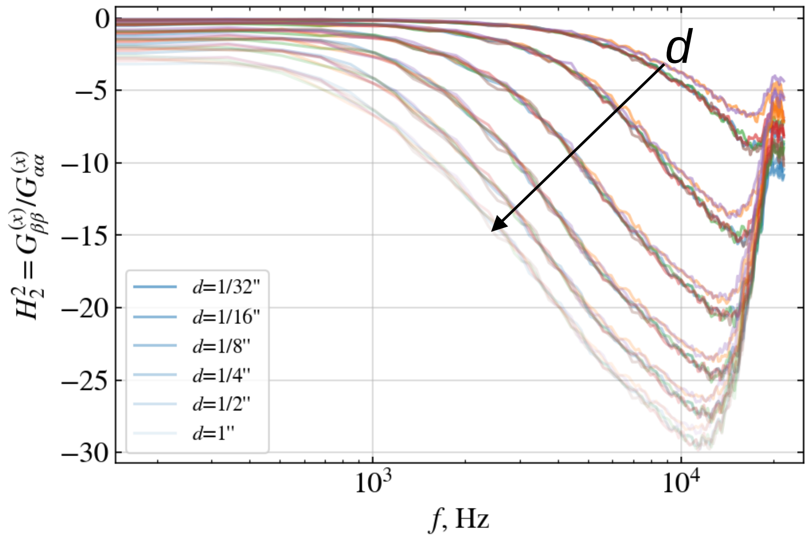


Sensor size attenuates the higher, most *energetic,* frequencies first. Then to the lower frequencies as the size increases.

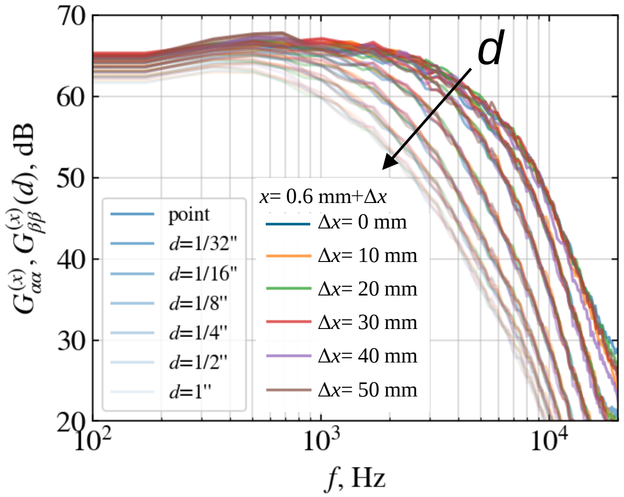
Low freq. coherence increases with larger sensor size.

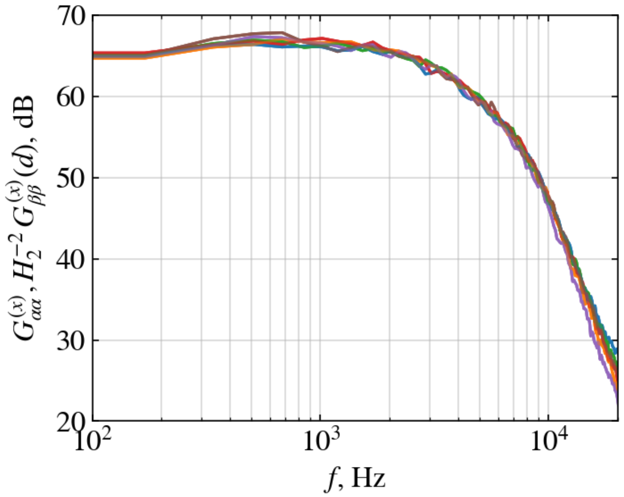
H_2 Correction

$(H_2)^2 = G_{\beta\beta}^{(x)}/G_{\alpha\alpha}^{(x)}$



Auto-PSD scales with H_2^{-2}





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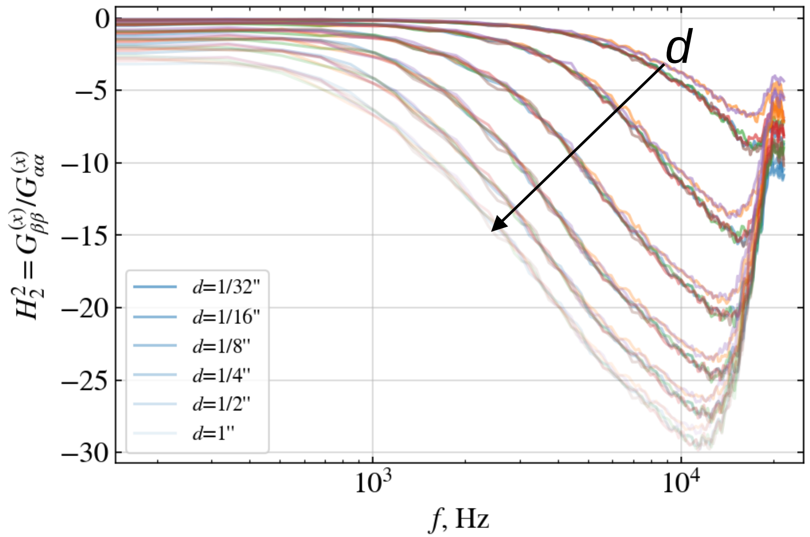

