Measuring by Light...
...Down-Under!

Dr Ben Halkon BEng PhD FIMechE CEng FIEAust CPEng MAAS

Associate Professor and Vibration Lab/Structural Testing Facility Lead

Centre for Audio, Acoustics and Vibration,
University of Technology Sydney

Measuring by Light 2025, Invited Keynote, TU Delft, 2nd April 2025

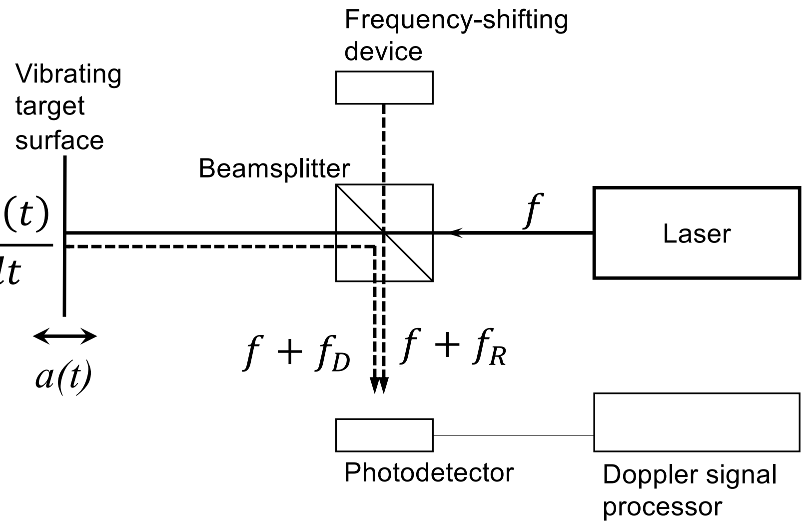
Contents

- Some very brief fundamentals of LDV
- Measurements from vibrating platforms:
  - Time and frequency domain approaches
  - 6DoF vibration compensation for scanning LDV
  - Vibrating beam steering optics
- Applications in control:
  - Refracto-Vibrometry based active noise control
  - Active vibration control for 3D printing (from vibrating platforms)
  - Acoustic levitation applications including particle manipulation
  - Insect biomechanics research using LDV
- Q(&A)

Some brief fundamentals of laser Doppler vibrometry

How does a laser vibrometer measure target surface vibration?

$$f_D = \frac{2}{\lambda}\frac{da(t)}{dt}$$



In an interferometer arrangement:

Split laser into target and reference beams

Back-scattered light collected on photodetector

What turns it into a **vibrometer**:

Introduce a known reference frequency shift

$$\boxed{2\sqrt{I_R I_T}\cos\left[2\pi f_R t - 2ka(t) + (\phi_R - \phi_T)\right]} \quad \left| f_R - \frac{2}{\lambda}\frac{d}{dt}a(t) \right|$$

Some further important points:

<u>Any</u> path length changes lead to Doppler signal, c.f. "Refracto-Vibrometry"

Will work in other fluids, e.g. underwater (noting different μ…subject to absorption)

Other interferometric optical arrangements (e.g. D-LDV)

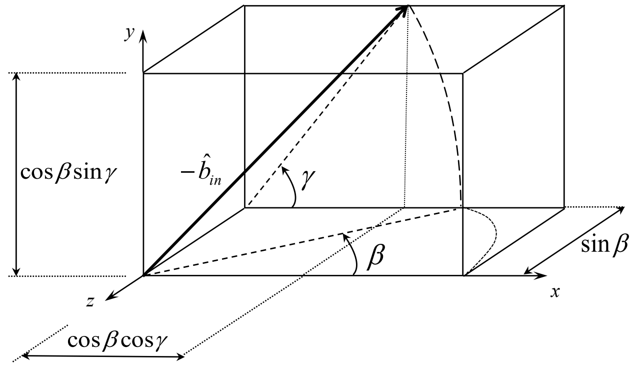
Other Doppler signal demodulation techniques (e.g. signal diversity)

Ok, but what do we *really* measure with LDV?!

Fundamentally, $f_D = {}^{2U_m}/_{\lambda}$

where U is the (arbitrary target) velocity in the direction of the beam:

$$U_m = -\hat{b}_n . \overrightarrow{V_{P'}}$$



But…

…if the target *vibration is complex* (e.g. 6DoF vibration), is *U* still what we expect it to be?

And…

…what happens if the *beam orientation changes* with time, e.g. scanning LDV?

…or, if the instrument itself or a device used to steer the beam vibrates, does *this* motion/vibration also appear as *U*?

Yes, of course – it all does!

Base vibration correction…

…using time and frequency domain approaches

Base vibration correction challenges

Instrument vibration measurement sensor locations/orientation

Geometrical model shows us where to put them!

Sensors must deliver flat amplitude and phase freq. response

Choose a rigid location on the sensor head!

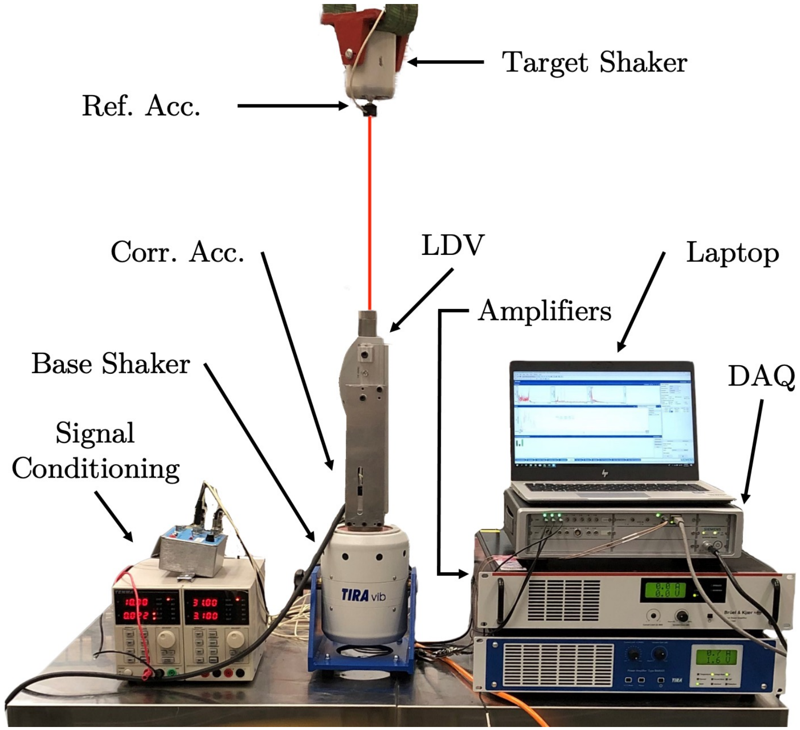
Accels. “easiest” but must be integrated and time-aligned

Early attempts used frequency domain processing

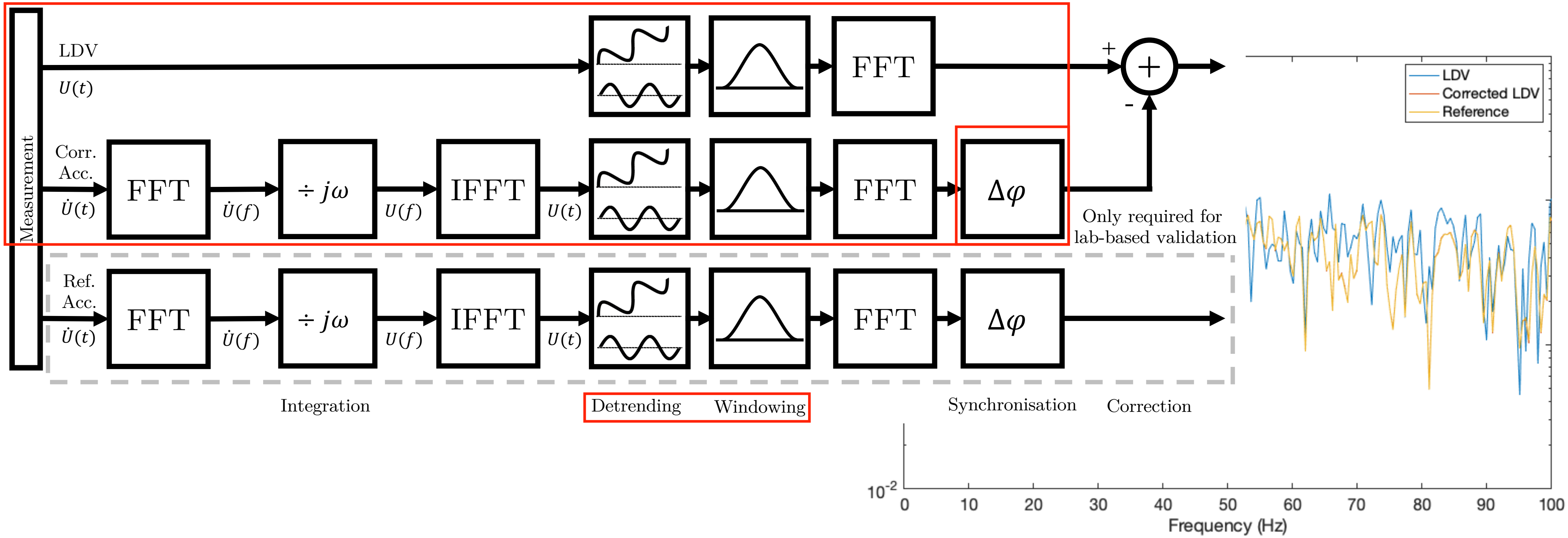
Easier to implement, including “jω” integration

