May 14, 2020

Measurements using Smart Phone Apps and the PU Probe

Vibro-Acoustics Consortium Web Meeting

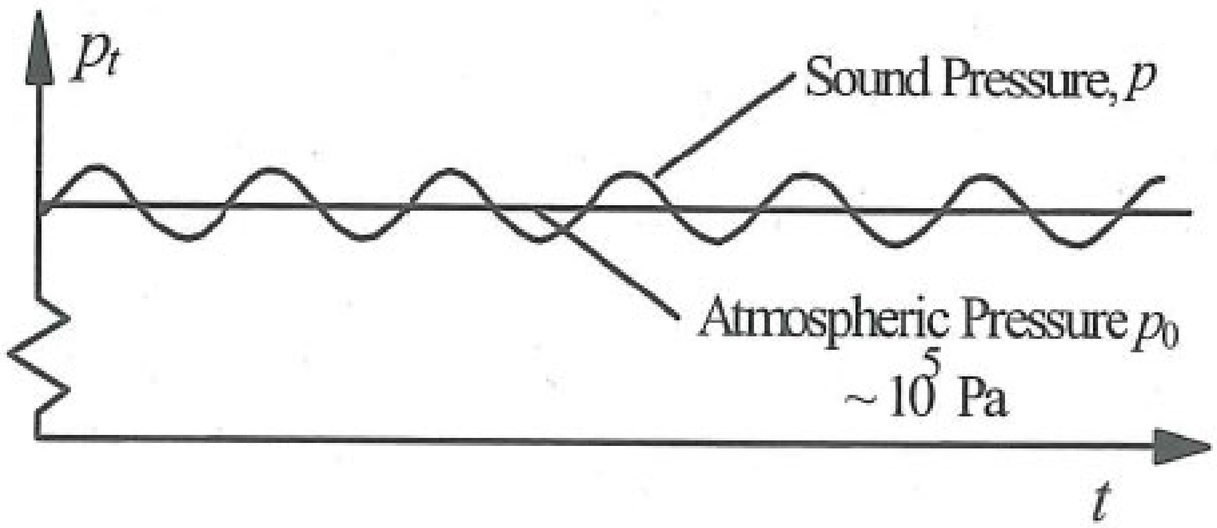
University of Kentucky

Overview

- Introduction
- Smart Phone Measurements Hardware and Software
- Smart Phone Measurements Level Tests
- Smart Phone Measurements Application Cases
- PU Probe Hardware
- PU Probe Engine Application
- PU Probe UAV Application
- PU Probe Radiation Efficiency
- Future Directions

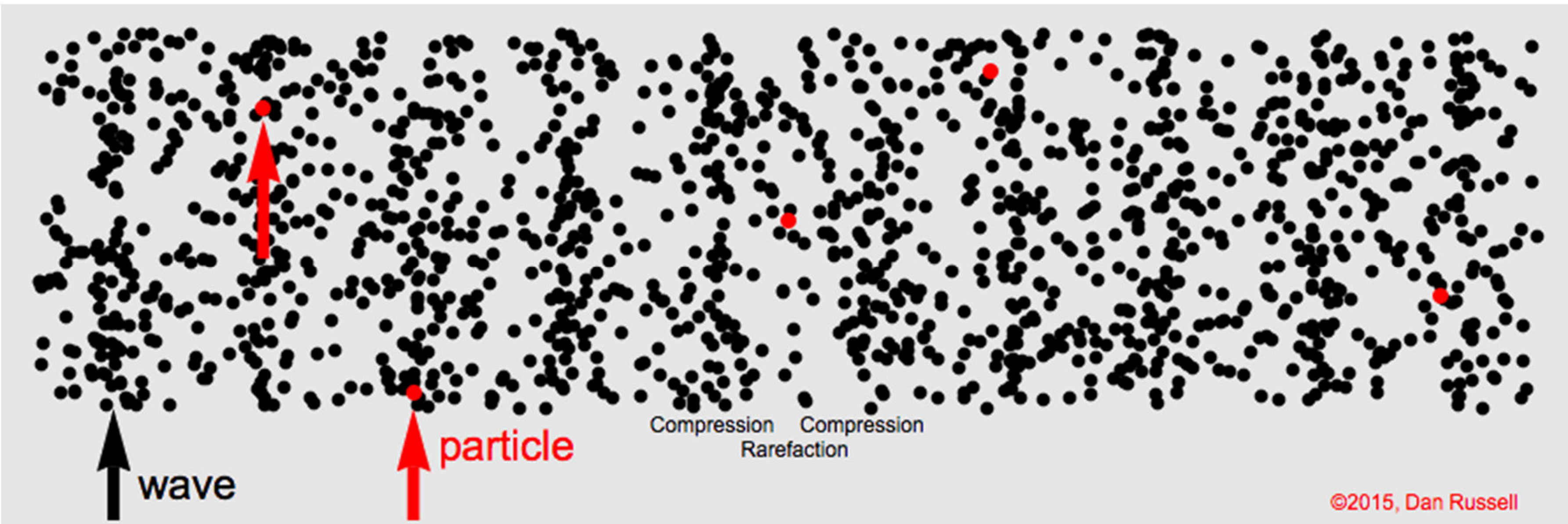
Sound and Vibration Fields

An acoustic field implies a small disturbance. Sound pressure disturbances are only on the order of 1 Pa for 94 dB.