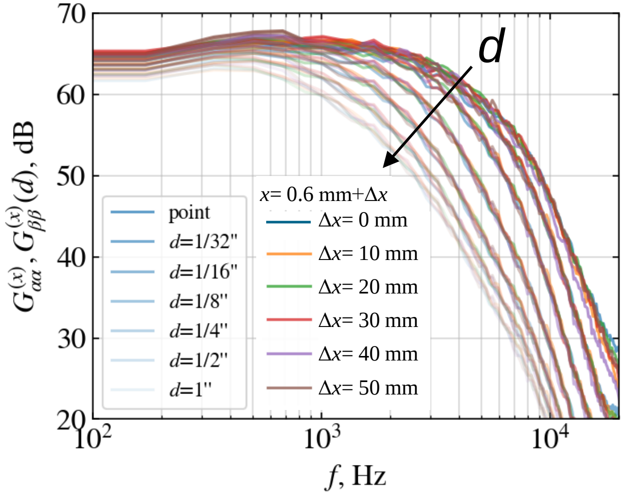

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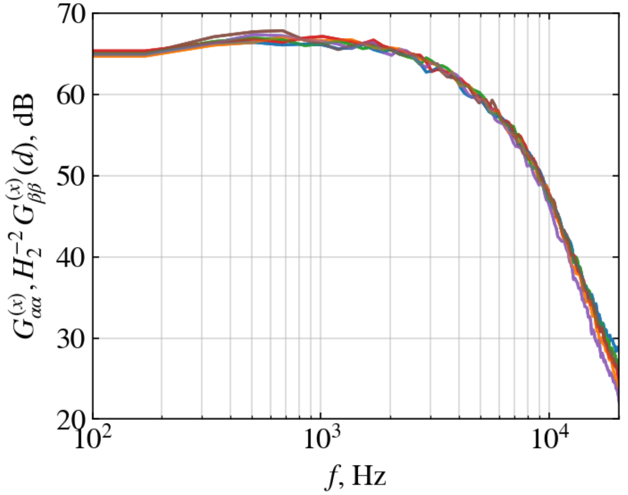
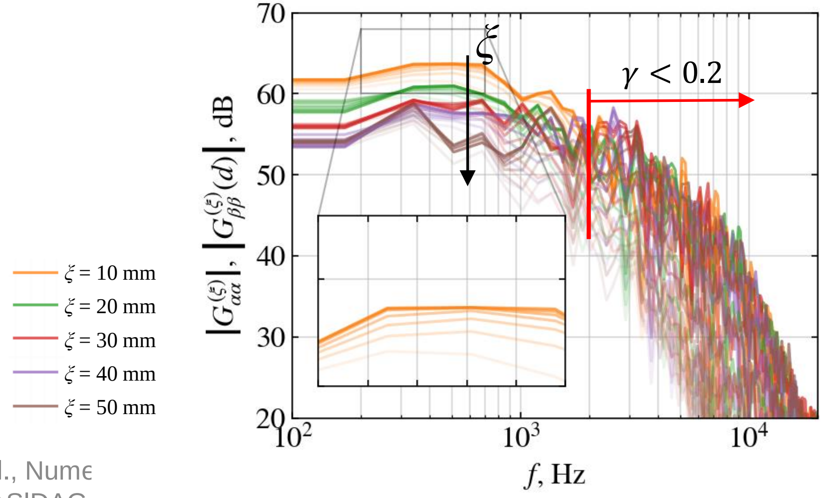
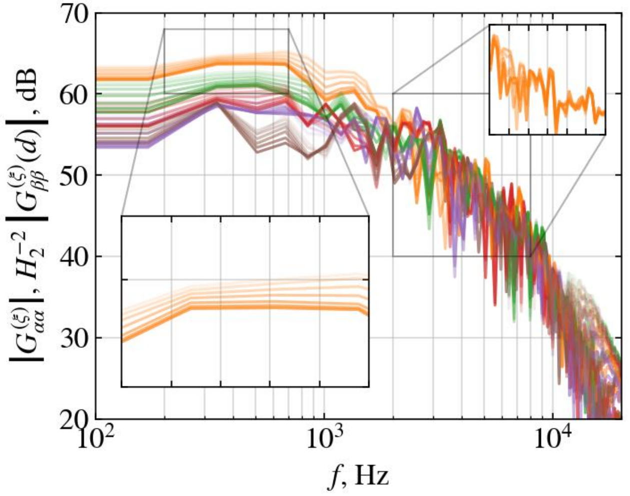
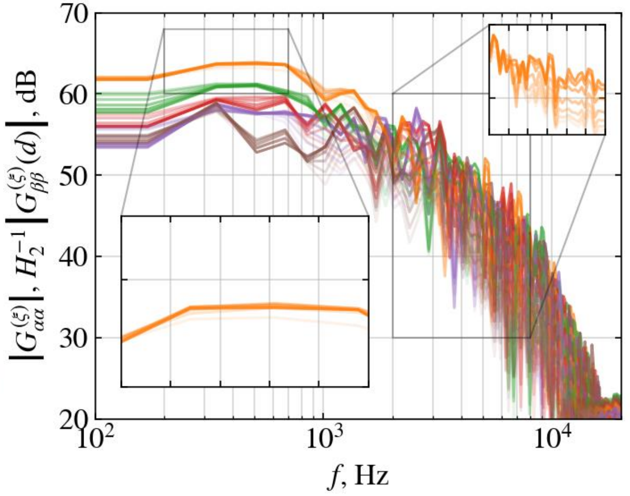