Contemporary approaches use time domain processing

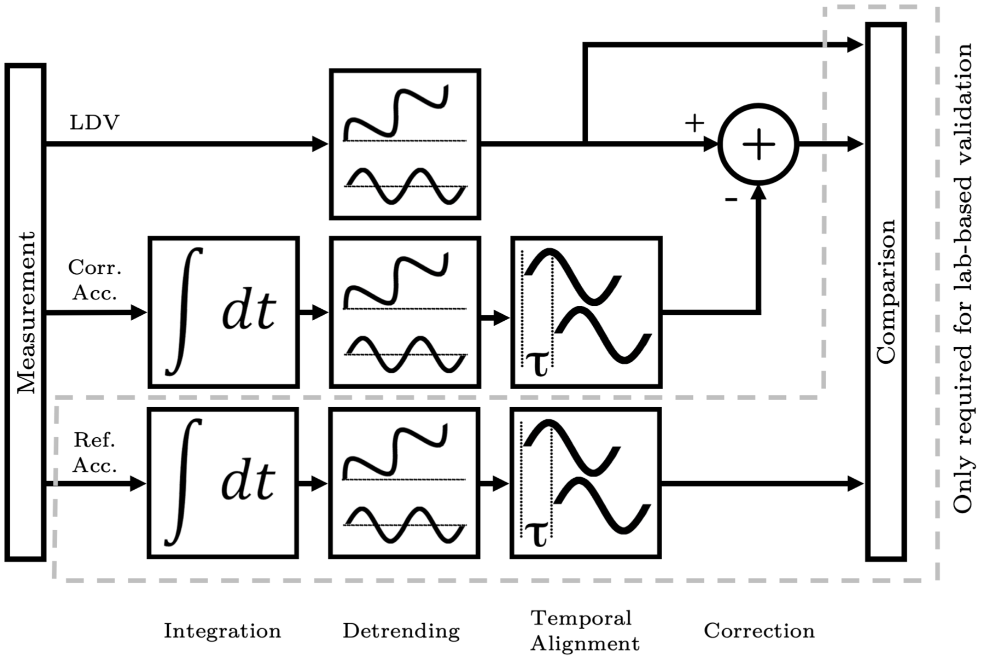
Application to transient signals

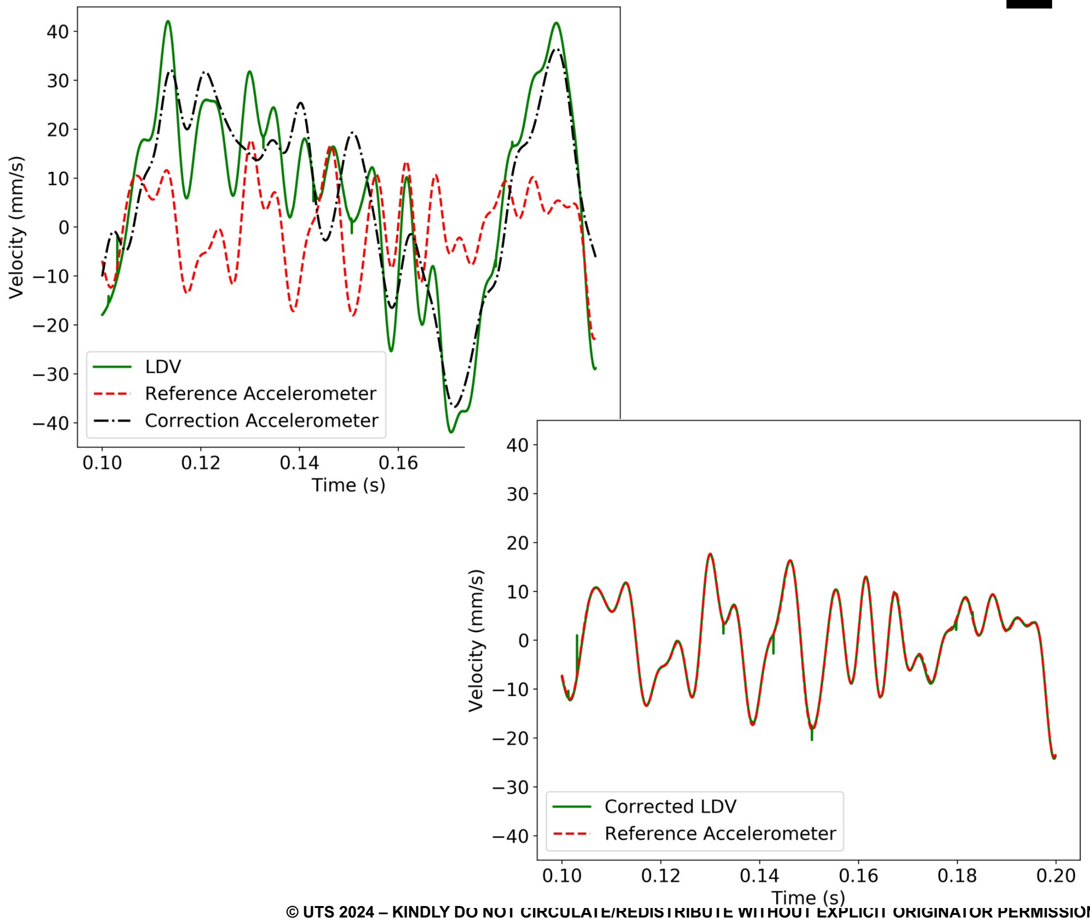


Base vibration correction procedure…
…frequency domain based approach



Base vibration correction procedure…
…time domain based approach





Scanning LDV measurements from vibrating platforms

Scanning LDV base motion correction

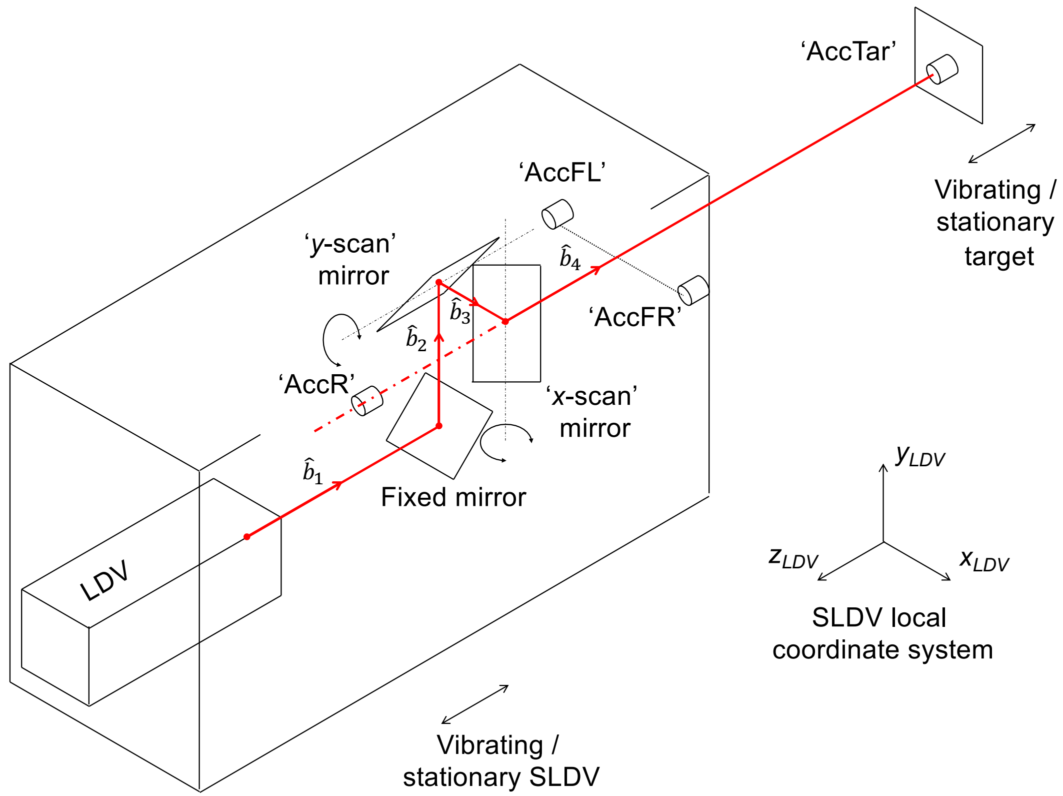
Remember, LDV measures velocity in direction of laser beam:

$$U_m = -\hat{b}_n(t).\overrightarrow{V_{P'}}(t)$$

We can correct for the non-scanning case:

Use AccR; same as for single beam

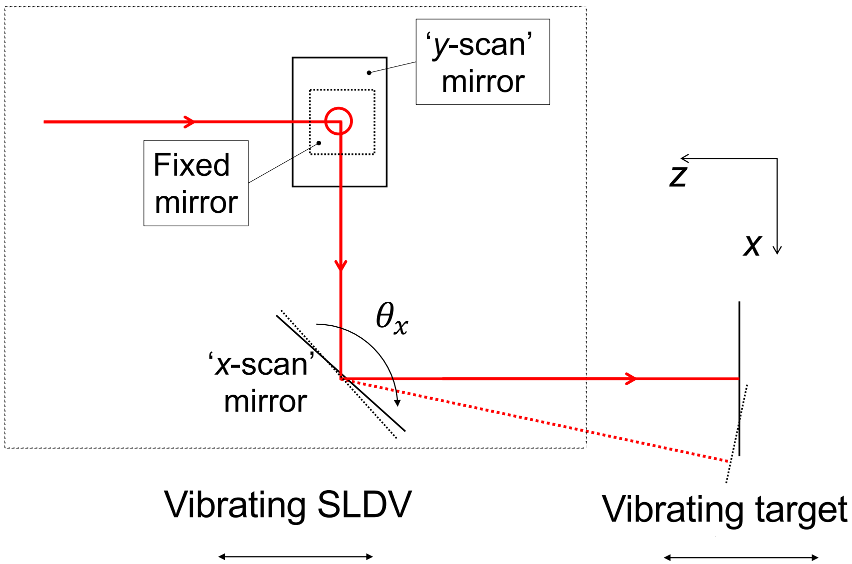
But what about when the laser beam moves?

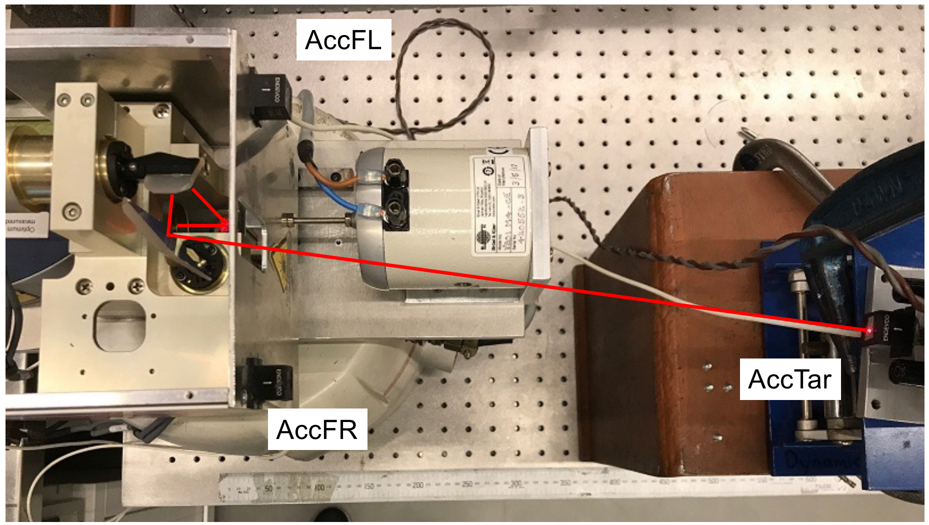


Correction during scanning

How does changing the beam angle affect the correction performance?

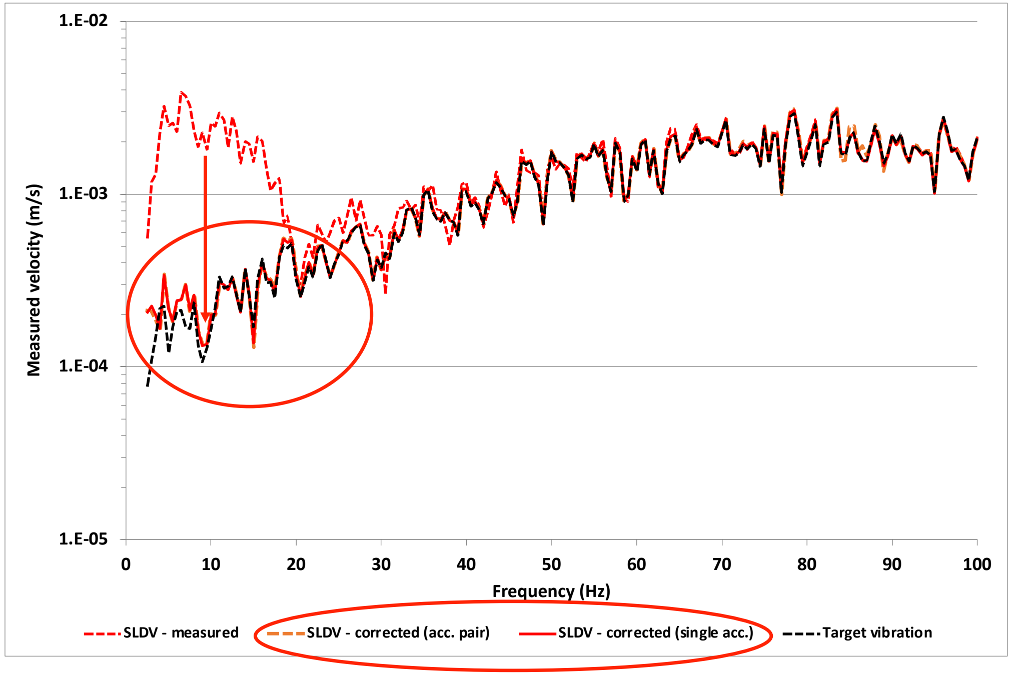
Top view (x-scan shown)