Wallin et al., 2011

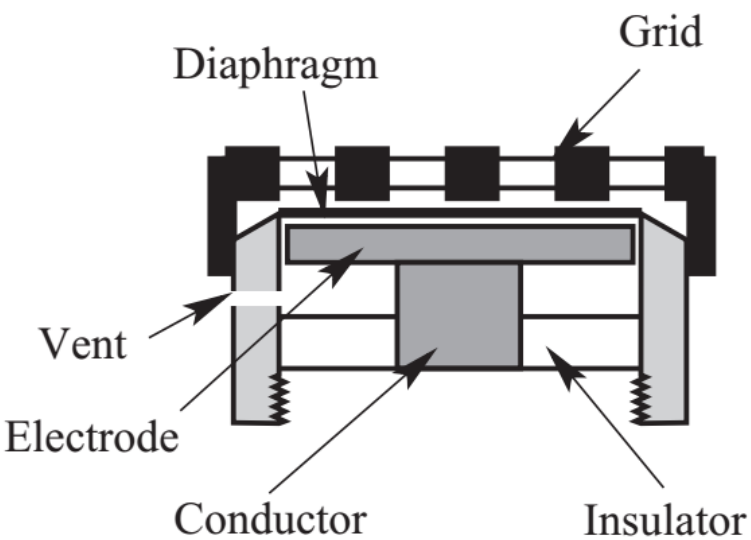
Particle Motion

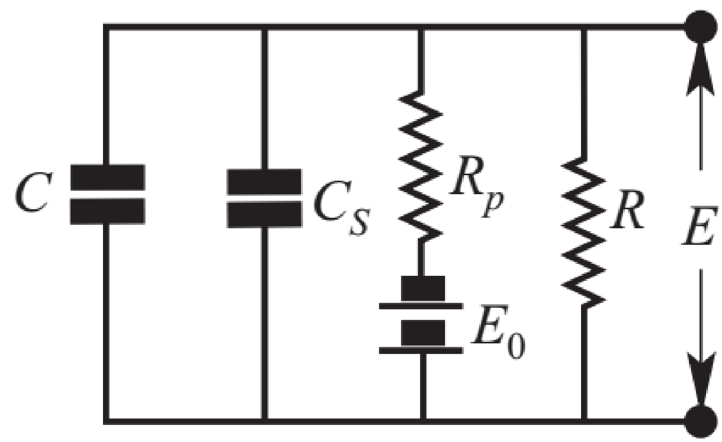


- Particles oscillate (but no net flow)
- Waves move much faster than particles

https://www.acs.psu.edu/drussell/demos.html

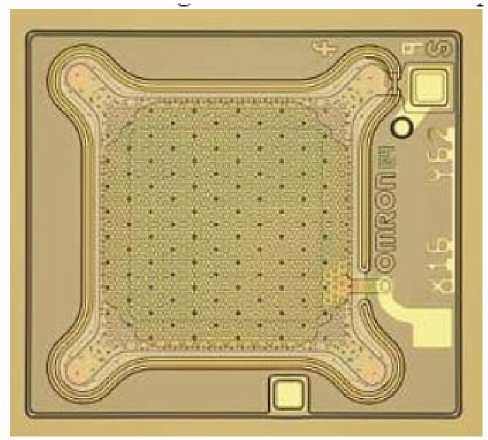
Condenser Microphones

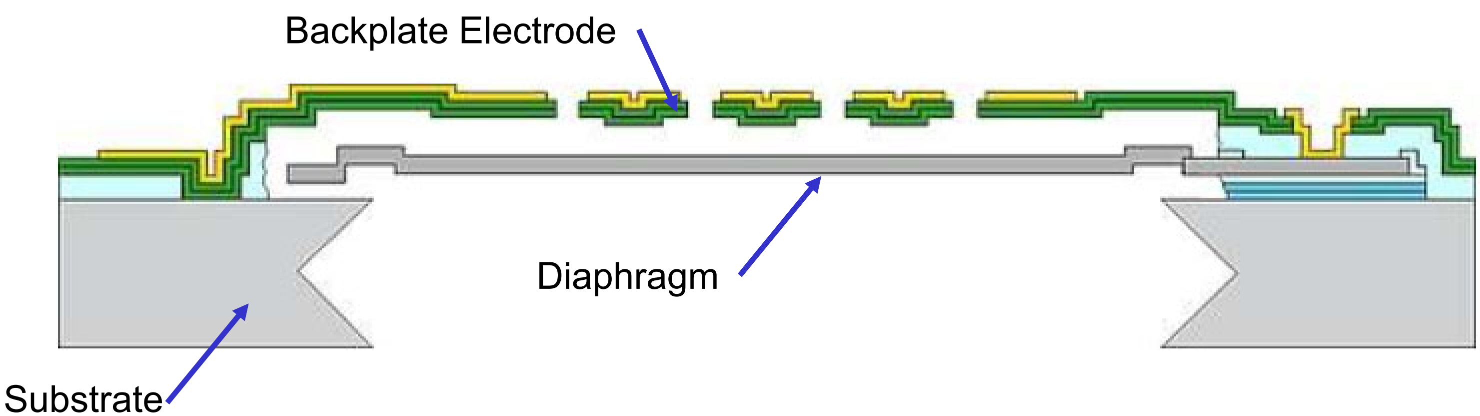




Bies, Hansen and Howard, 2018

MEMS Microphones





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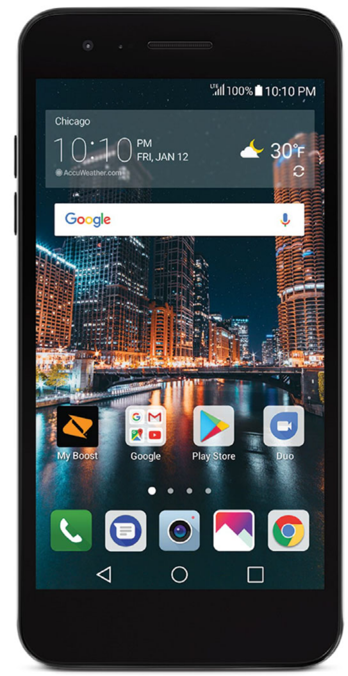
Smartphone Types

iPhone 6 Plus

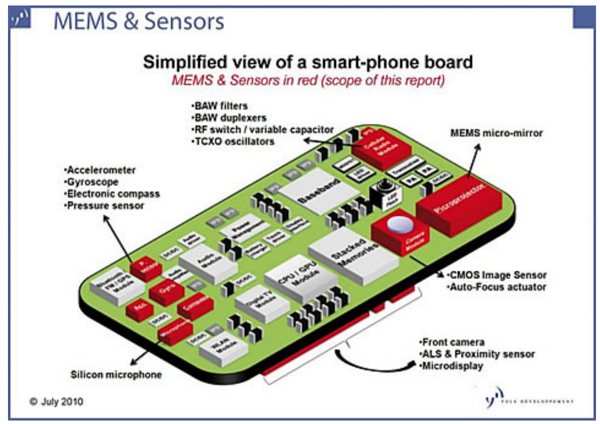
iPhone 7 Plus



LG Tribute Dynasty

Microphones

PCB 378B11
Siemens DAQ

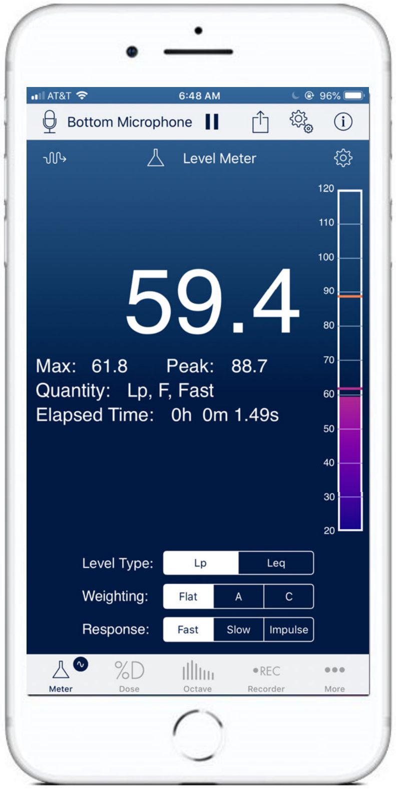


Internal Microphone

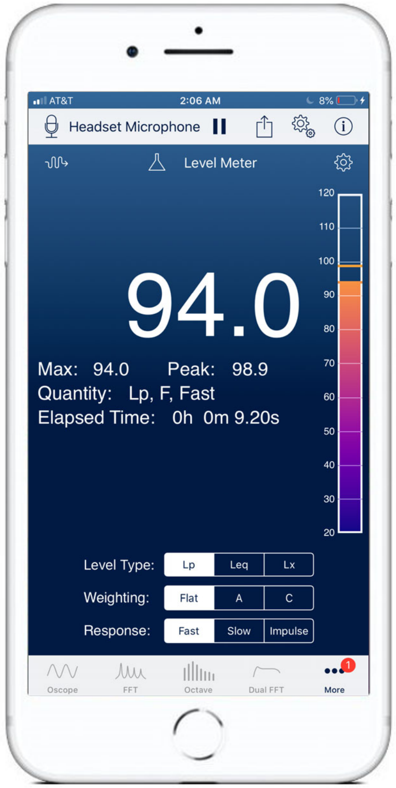
https://www.engineering.com/ElectronicsDesign/ElectronicsDesignArticles/ArticleID/6124/How-MEMS-Enable-Smartphone-Features.aspx

Mic-W
BSWA

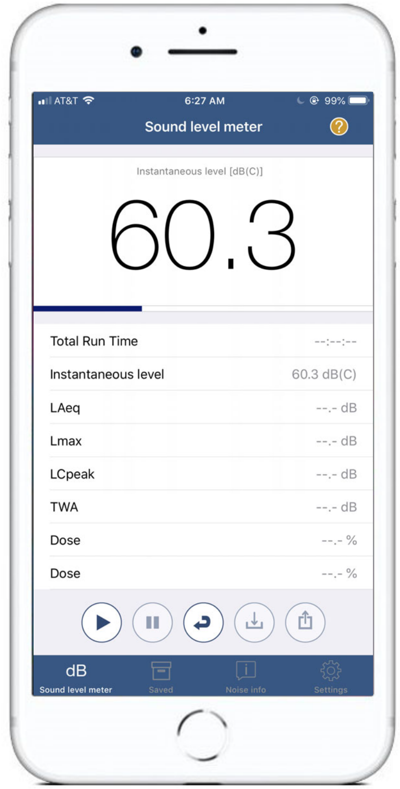
Smartphone Apps Used



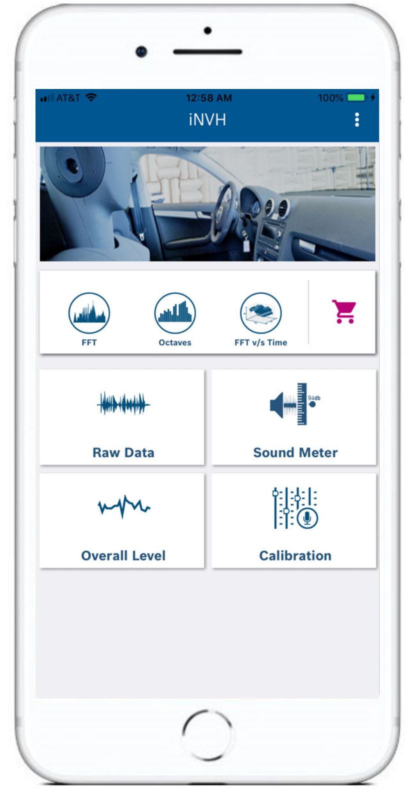
Sound Meter X
Faber Acoustical



Signal Scope X
Faber Acoustical



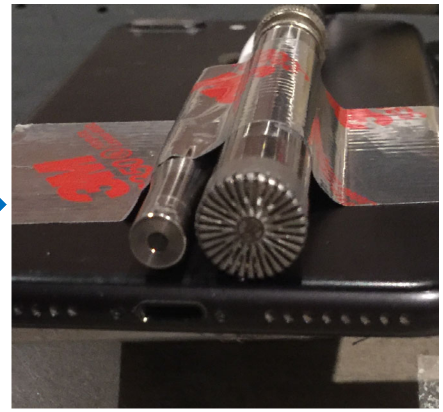
NIOSH SLM



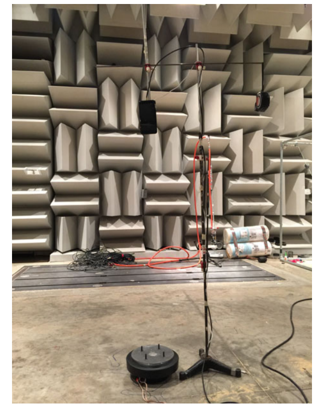
iNVH
Bosch

Microphone Calibration

Calibrate the PCB microphone



Mount the sensors together



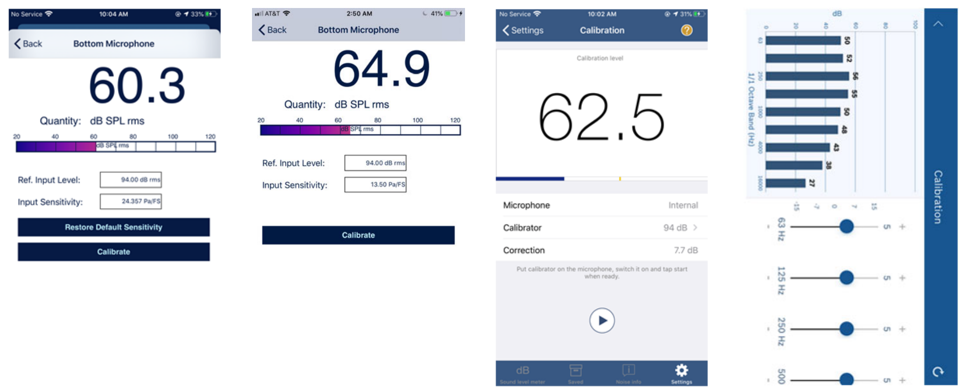
Measure in "free field"