High freq. cross-PSD scales with H_2^{-2}



Low freq. cross-PSD scales with H_2^{-1}



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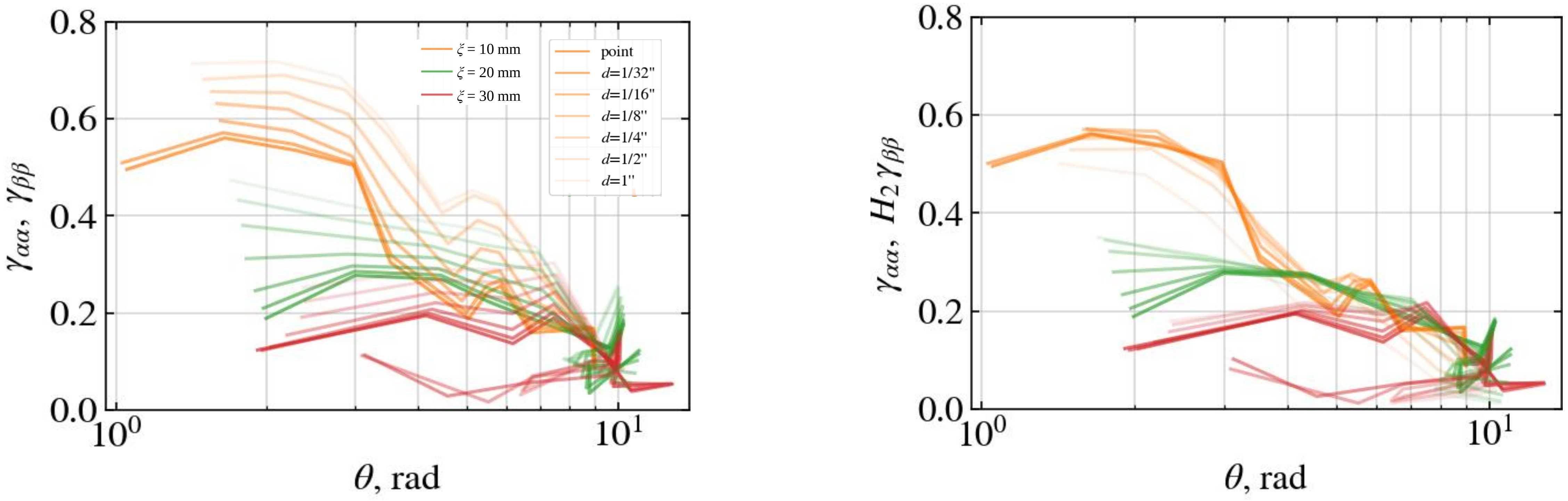
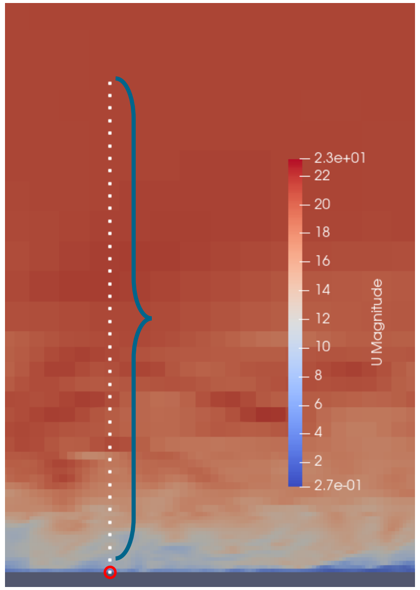
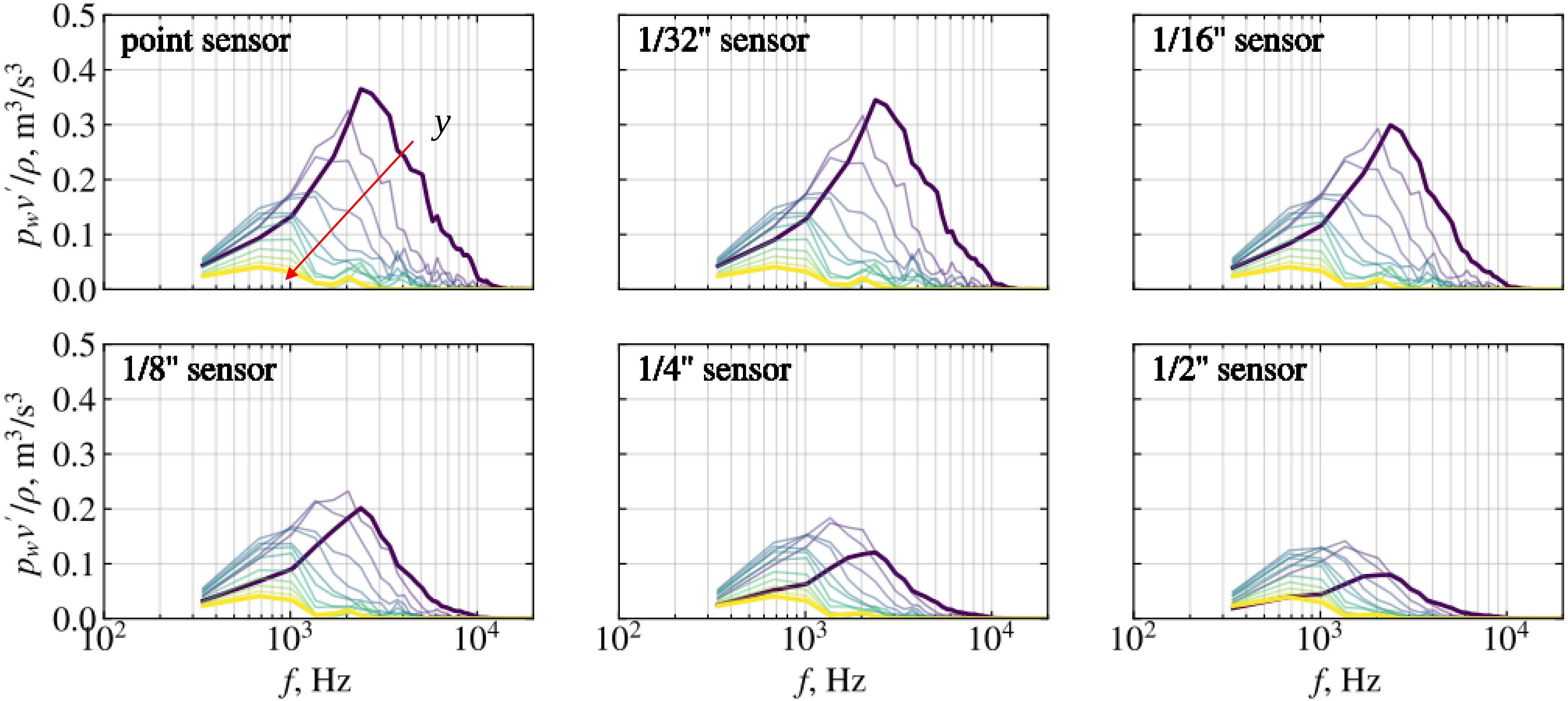
Coherence Correction



Coherence correction at low frequency scales with H as a result of the cross-PSD scaling with H^{-1} and auto-PSD with H^{-2}

$p_w(x = 0.6) - v'(y; x = 0.6)$ Correlations





- Sensor with large diameter attenuates fluctuations nearest to the wall (high freq.) first
- Low freq. contributions remain largely intact

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Summary and Conclusions

- With refined grid we achieve a good comparison between WMLES and measurements.
- With different sensor diameters, coherence scales with H at low freq., whereas high freq. content evaluated here is incoherent.
- p_w and v' correlation shows:
  - Low freq. are less attenuated than high freq with larger diameter sensors.
  - With large diameter sensor the low freq. can be more energetic than the near-wall high freq. part.