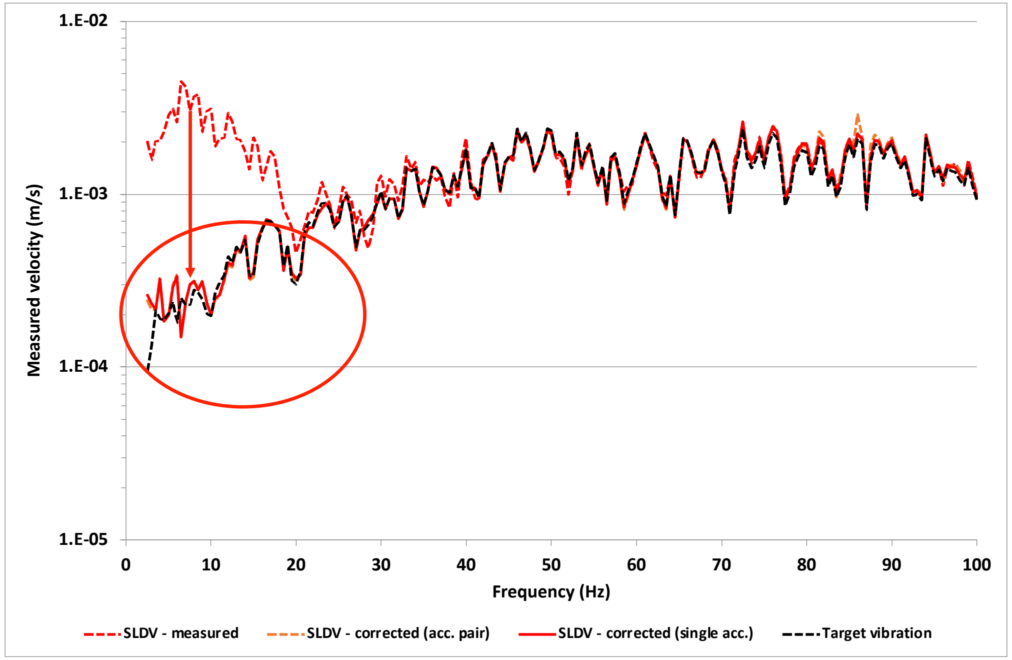


Example results during scanning

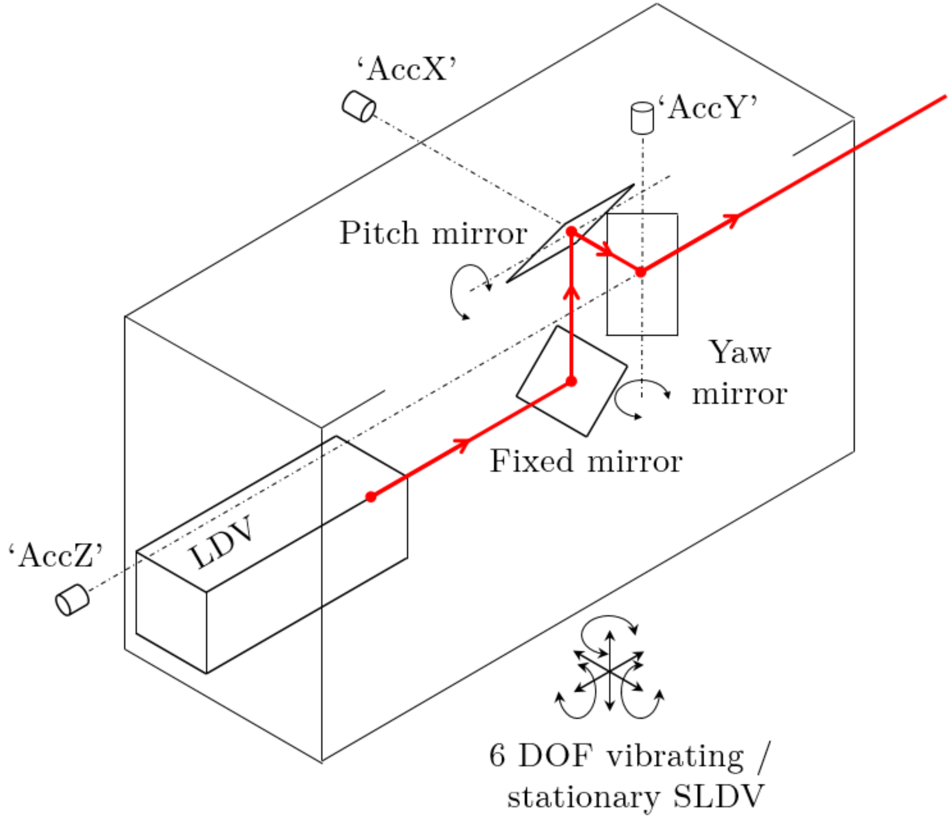
-4° y-scan



+12° y-scan

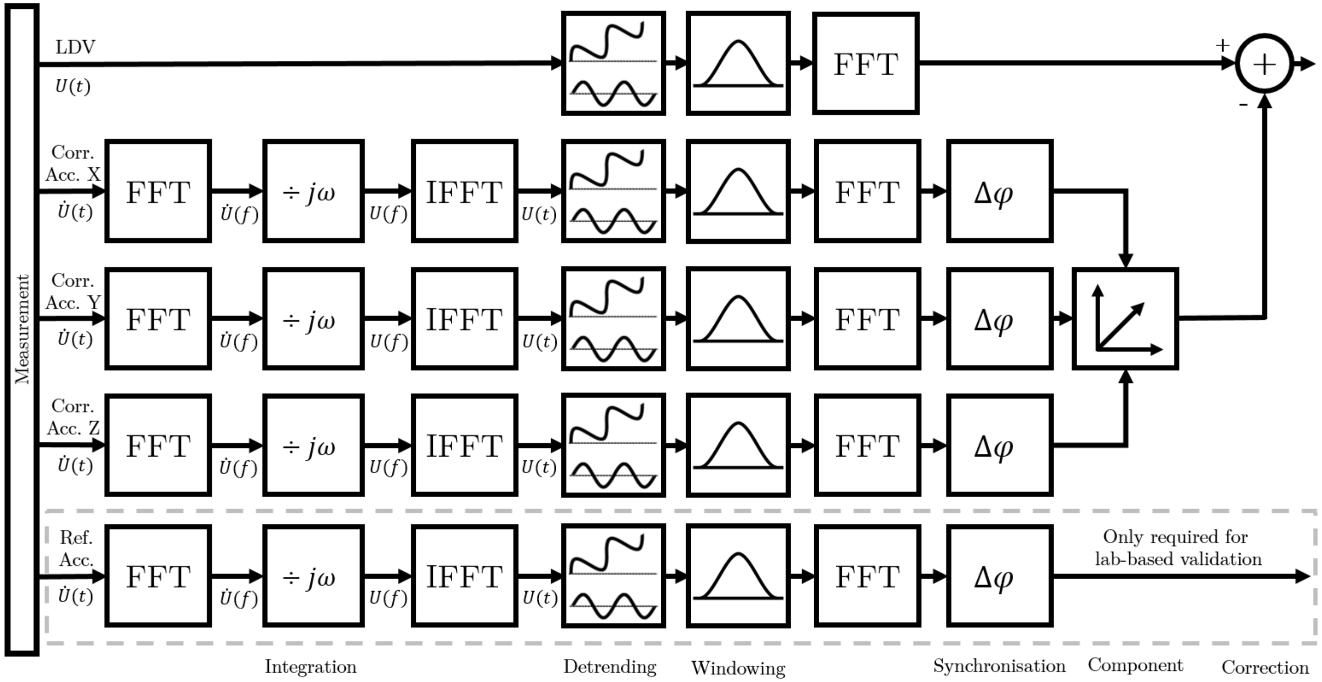


6 DoF correction for scanning LDV measurements



Frequency domain processing for scanning LDV correction

$$U_{corr} = -U_x \cos(\phi_{out}) \sin(\theta_{out}) + U_y \sin(\phi_{out}) - U_z \cos(\phi_{out}) \cos(\theta_{out})$$

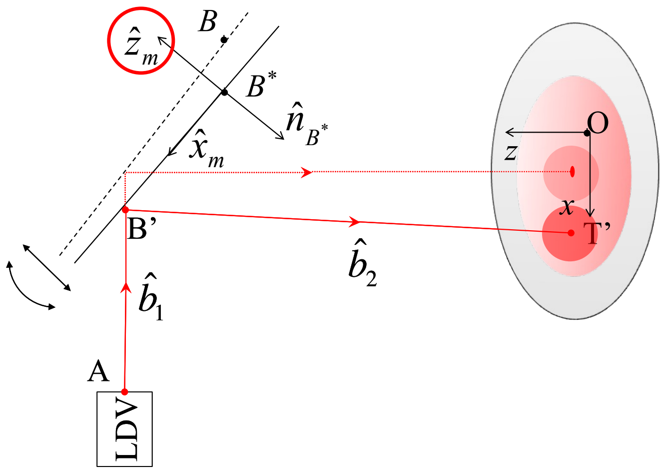


LDV measurements using a vibrating steering mirror

Compensating for steering mirror vibration

Measurement inherently sensitive to steering mirror/optic vibration

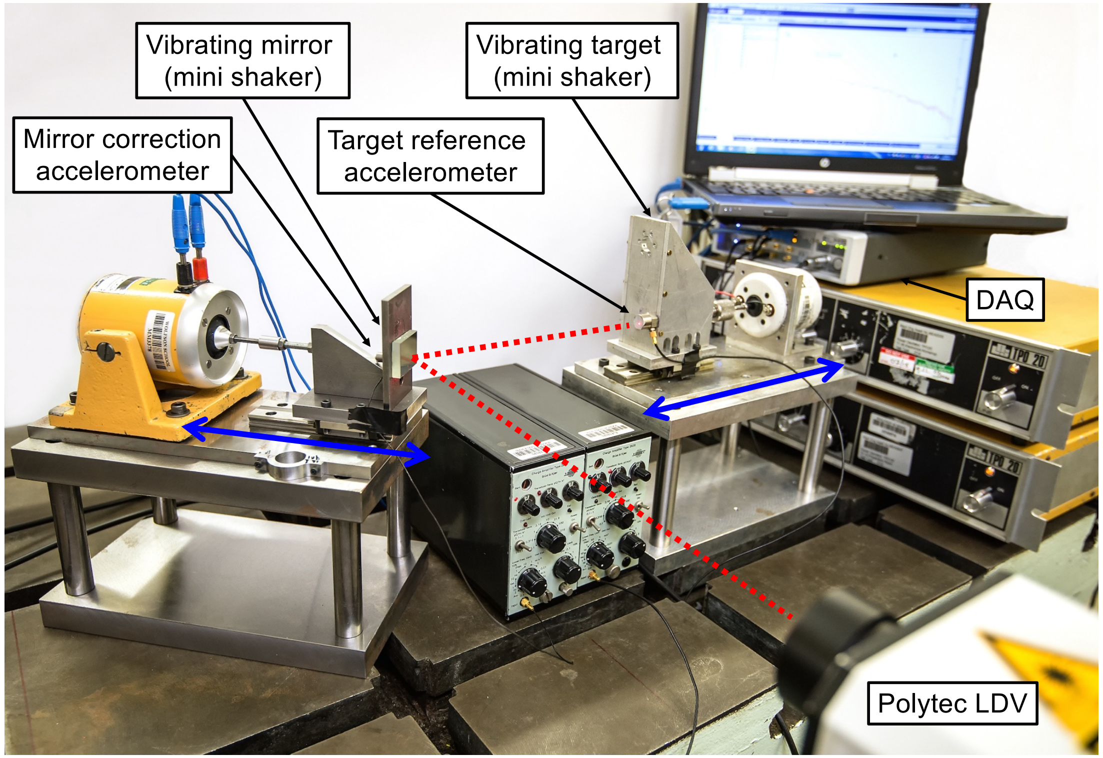
Sensitivity can be predicted from knowledge of geometry …

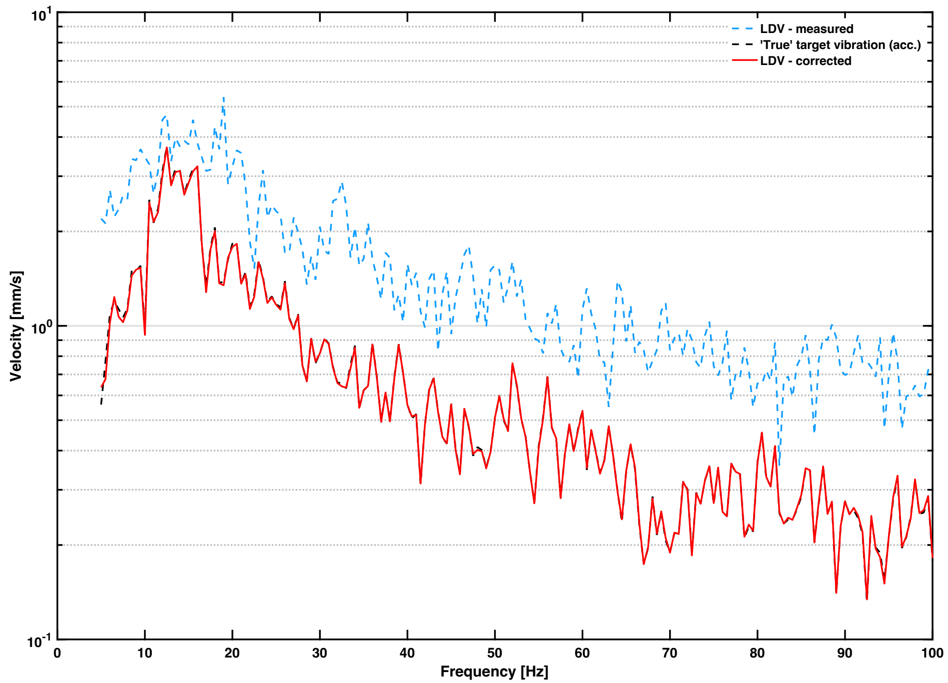


$$U_m = -\hat{b}_2.\overrightarrow{V_{T'}} + (\hat{b}_2 - \hat{b}_1).\overrightarrow{V_{B'}}$$

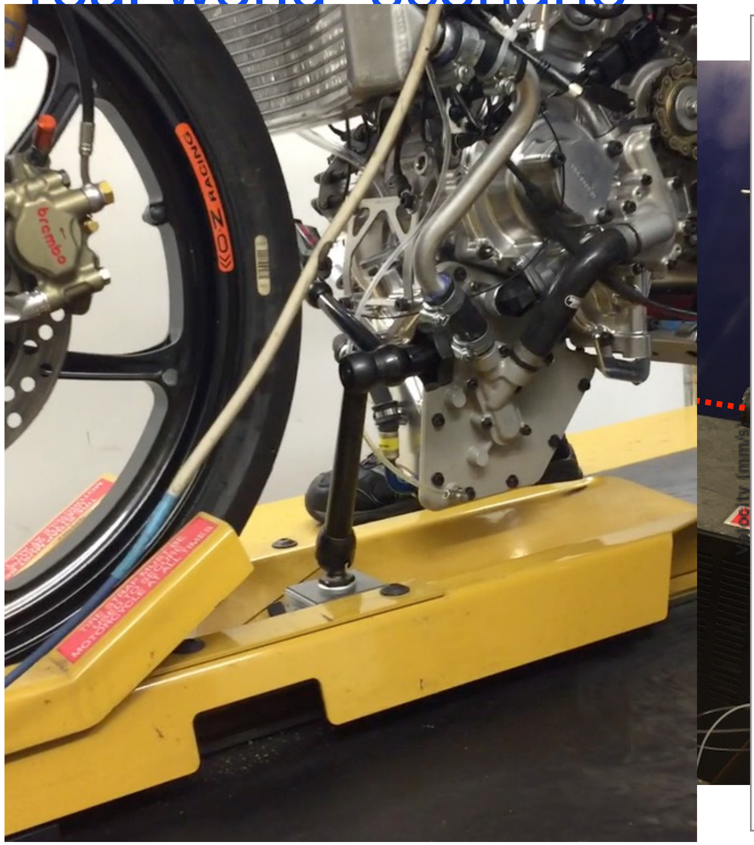
…measure the mirror vibration independently then we can compensate the measurement