Sources Control

	Source	On/Off	Signal Type	Level (V)	More
1	Output1	☑	Random	1.0000	More
2	Output2	☐	Sine	0.0000	More

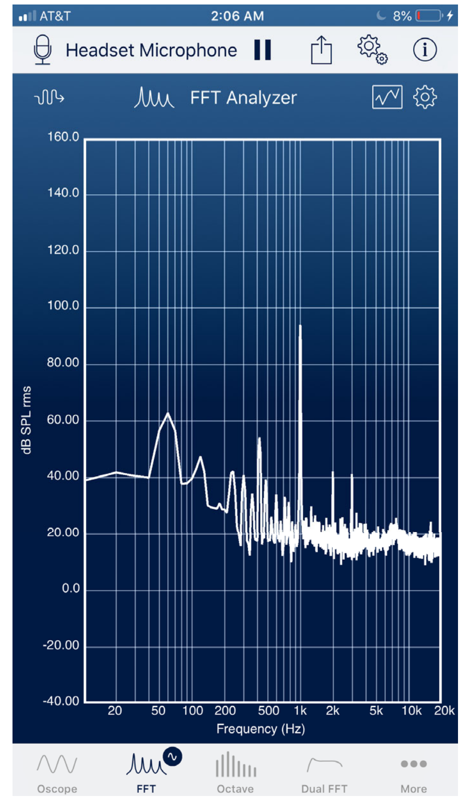
Start Source | Stop Source

Generate a 94 dB noise
(measured by PCB microphone)



Calibrate the Apps

Microphone Calibration



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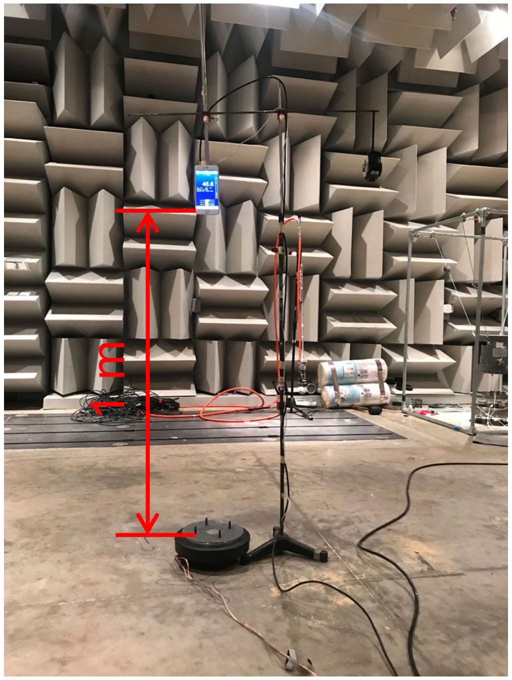
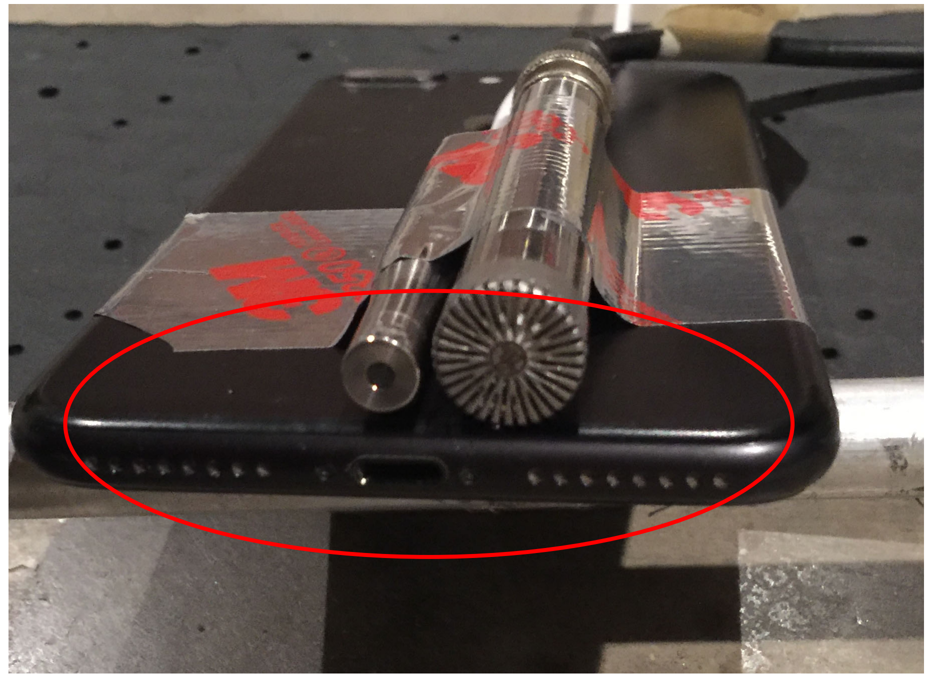
Test Setup



Free space measurement



Smartphone and microphones

The Smart phone, Mic-W and PCB microphone are mounted directly above (1 m) the loudspeaker.

iPhone 6 Plus with Internal Microphone

White noise source with internal microphones uncalibrated.

Sound Pressure Level (dB)					
Sound Meter	PCB	NIOSH	PCB	iNVH	PCB
60.0	62.0	60.0	58.7	60.0	61.5
65.0	66.8	65.0	63.2	65.0	66.5
70.0	71.7	70.0	68.1	70.0	72.0
75.0	76.6	75.0	73.2	75.0	76.2
80.0	81.4	80.0	78.1	80.0	81.3
85.0	86.5	85.0	83.2	85.0	86.2
90.0	91.5	90.0	88.2	90.0	91.3
95.0	96.5	95.0	93.2	95.0	96.3
100.0	102.3	100.0	98.5	100.0	101.8

iPhone 6 Plus with Internal Microphone

White noise source with internal microphones calibrated.

Sound Pressure Level (dB)					
Sound Meter	PCB	NIOSH	PCB	iNVH	PCB
61.5	62.0	58.2	58.7	61.3	61.5
66.5	66.8	63.2	63.2	66.3	66.5
71.5	71.7	68.2	68.1	71.3	72.0
76.5	76.6	73.2	73.2	76.3	76.2
81.5	81.4	78.2	78.1	81.3	81.3
86.5	86.5	83.2	83.2	86.3	86.2
91.5	91.5	88.2	88.2	91.3	91.3
96.5	96.5	93.2	93.2	96.3	96.3
101.5	102.3	98.2	98.5	101.3	101.8

iPhone 6 Plus with Mic-W

White noise source with Mic-W calibrated with white noise.

Sound Pressure Level (dB)					
Sound Meter	PCB SCADAS	NIOSH	PCB SCADAS	iNVH	PCB SCADAS
60.7	60.2	60.5	59.9	63.0	60.2
65.4	65.2	65.3	65.2	66.0	64.8
70.2	70.1	70.0	70.0	70.0	69.5
75.0	75.1	75.0	75.1	75.0	74.6
80.0	80.0	80.0	80.0	80.0	79.4
85.0	85.1	85.0	85.0	85.0	84.4
90.0	90.2	90.0	90.0	90.0	89.6
95.0	95.2	95.0	95.0	95.0	94.6
100.0	100.1	100.0	99.9	100.0	99.5

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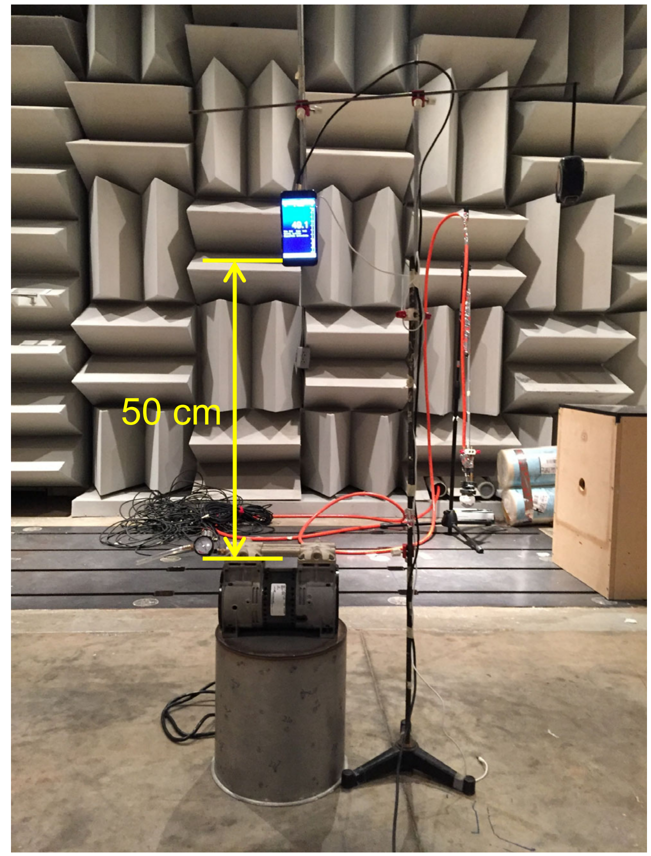
Compressor Noise SPL Comparison

The smartphone, Mic-W and PCB microphone are mounted directly above the compressor.