Outlook

- Derive the sensor-size-related attenuation function for *real* microphones
- Application of the numerical attenuation correction to the experimental data

Special mention to Dr. Nan Hu for sharing his experimental data

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Thank you for your attention

Impressum

Thema: **Numerical evaluation of the unsteady surface pressure attenuation due to finite sensor size**

Datum: 2025-03-19 (JJJJ-MM-TT)

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Institut: AS-WEA

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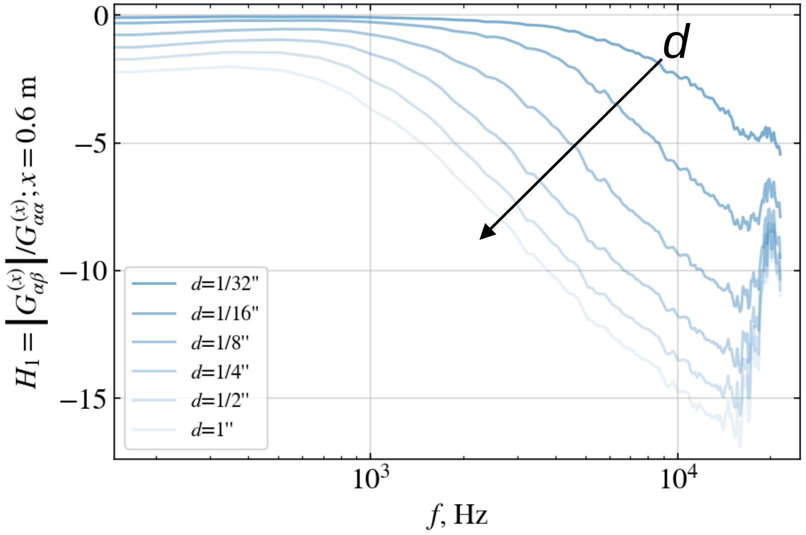
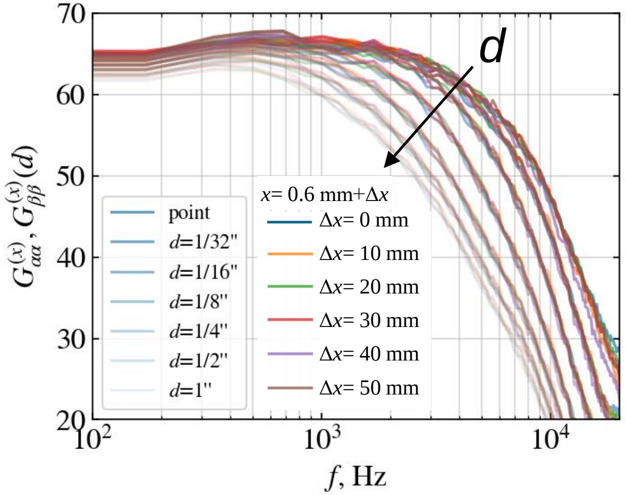
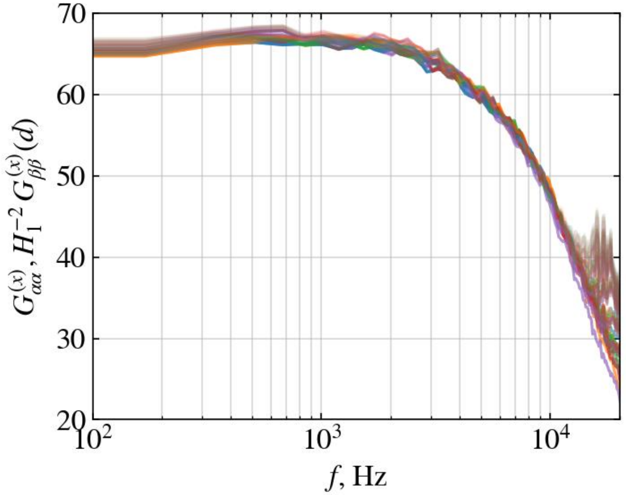
H_1 Correction

$H_1 = |G_{\alpha\beta}^{(x)}| / G_{\alpha\alpha}^{(x)}$



Auto-PSD scales with H_1^{-2}





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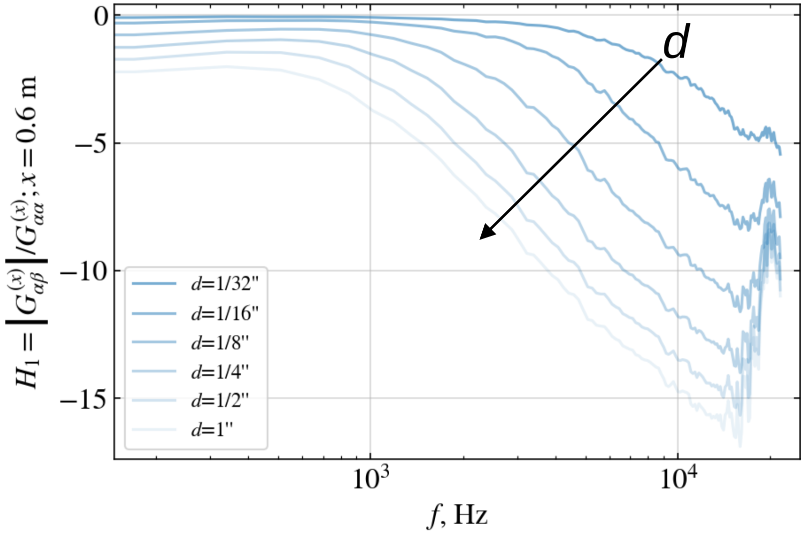