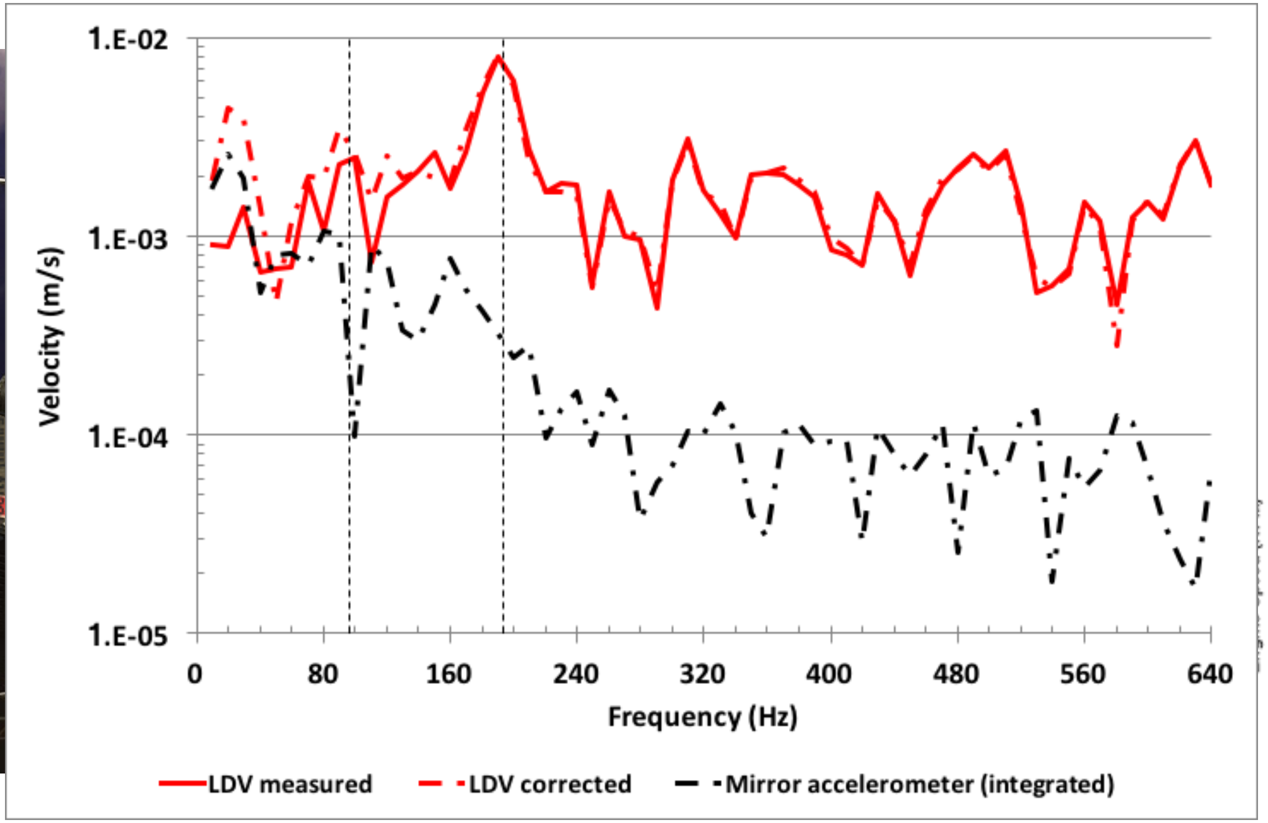
Experimental validation I – lab-based scenario



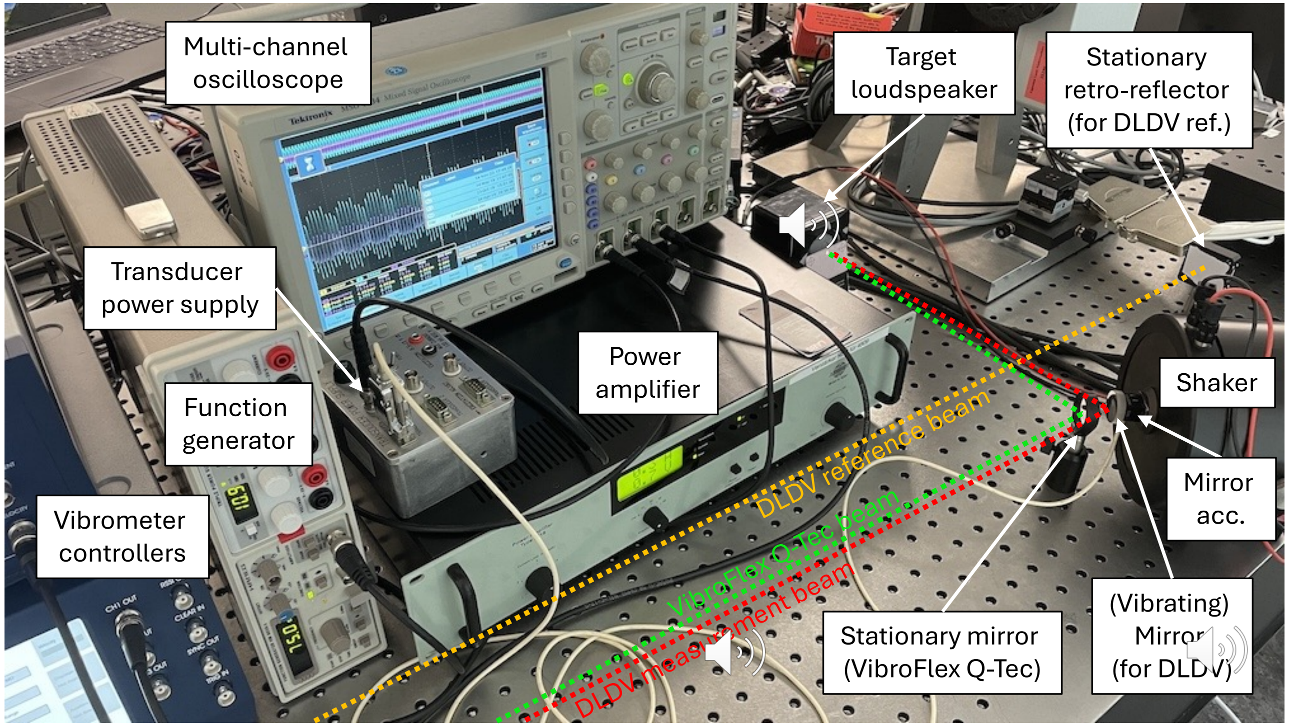


Experimental validation II – “real-world” scenario

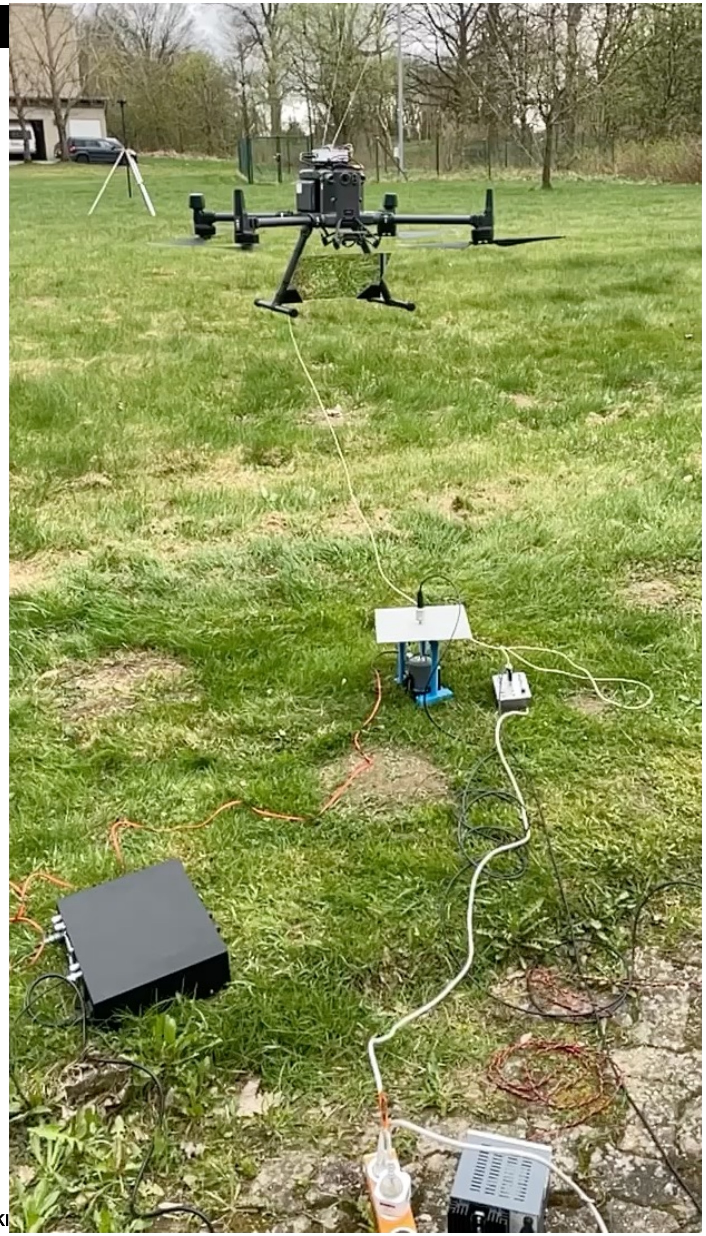




Experimental validation III – "Flyable Mirror" project



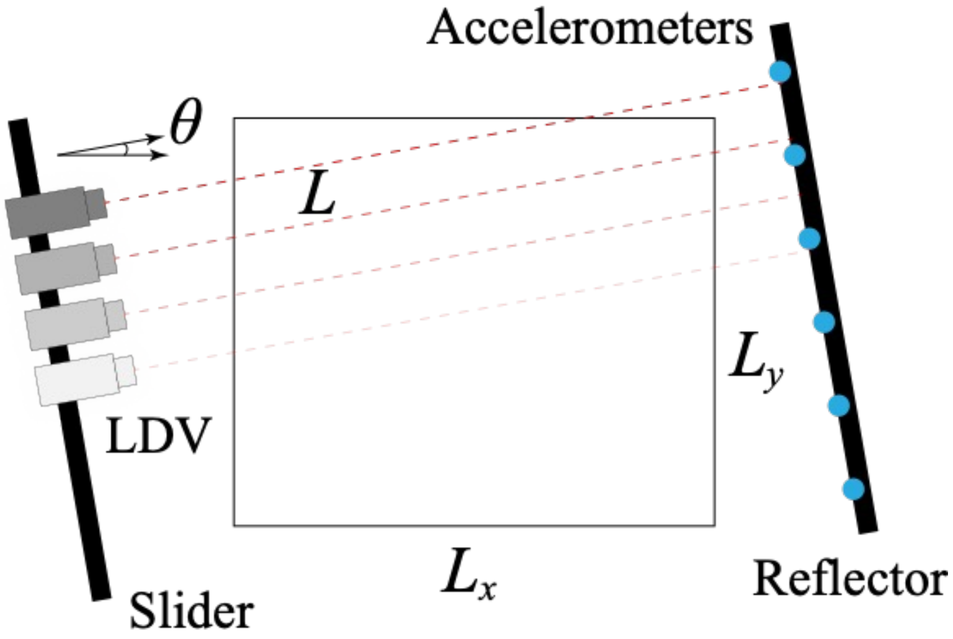
LDV measurement after correction:



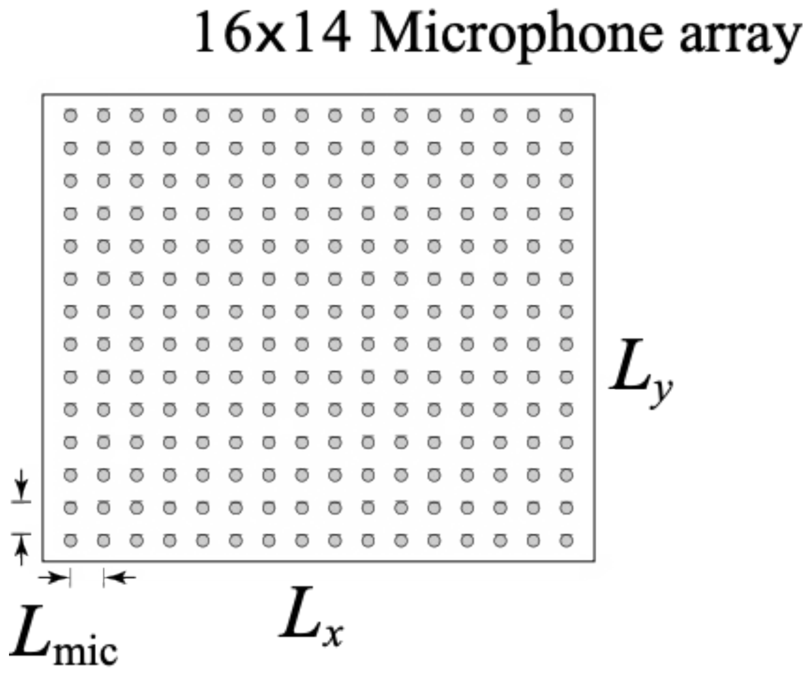
"Refracto-Vibrometry" across an aperture/opening for active noise control