Apps are calibrated using 94 dB @ 1 kHz.

SPL is in dB.

Device	Sound Meter	NIOSH	iNVH	PCB
Internal Microphone (iPhone 7 Plus)	85.2	83.6	85.2	86.7
Mic-W (iPhone 6 Plus)	85.1	83.4	84.8	86.7



Free space

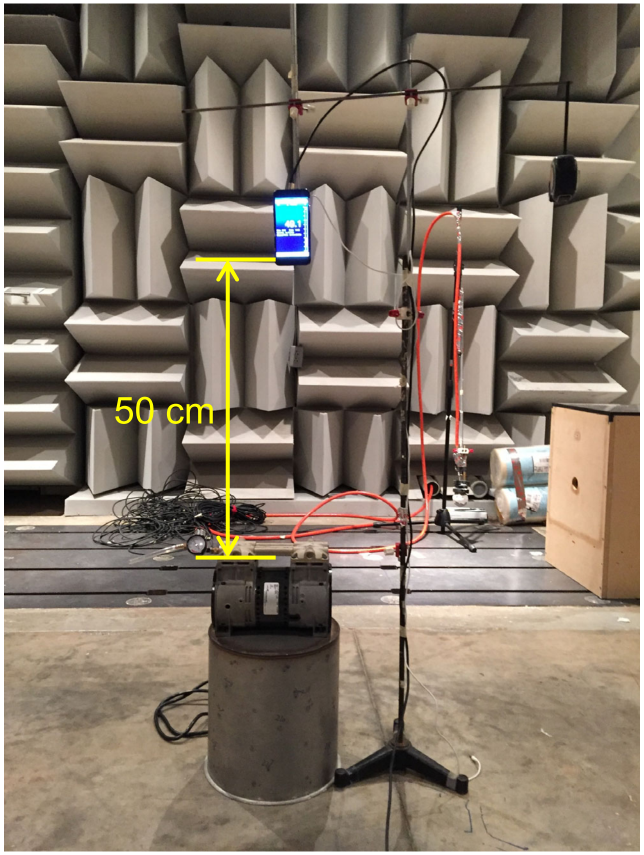
Compressor Noise SPL Comparison

The smartphone, Mic-W and PCB microphone are mounted directly above the compressor.

Apps are calibrated using 94 dB @ 1 kHz.

SPL in dBA.

Device	Sound Meter	NIOSH	iNVH	PCB
Internal Microphone (iPhone 7 Plus)	82.6	82.8	83.0	83.8
Mic-W (iPhone 6 Plus)	82.4	82.6	82.0	83.8



Free space

Impedance Tube SPL Comparison

- The Smartphone, Mic-W and PCB microphone are mounted adjacent to one another at the end of an impedance tube.

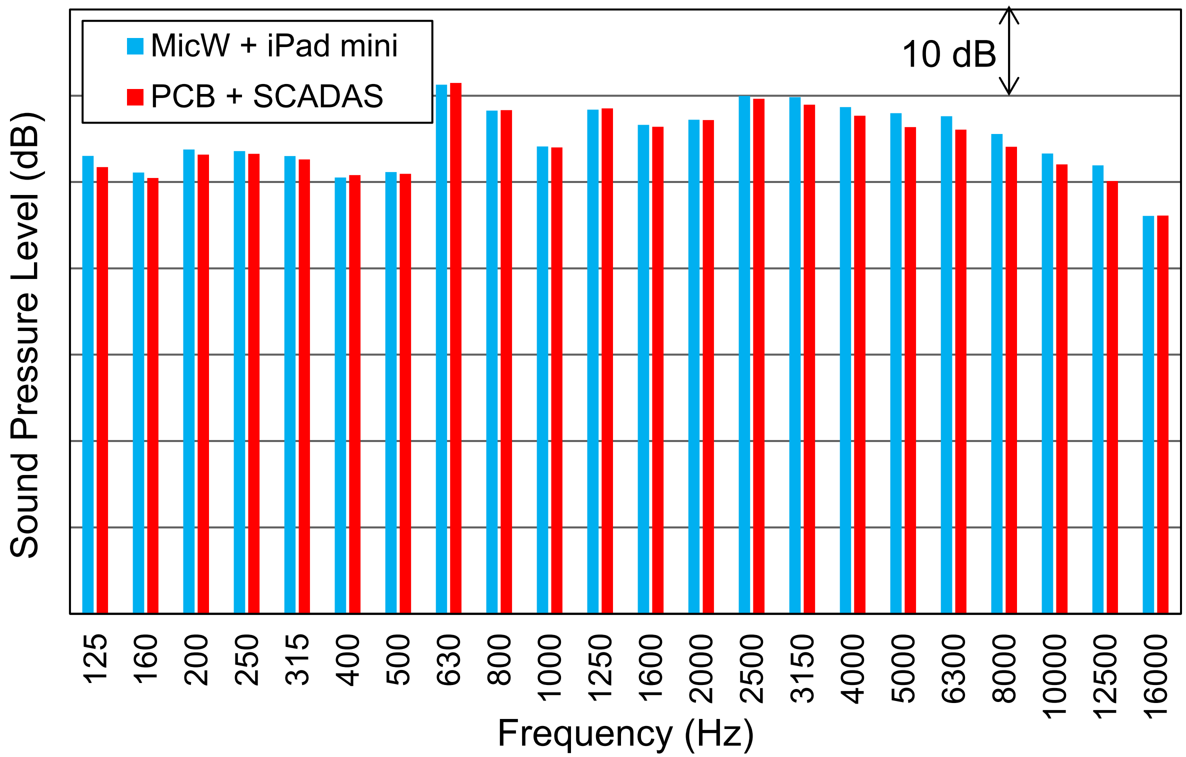
Impedance Tube SPL Comparison

White Noise Source

PCB Mic Siemens DAQ Reference	Mic-W Signal Scope	LG Internal Mic Sound Meter
84.5	85	81
89.7	90	83
94.5	95	85
99.2	100	86
104.5	105	87
109.8	110	88

Motorcycle Engine SPL Comparison

Microphones are placed 1 m far away from Harley Davidson Engine (idle running).