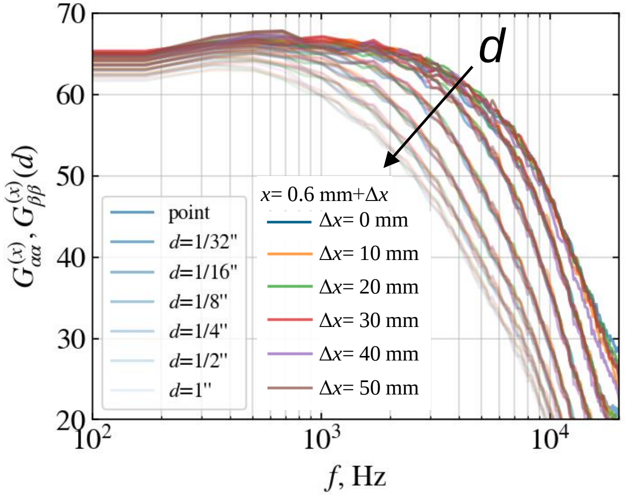

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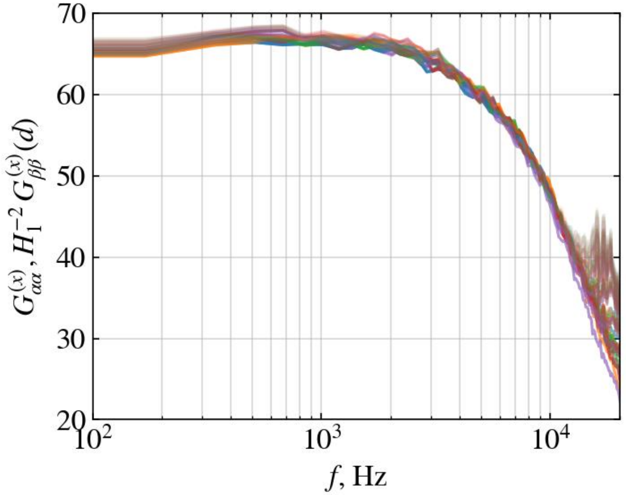
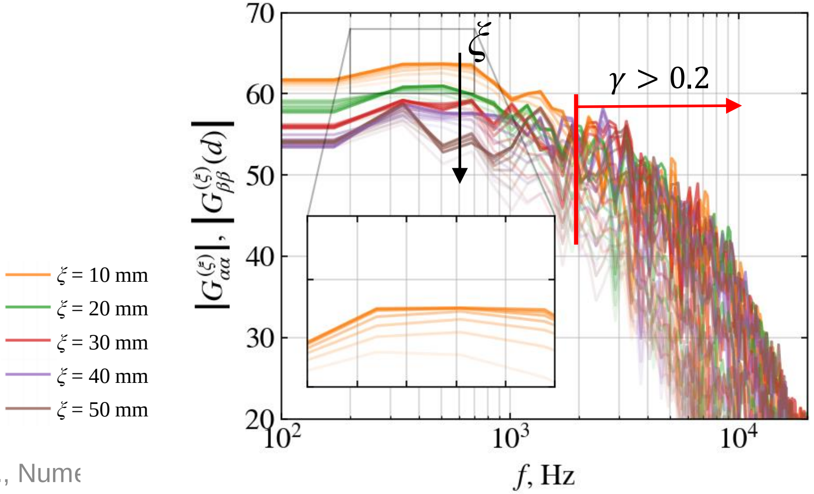
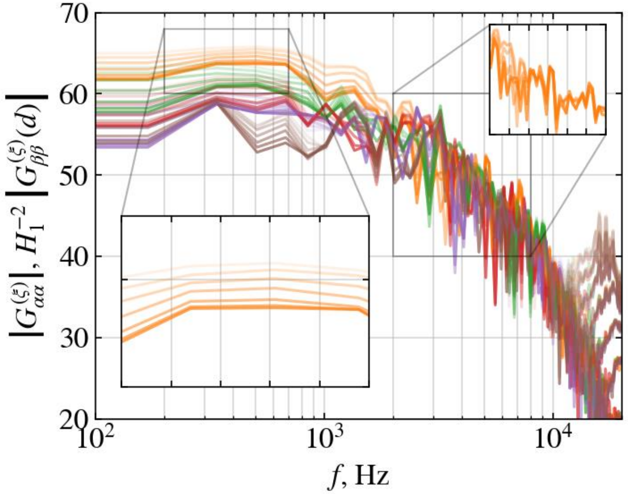
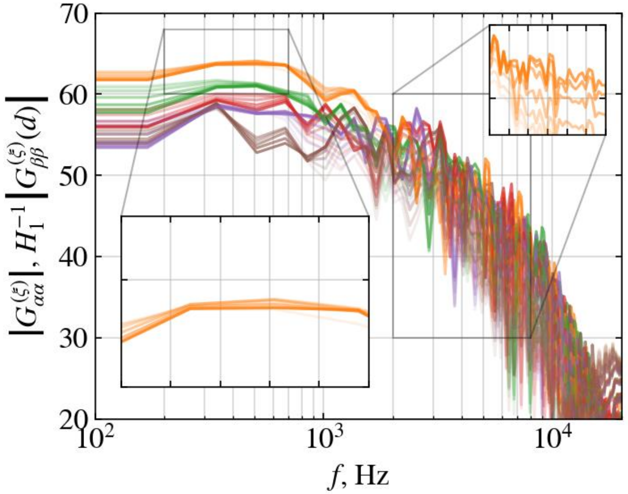