Wide Area Refracto-Vibrometry (to replace a microphone array)

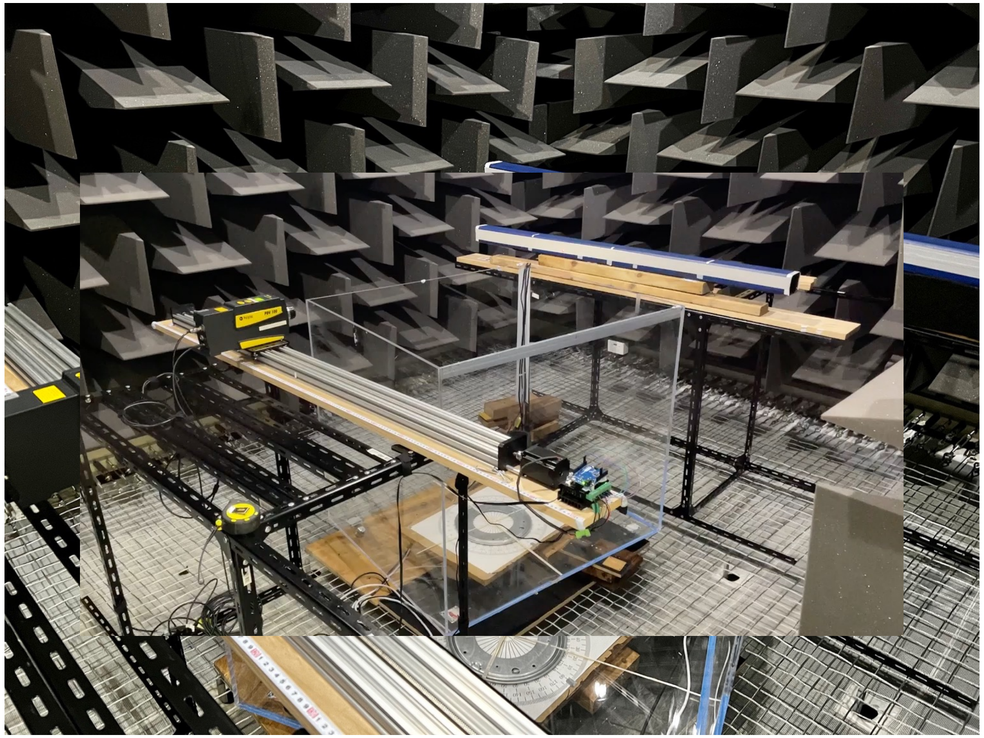
Remember, LDVs measure path length fluctuations…which includes refractive index changes!

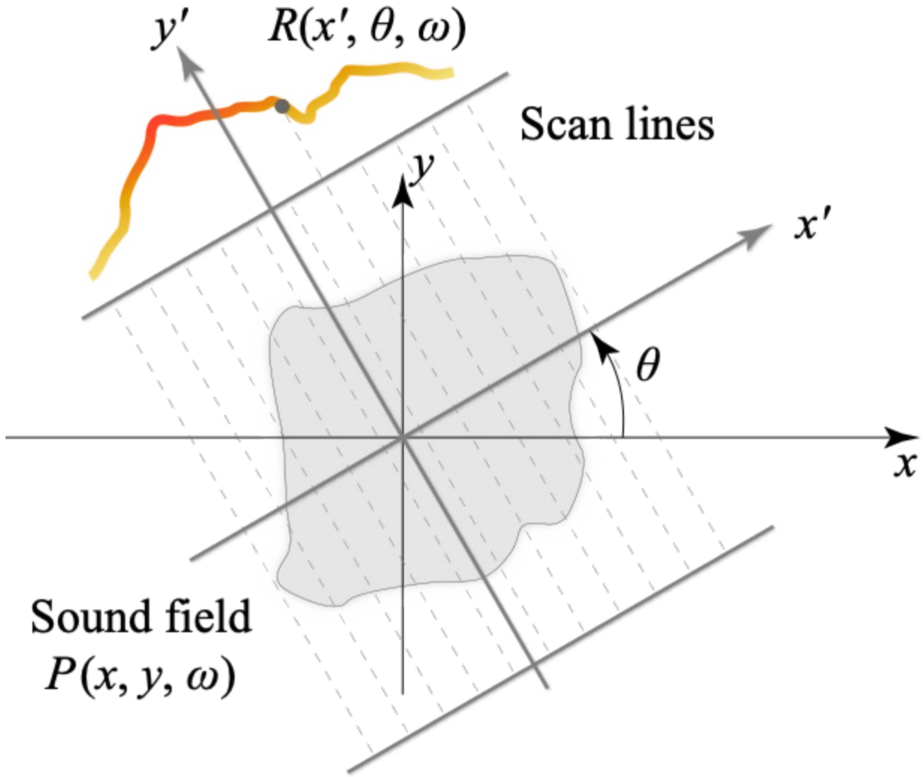


vs.



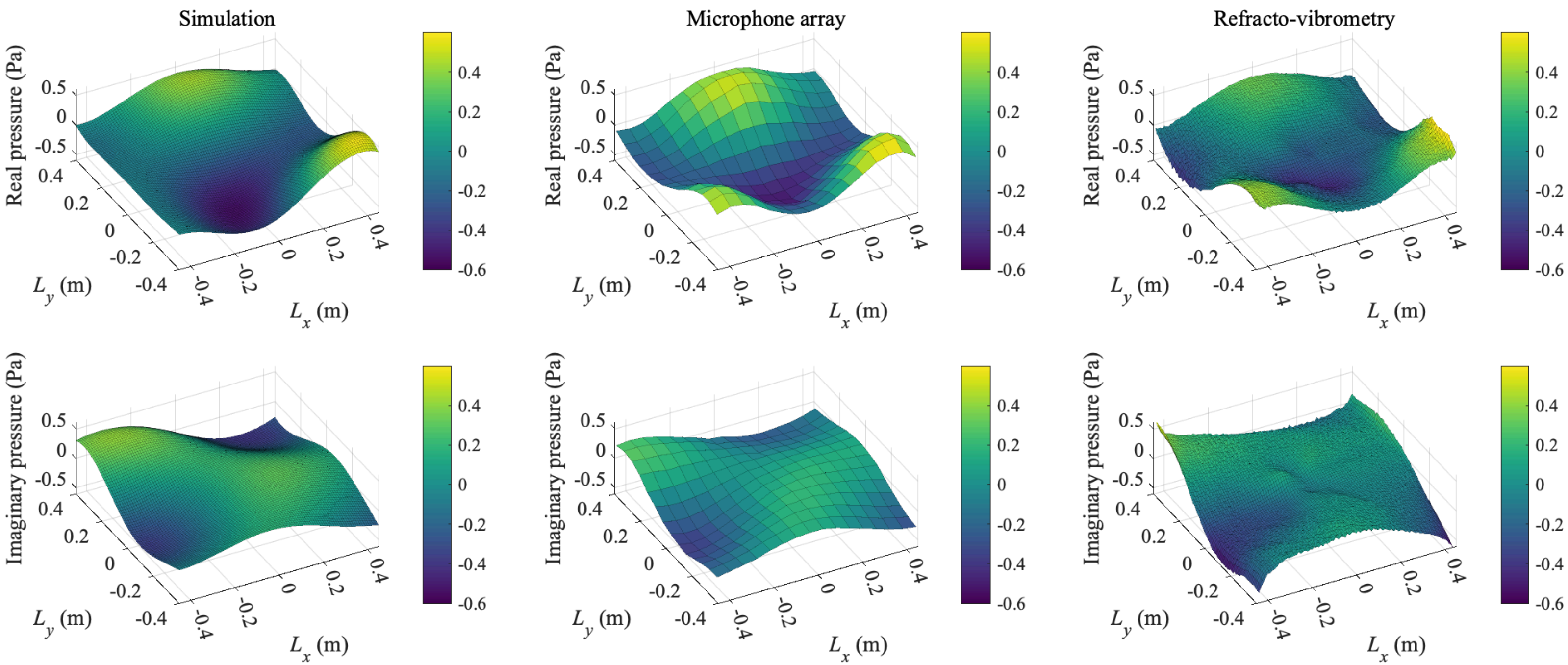
Experimental arrangement and (some) signal processing





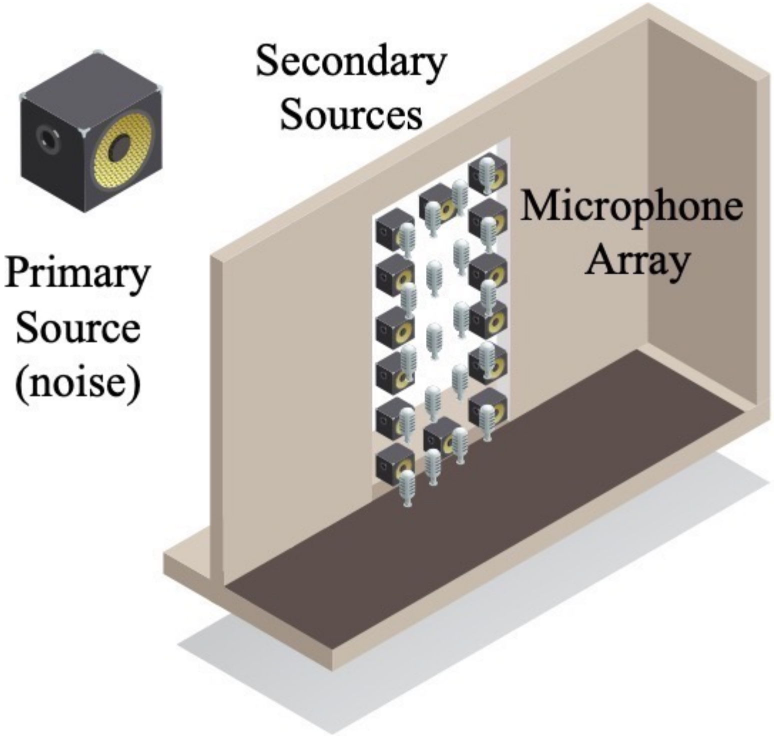
Results

Simulation vs. microphone array vs. refracto-vibrometry:

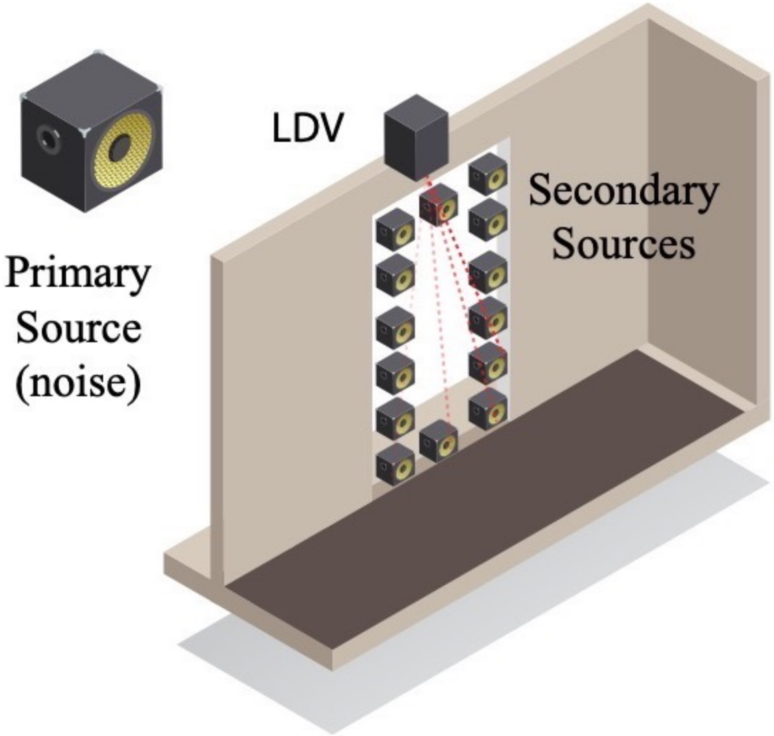


: PERMISSION

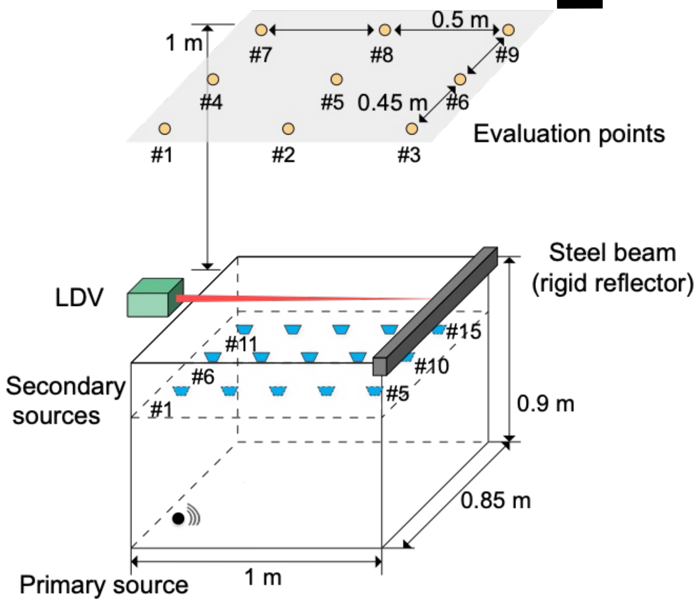
ANC at a window opening

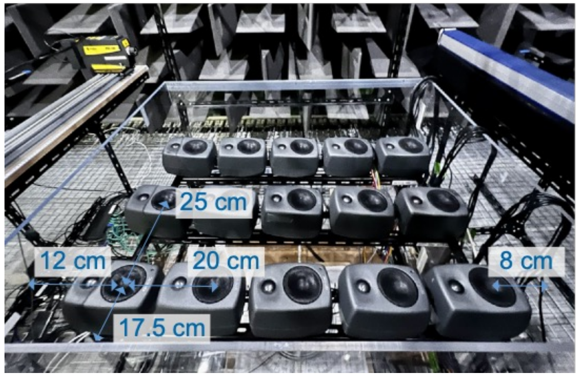


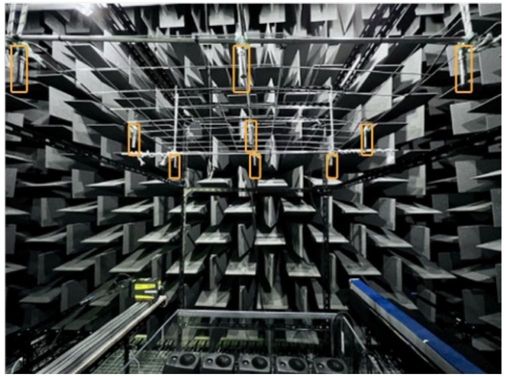
vs.



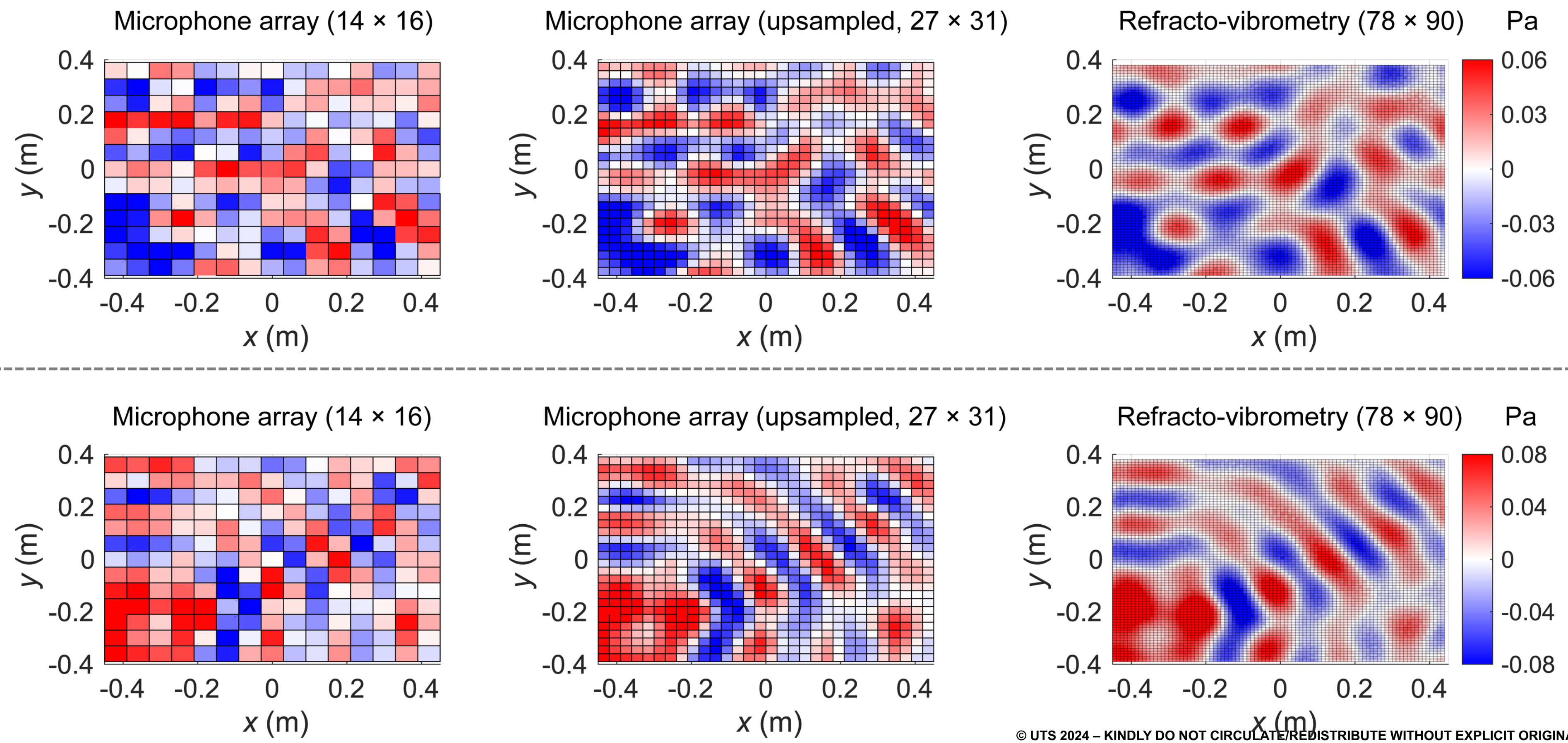
Experimental setup





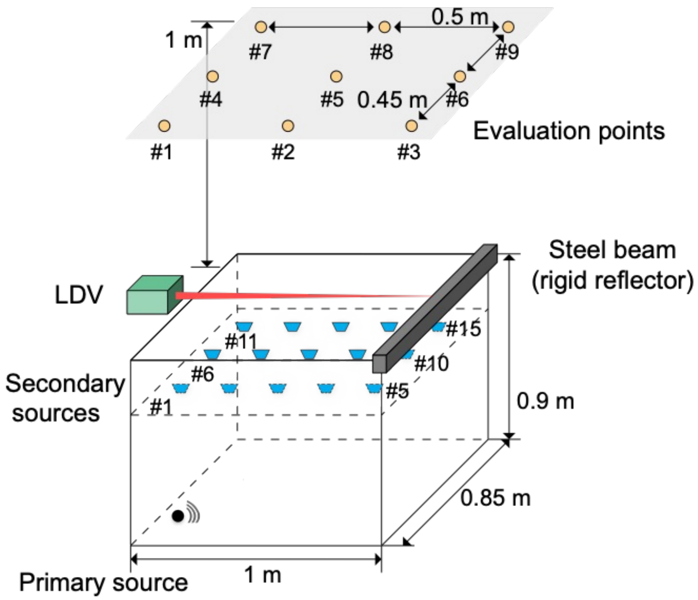


Sound Field Reconstruction @ 2 kHz (two sound fields)



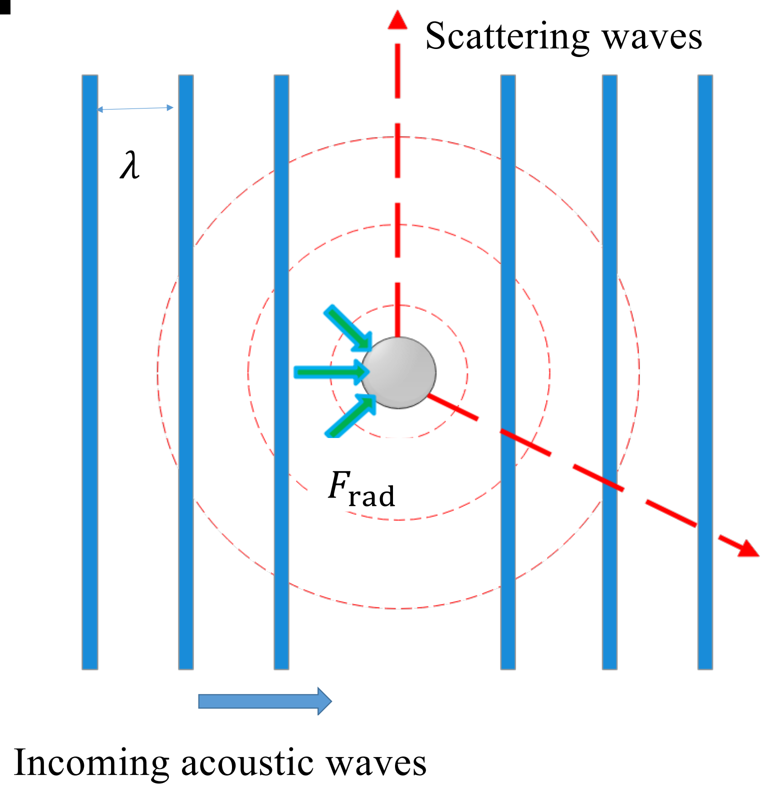
ANC Performance with 15 Secondary Sources @ 2 kHz

No. of errors	Noise reduction level	
	Microphone array	Refracto-vibrometry
15	−11.2 dB	−10.1 dB
21	−4.2 dB	−5.8 dB
30	−3.6 dB	−3.4 dB
56	−2.5 dB	−2.2 dB
224	−0.8 dB	0.2 dB
9216	–	0.1 dB



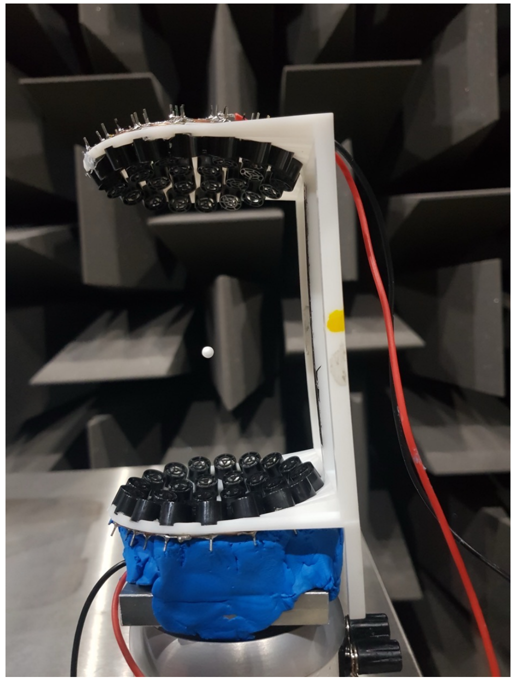
Manipulation of an acoustically levitated object using externally excited standing acoustic waves

Acoustic Radiation Force (ARF)