Summary

Pros

- Portable
- Easy to use
- Good accuracy below 10 kHz
- Inexpensive

Cons

- Issues at low frequency and low sound pressure levels

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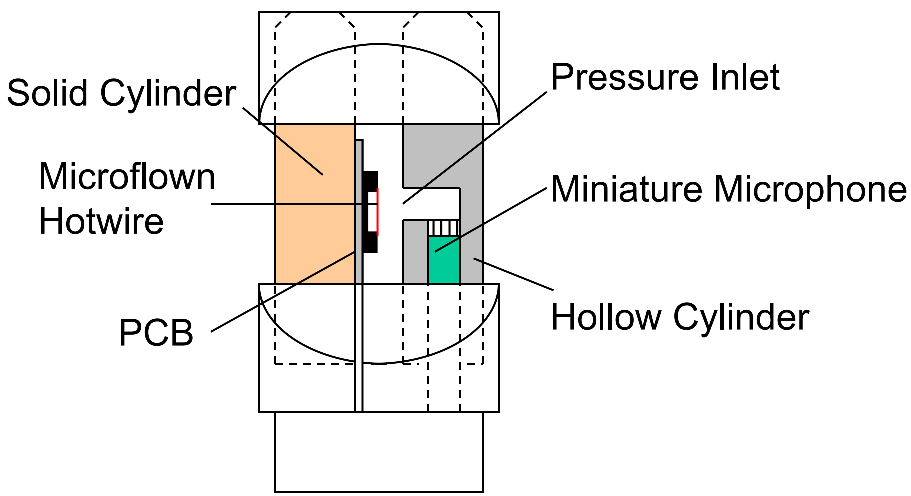
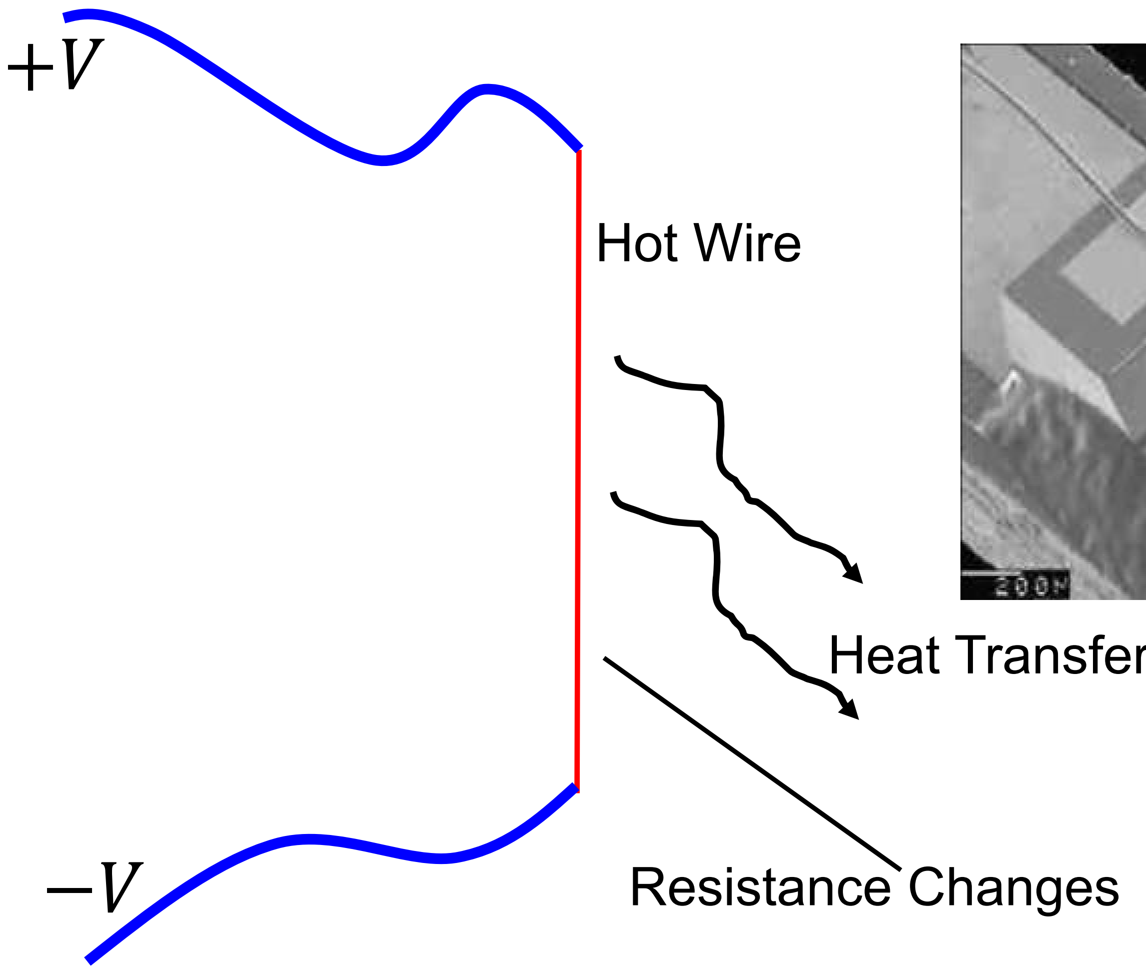
Microflown PU Probe

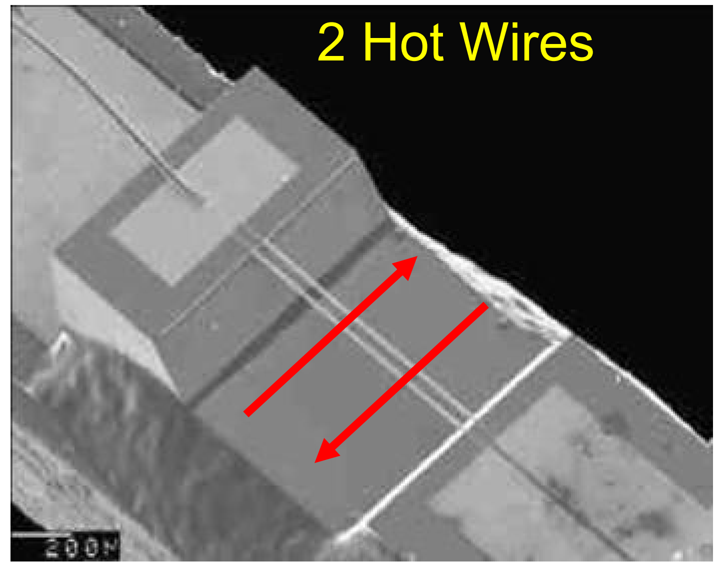


P-U Probe

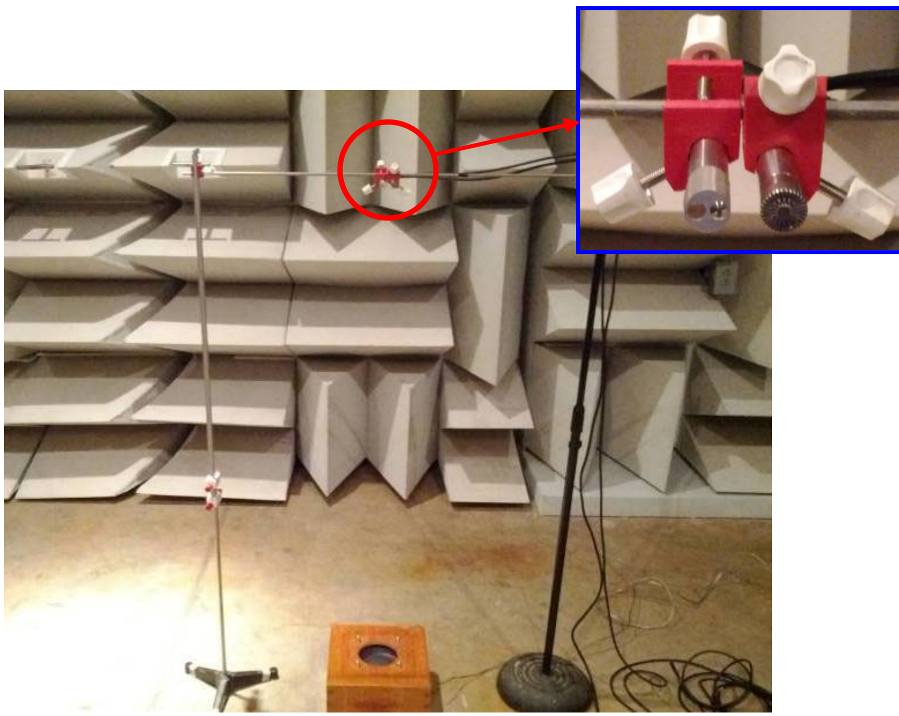
P-U Probe with Wind Shield

Microflown PU Probe





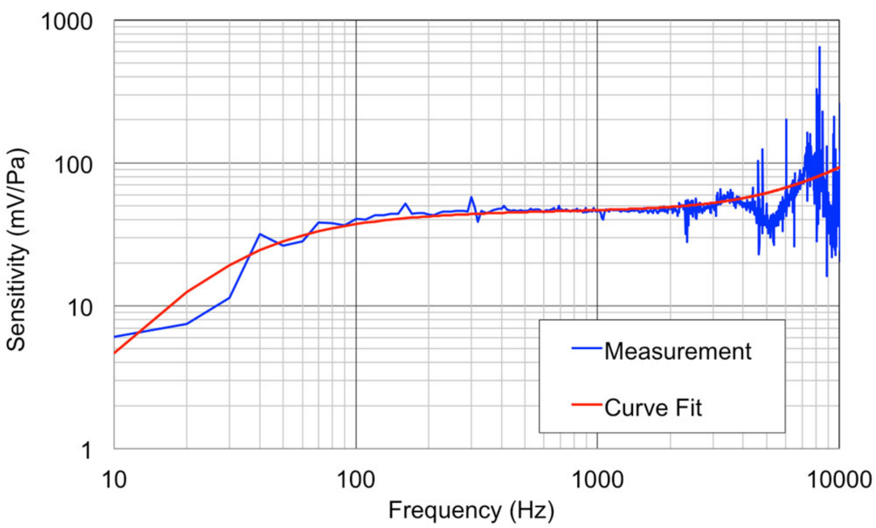
Microflown PU Probe Calibration

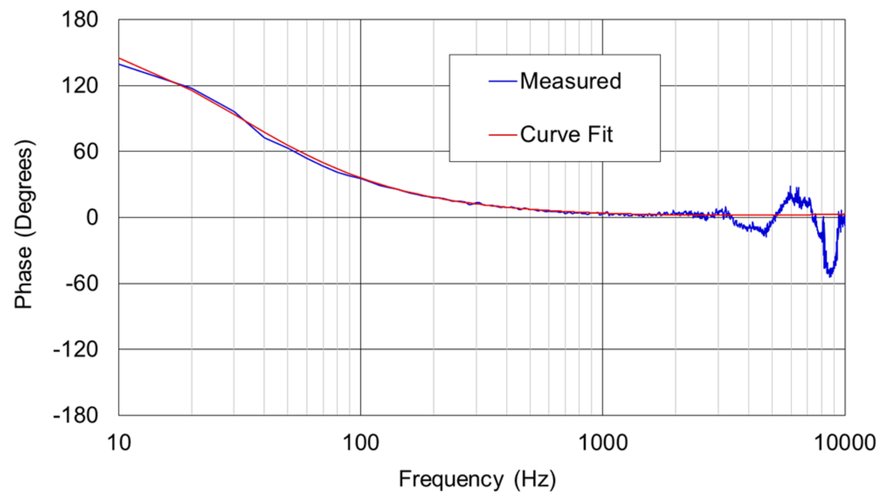


Impedance: $Z = \rho c \dfrac{ikr}{1 + ikr}$

1. Use microphone to calibrate pressure sensor.
2. Use $|Z|$ to calibrate the sensitivity of the velocity sensor.
3. Use $\angle Z$ to calibrate the phase of the velocity sensor.