High freq. cross-PSD scales with H_1^{-2}

Low freq. cross-PSD scales with H_1^{-1}







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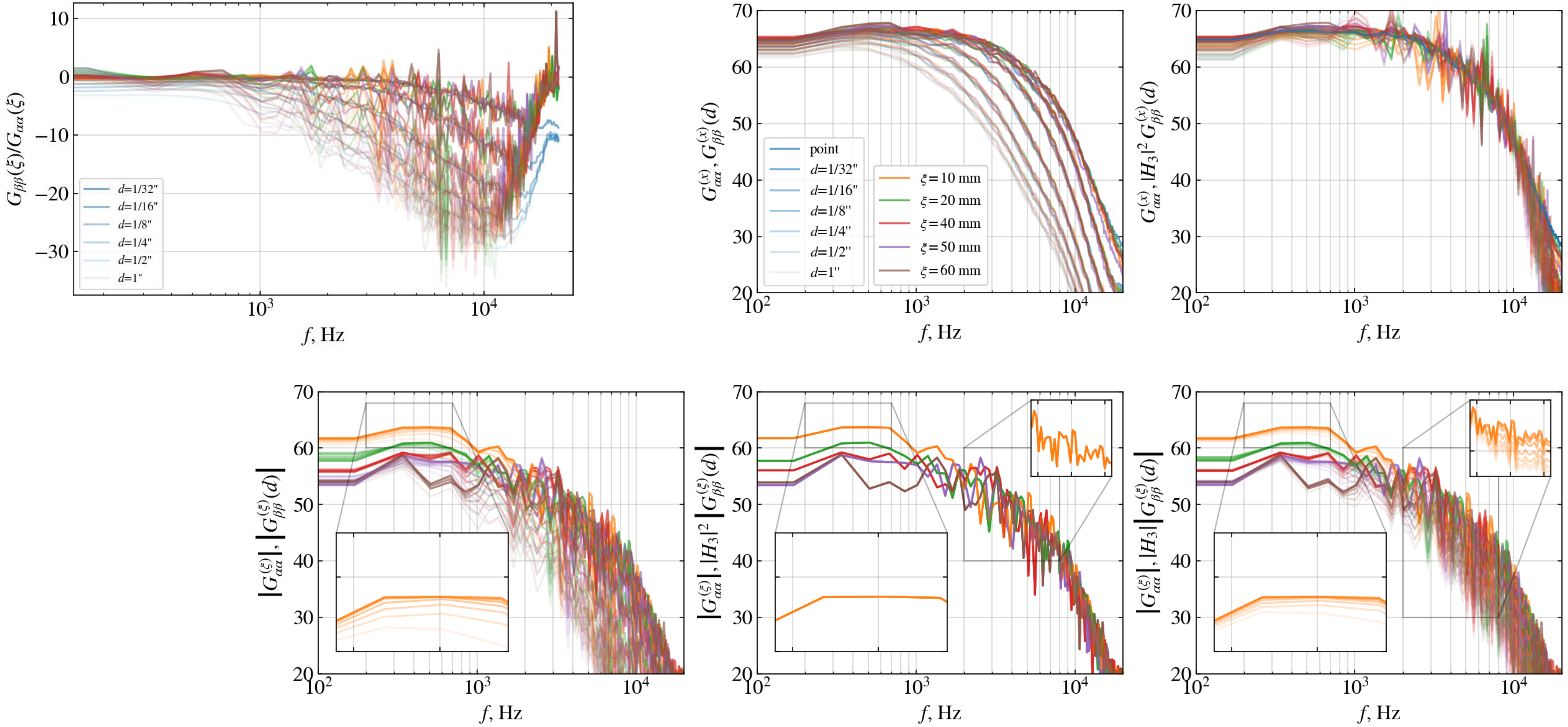
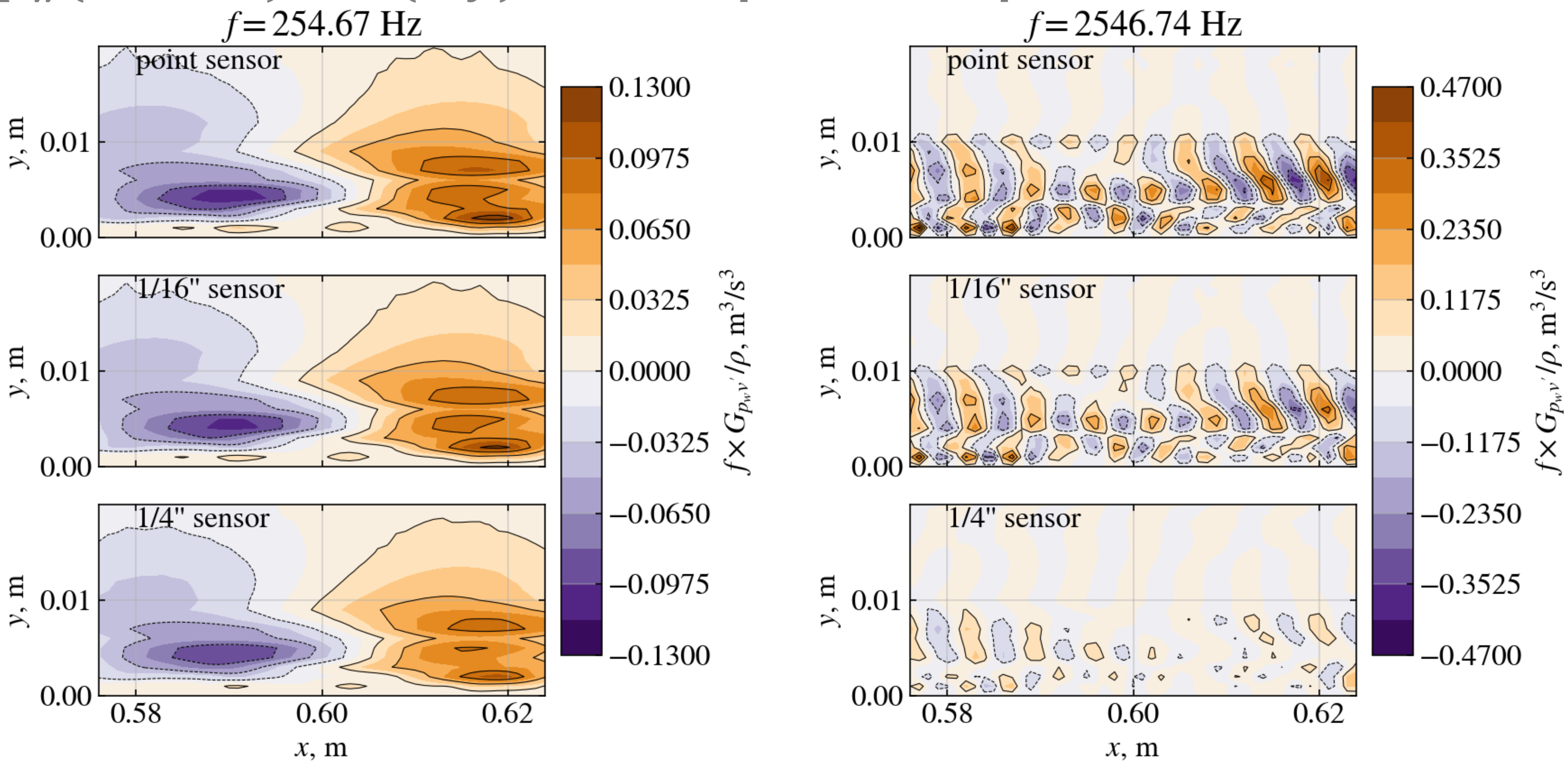
H_3 correction

$(H_3)^2 = |G_{\beta\beta}^{(\xi)}| / |G_{\alpha\alpha}^{(\xi)}|$



$p_w(x = 0.6) - v'(x, y)$ Cross-Spectral Map



Negligible to small attenuation in the low freq. range

Large attenuation in the high freq. range with ¼” sensor