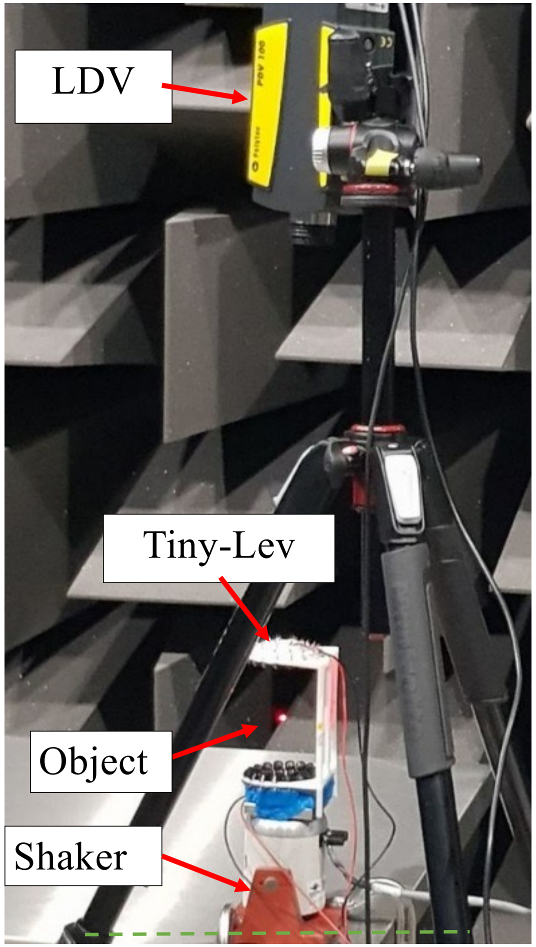


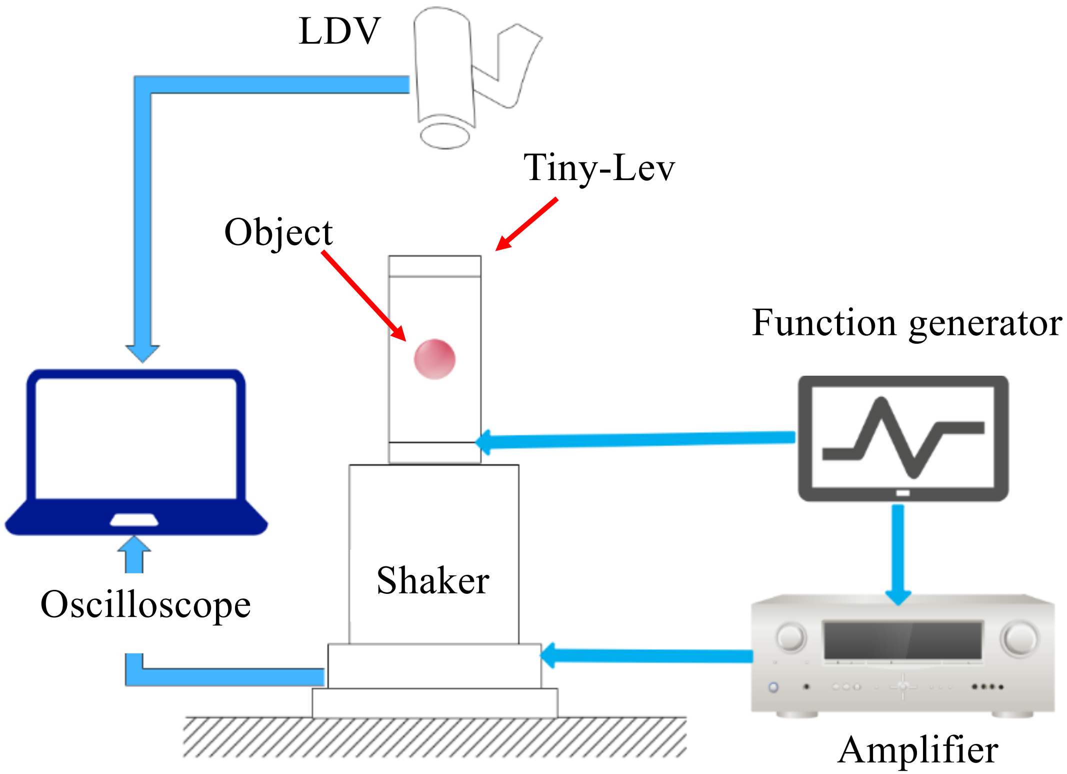
Interaction between Incoming and scattering acoustic waves

ARF

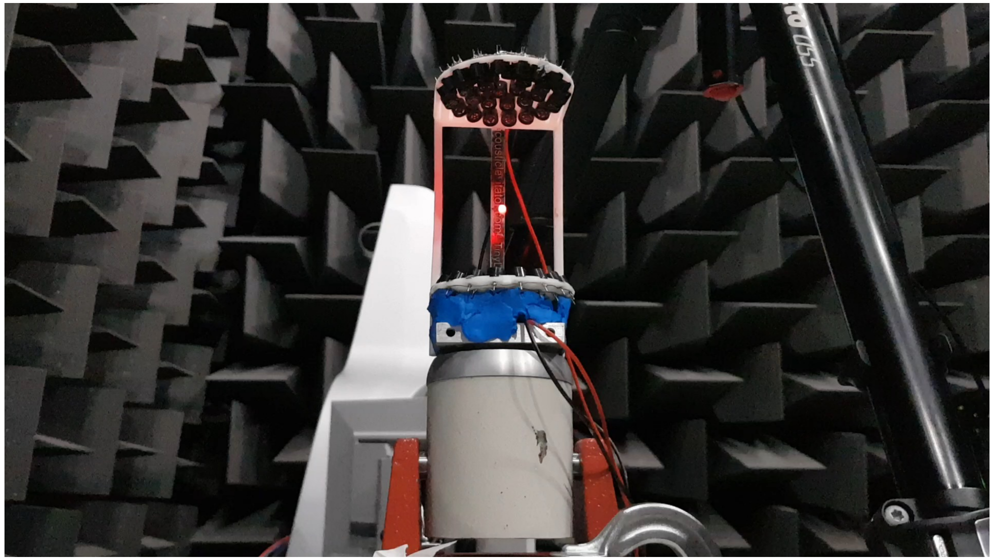


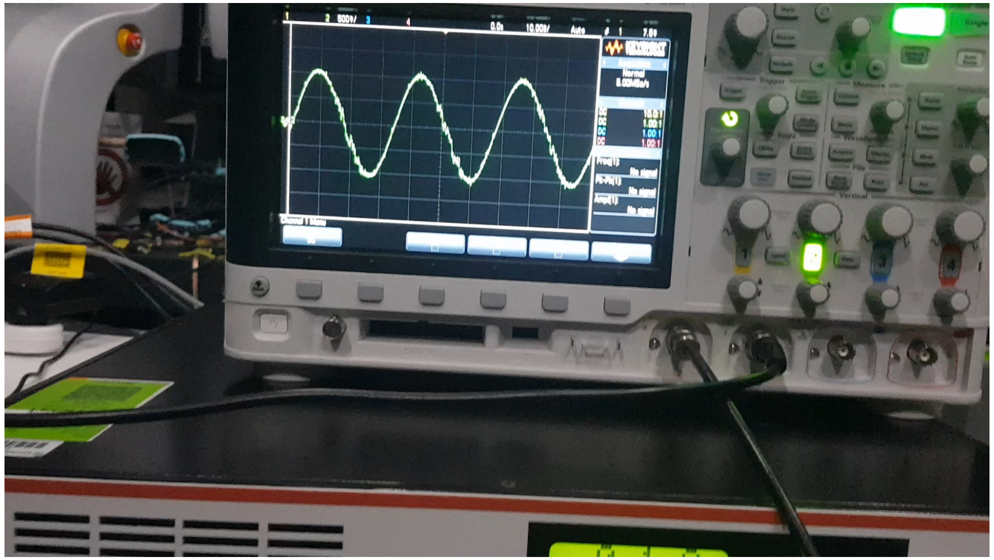
Our experimental set up





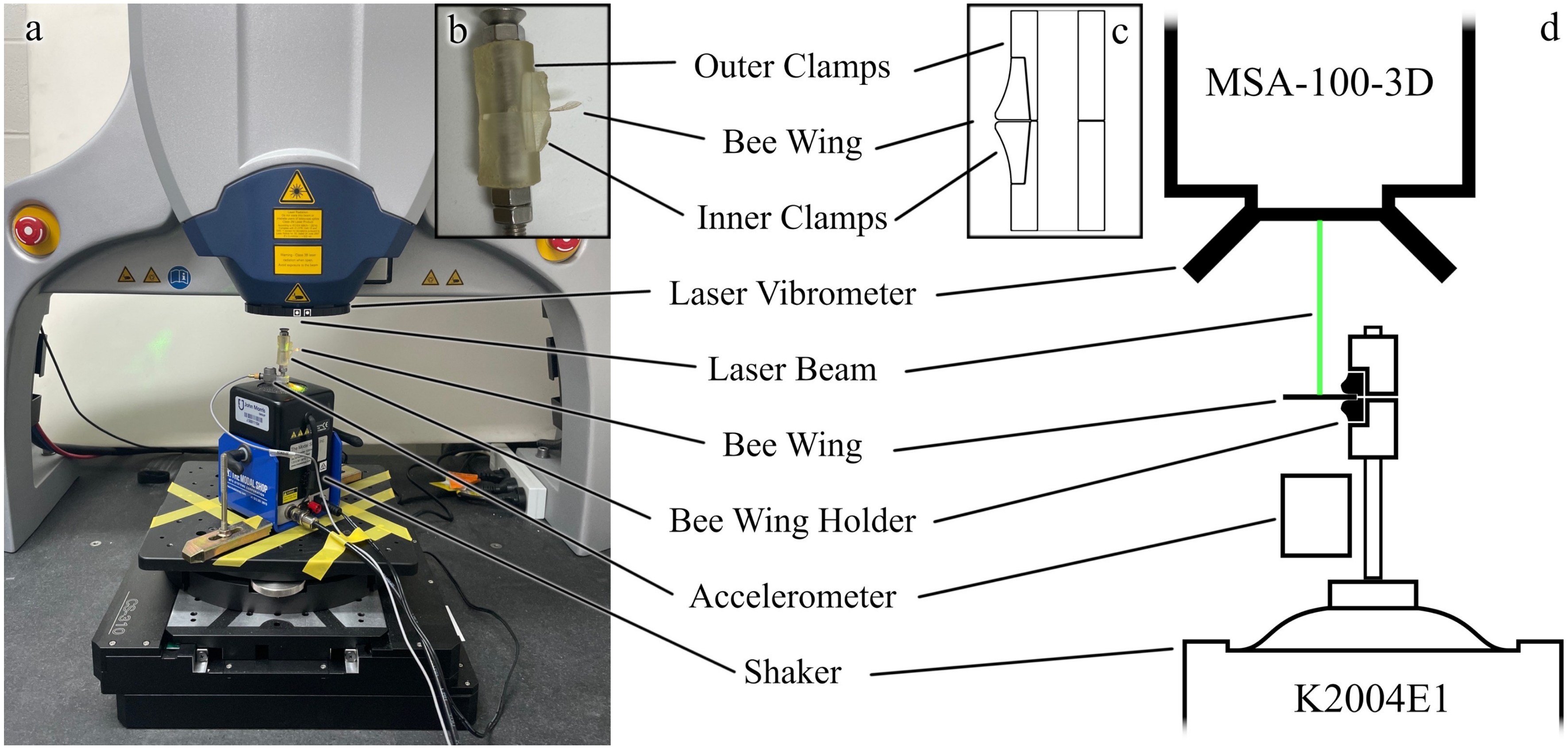
Experimental demonstration – object trap change and chaos



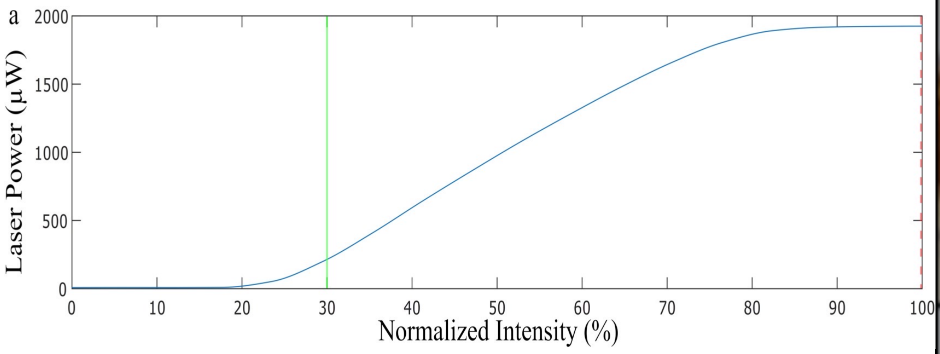


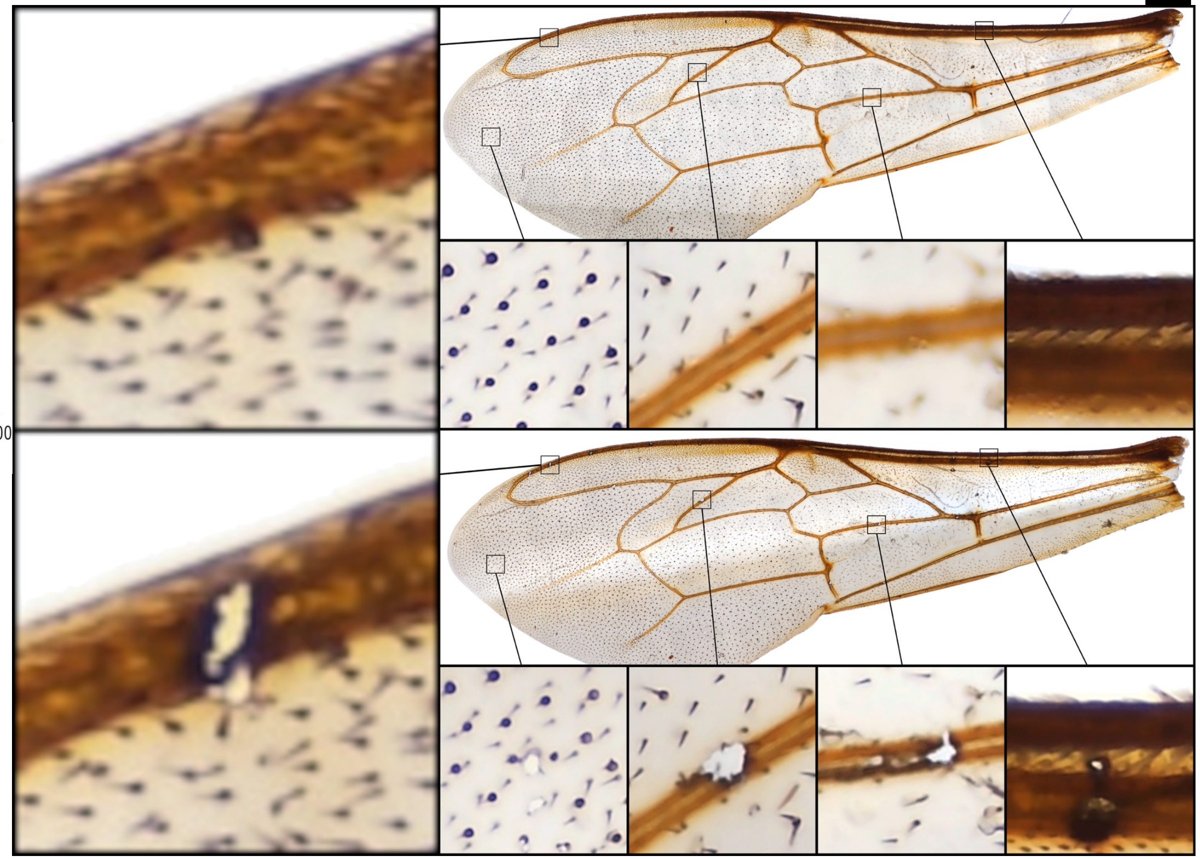
Laser vibrometry etc. in insect biomechanics research