Sound Pressure Sensitivity and Phase





Microphone Calibration

Parameters Pressure	
S_p	47
f_{c1p}	32
f_{c2p}	20
f_{c3p}	5848
C_{1p}	28
C_{2p}	37
C_{3p}	200000

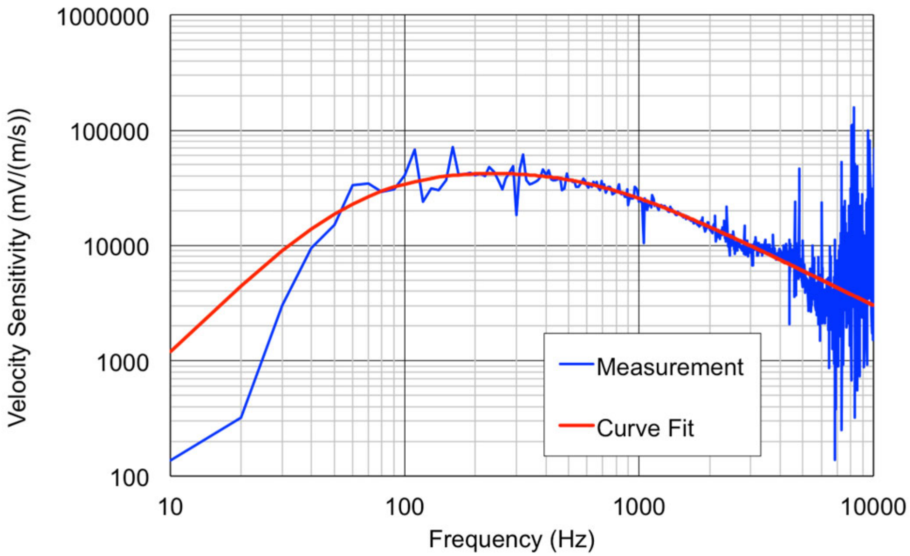
Sensitivity

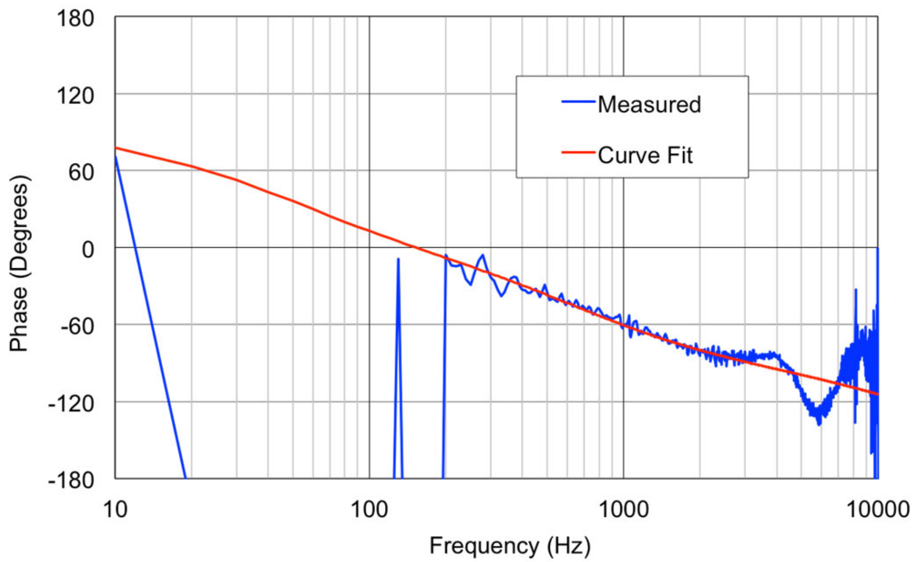
$$S_p\left[\frac{\mathrm{mV}}{\mathrm{Pa}}\right] = S_p@1\ \mathrm{kHz}\,\frac{\sqrt{1+\left(\frac{f}{f_{c3p}}\right)^2}}{\sqrt{1+\left(\frac{f_{c1p}}{f}\right)^2}\sqrt{1+\left(\frac{f_{c2p}}{f}\right)^2}}$$

Phase

$$\varphi_p[\mathrm{deg}] = \arctan\left(\frac{C_{1p}}{f}\right) + \arctan\left(\frac{C_{2p}}{f}\right) + \arctan\left(\frac{f}{C_{3p}}\right)$$

Particle Velocity Sensitivity and Phase





Particle Velocity Calibration

Parameters Velocity	
S_u	48000
f_{c1u}	63
f_{c2u}	633
f_{c3u}	97580
f_{c4u}	62
C_{1u}	1
C_{2u}	699
C_{3u}	24000
C_{4u}	50

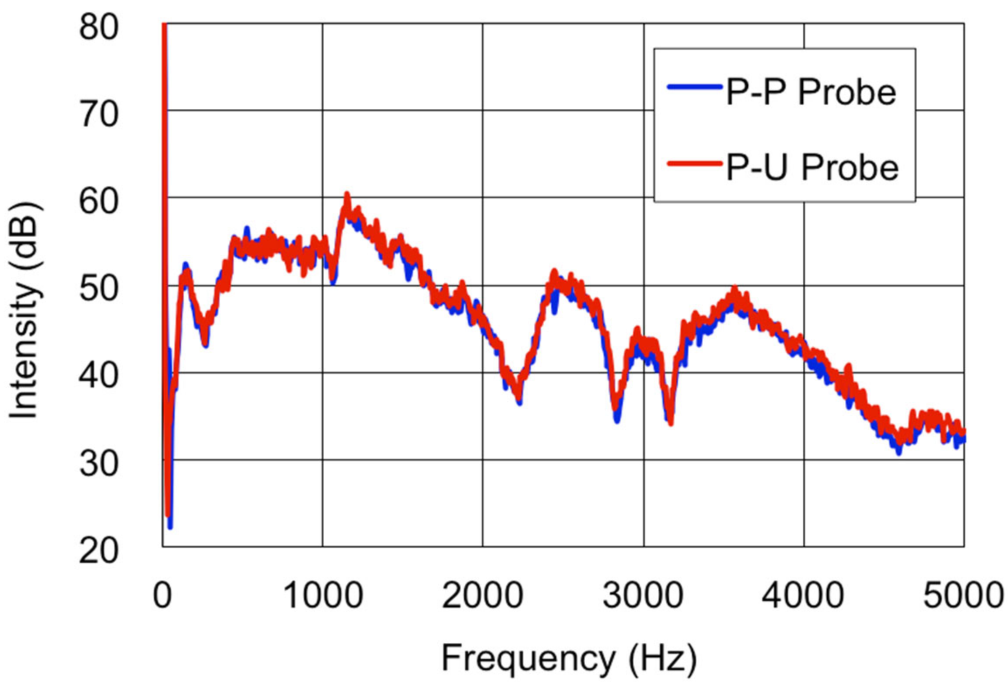
Sensitivity

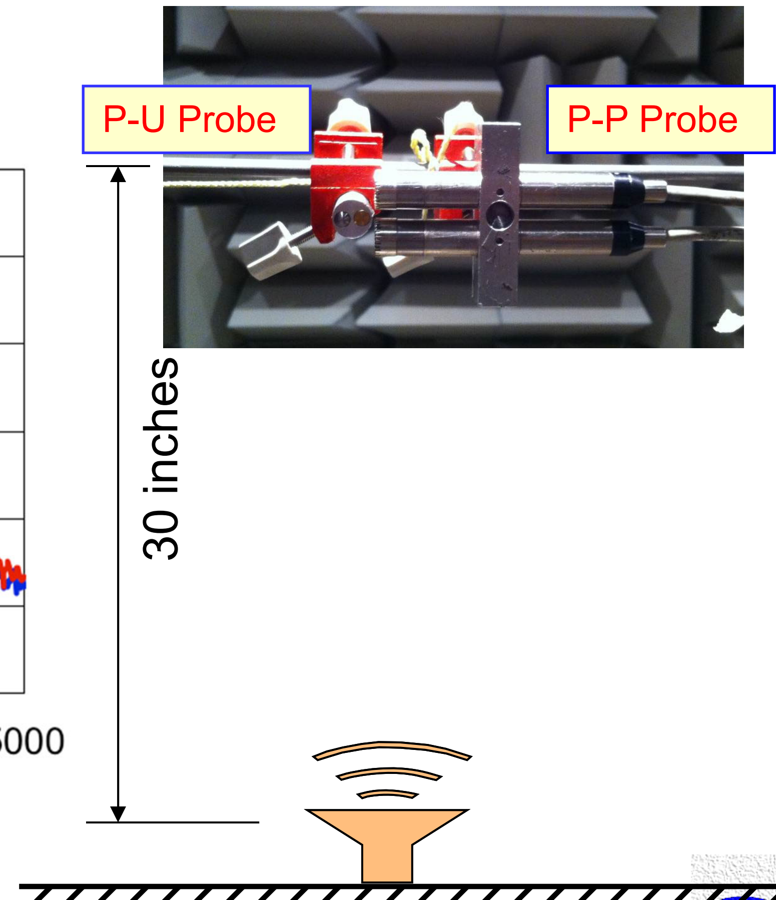
$$S_u\left[\frac{\mathrm{mV}}{\mathrm{m}/s}\right] = \frac{S_u@250\ \mathrm{Hz}}{\sqrt{1+\left(\frac{f_{c1u}}{f}\right)^2}\sqrt{1+\left(\frac{f}{f_{c2u}}\right)^2}\sqrt{1+\left(\frac{f}{f_{c3u}}\right)^2}\sqrt{1+\left(\frac{f_{c4u}}{f}\right)^2}}$$