LDV measurements of bee wing dynamics



Laser intensity causing damage (when focusing)

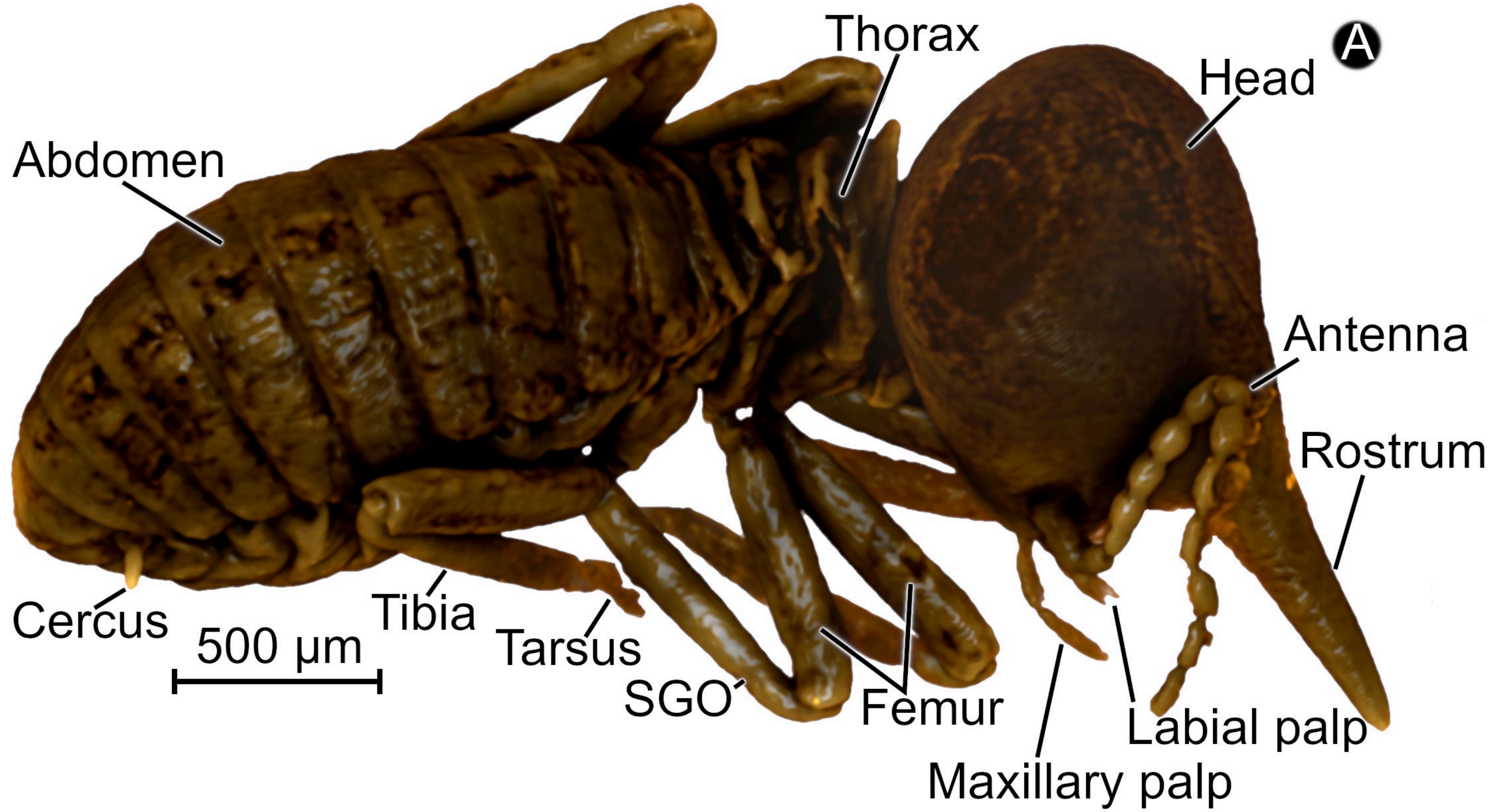




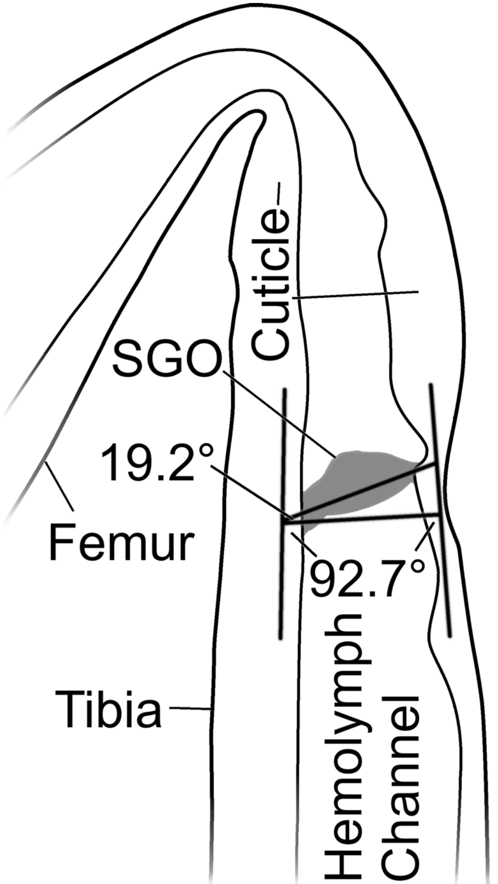
Damage to the bee wing occurs at above 30% intensity ~ 0.25 mW (green line)

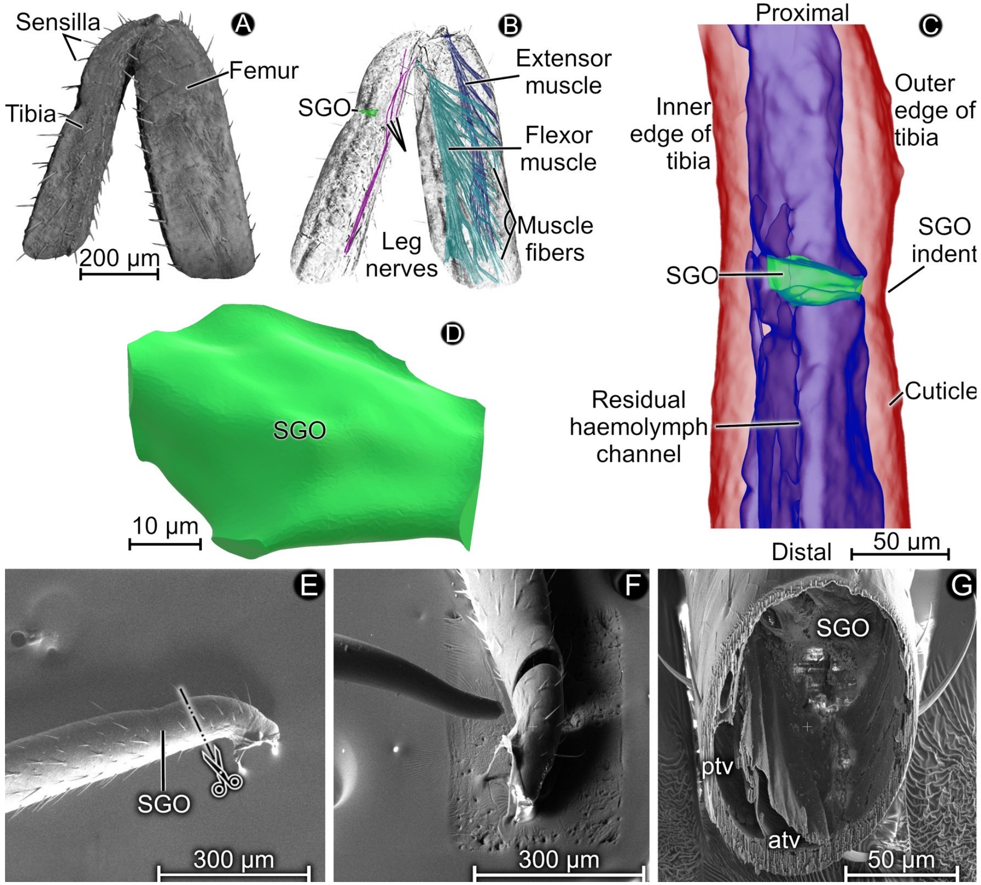
LDV system used is MSA-100-3D

µCT scans of termite leg and its subgenual organ (SGO)



µCT scans of termite leg and its subgenual organ (SGO)





Summary and conclusions

Modelling LDV velocity sensitivity allows prediction of (some) measurement “uncertainties”

Predictions can be used to determine which correction measurements are required for scenarios where additional velocity contributions are present

- Correction can be done in both frequency and time domain processing
- Vibrating scanning LDV, even for 6DoF sensor head vibration!
- Vibrating steering mirror, applicable to “Flyable Mirrors”!

Refracto-Vibrometry can be used for effective active noise control at an opening

Active vibration control benefits from LDV reference sensor

Acoustic levitation for manipulation of lightweight structures

Insect biomechanics

Thank you

Questions?

Credits (special thanks to!)

Colleagues and collaborators

Prof. Christian Rembe, Prof. Steve Rothberg, Assoc. Prof. Sebastian Oberst, Prof. Robert Fitch, Dr Hamed Kalhori, Dr Mohamed Ismail …

Junior researchers & project students

Chunlin Gao, Mahdi Mohammadi, Zimu Guo, Tong Xiao, Abdel Darwish, Travers Sansom, Mehdi Akbarzadeh …

Industry/government support

German Research Foundation (DFG), German Aerospace Centre (DLR) Institute of Flight Systems Engineering; Warsash Scientific Pty Ltd; Polytec GmbH; GE Precision …

Technical support

Steve Carr, Max Farrand, Chris Chapman, Yaser Jazayeri, Peter Brown, Simon Myslinski …

An upcoming opportunity!

Some (optional) further reading!

Halkon, BJ and Rothberg, SJ, Taking laser Doppler vibrometry off the tripod: correction of measurements affected by instrument vibration, *Optics and Lasers in Engineering*, **99** (2017), DOI: 10.1016/j.optlaseng.2016.11.006

Halkon, BJ and Rothberg, SJ, Restoring high accuracy to laser Doppler vibrometry measurements affected by vibration of beam steering optics, *Journal of Sound and Vibration*, **405** (2017), DOI: 10.1016/j.jsv.2017.05.014

Halkon, BJ and Rothberg, SJ, Establishing correction solutions for scanning laser Doppler vibrometer measurements affected by sensor head vibration. *Mechanical Systems and Signal Processing*, **150** (2020), DOI: 10.1016/j.ymssp.2020.107255

Darwish, A, **Halkon, B**, Rothberg, SJ, Oberst, S, and Fitch, R, A comparison of time and frequency domain-based approaches to laser Doppler vibrometer instrument vibration correction, *Journal of Sound and Vibration*, **520** (2022), DOI: 10.1016/j.jsv.2021.116607

Rembe, C, **Halkon, B**, Ismail, M, Measuring Vibrations in Large Structures with Laser-Doppler Vibrometry and Unmanned Aerial Systems: A Review and Outlook, *accepted*, (2025)

Some (optional) further reading continued?!

Rothberg, S, … **Halkon, B**, et al., An international review of laser Doppler vibrometry: Making light work of vibration measurement, *Optics and Lasers in Engineering*, **99**, (2017), DOI: 10.1016/j.optlaseng.2016.10.023

Xiao, T., Qiu, X., & **Halkon, B.** (2020). Ultra-broadband local active noise control with remote acoustic sensing. *Scientific Reports*, *10*(1), 1-12.

Xiao, T., **Halkon, B.**, et al., Refracto-vibrometry for active control of sound radiation through an opening, *Journal of Sound and Vibration*, **577** (2024), DOI: 10.1016/j.jsv.2024.118242

Guo et al.

Sansom et al. (2022) LASER_INTENSITY-INDUCED_DAMAGE_EFFECTS_ON_DYNAMIC_CHARACTERISATION_OF_WINGS_OF_THE_EUROPEAN_HONEYBEE_APIS_MELLIFERA/links/633a34fc76e39959d69032fe/

Sansom et al., … (2022) https://doi.org/10.1016/j.asd.2022.101191