Phase

$$\varphi_u[\mathrm{deg}] = \arctan\left(\frac{C_{1u}}{f}\right) - \arctan\left(\frac{f}{C_{2u}}\right) - \arctan\left(\frac{f}{C_{3u}}\right) + \arctan\left(\frac{C_{4u}}{f}\right)$$

Sound Intensity Comparison





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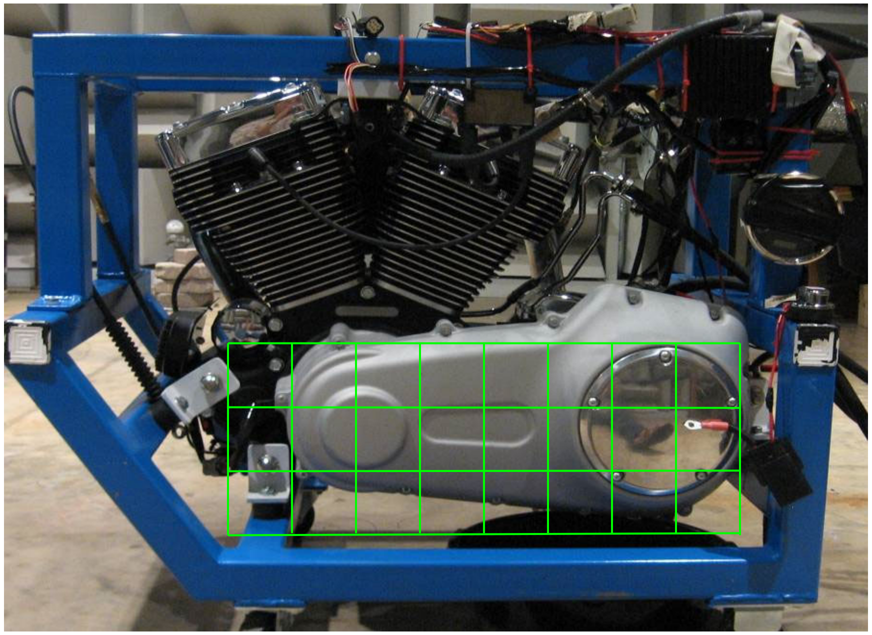
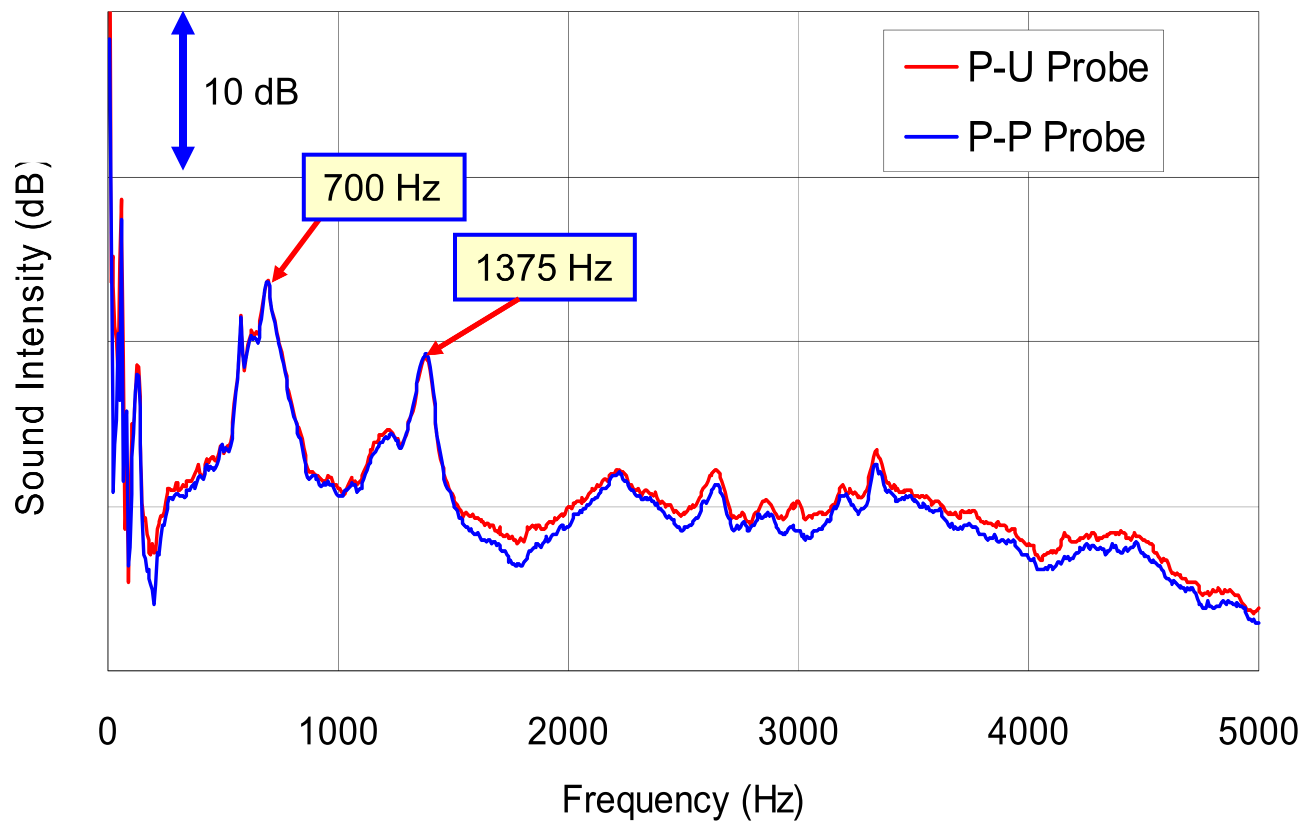
Motorcycle Engine Transmission

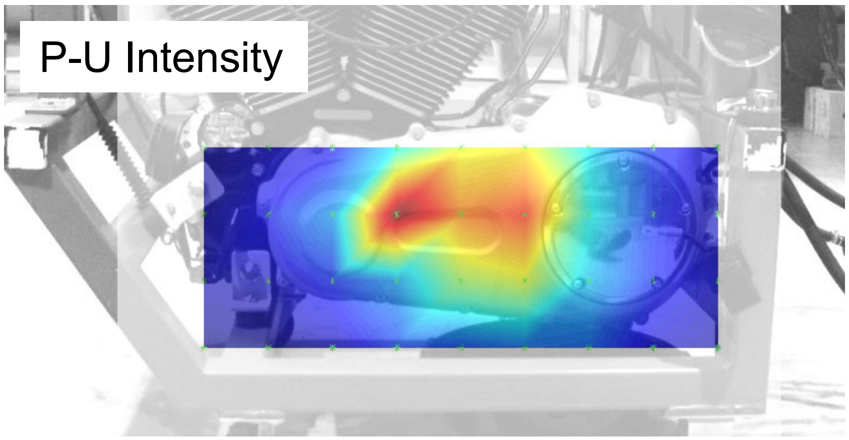
36 Grid Locations

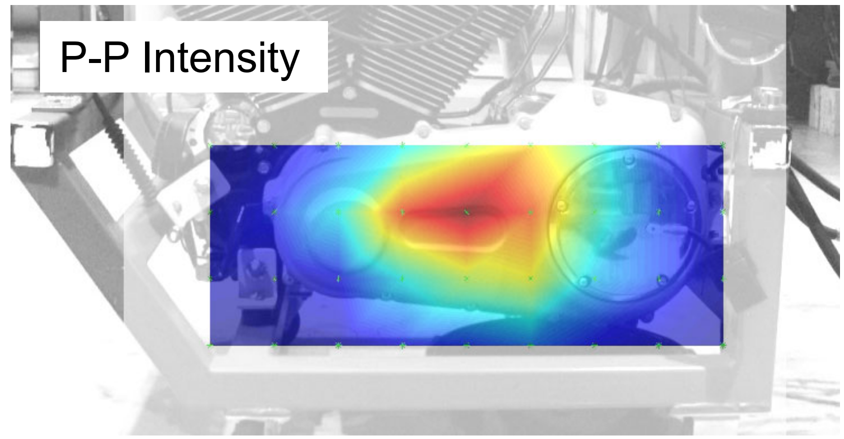


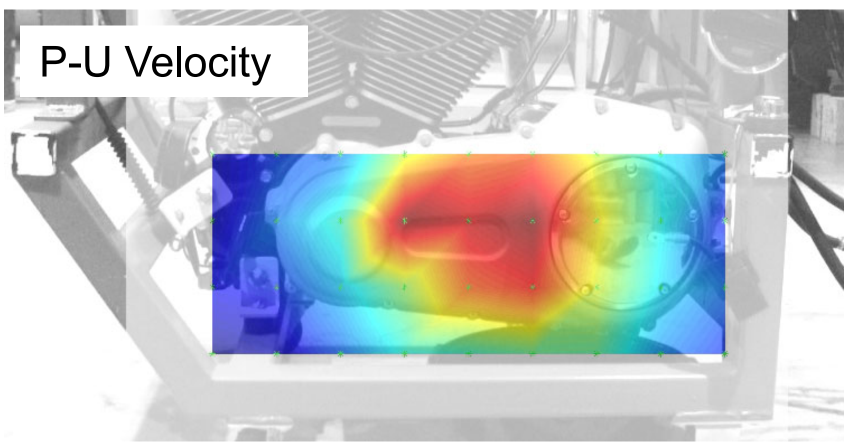
Averaged Sound Intensity Comparison



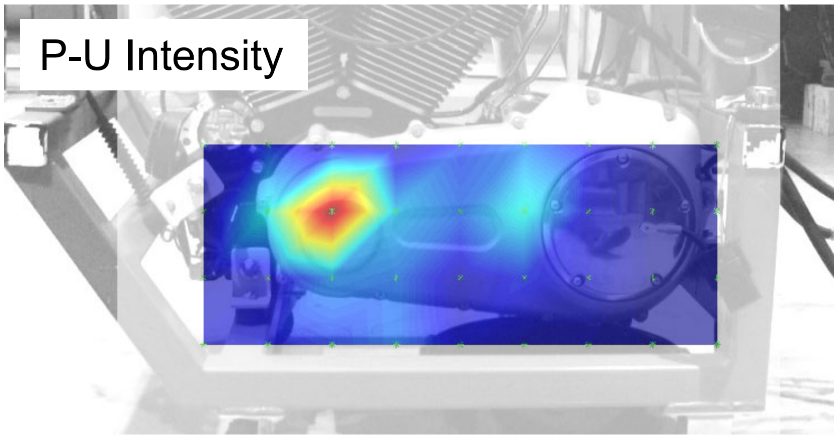
Intensity and Velocity Mapping (700 Hz)

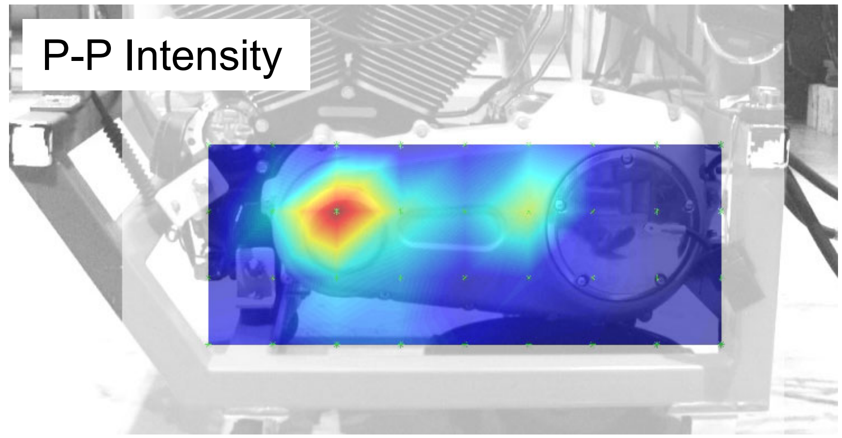


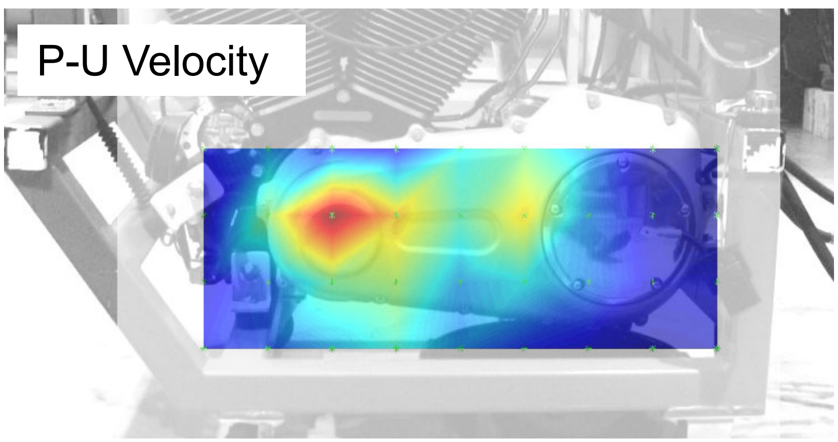




Intensity and Velocity Mapping (1375 Hz)







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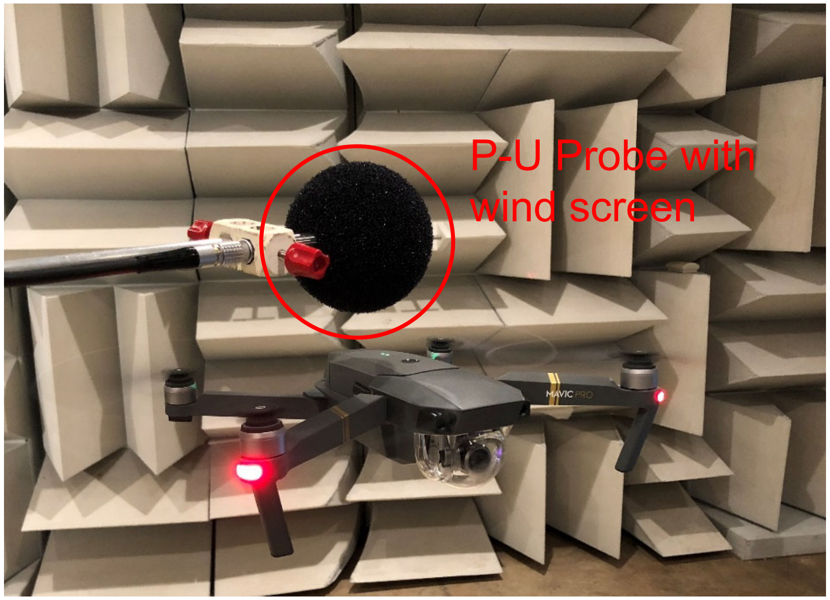
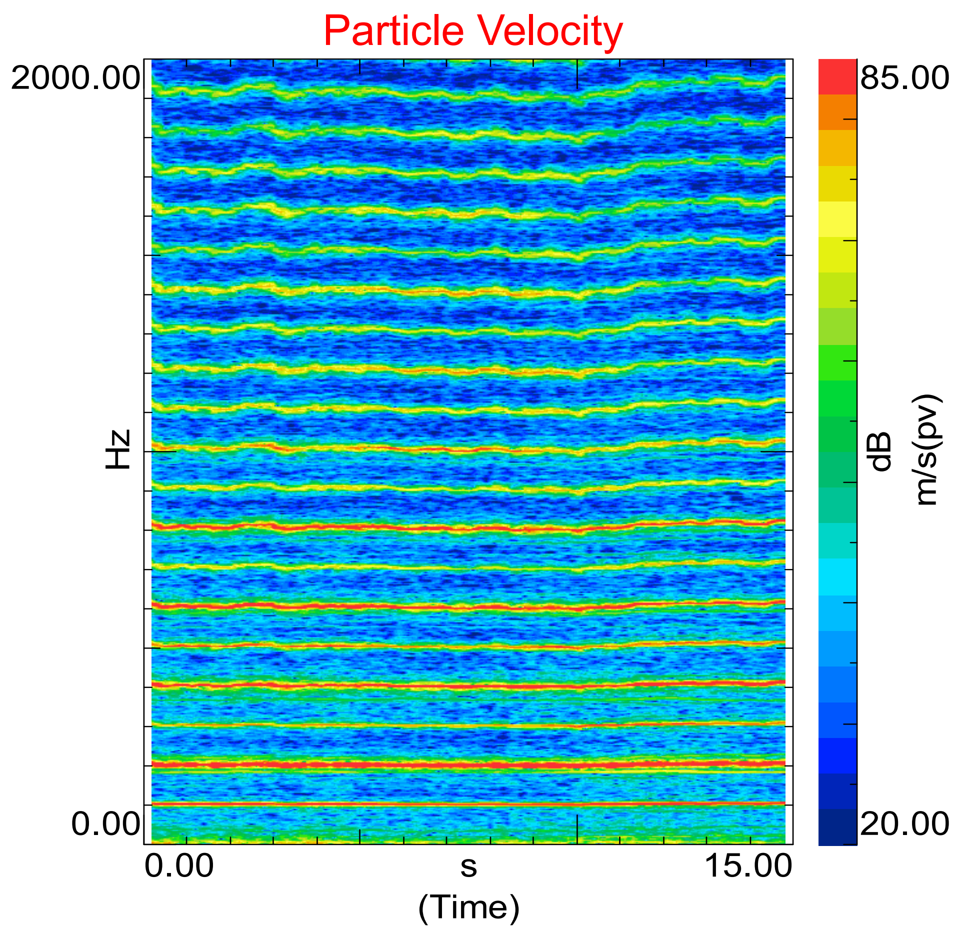
UAV Measured by P-U Probe

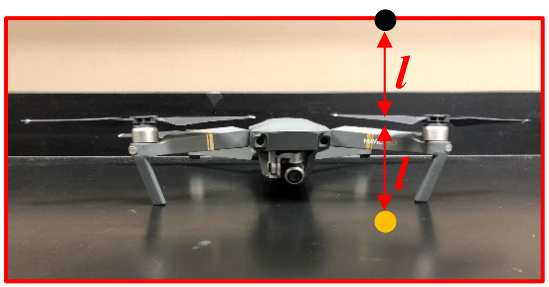


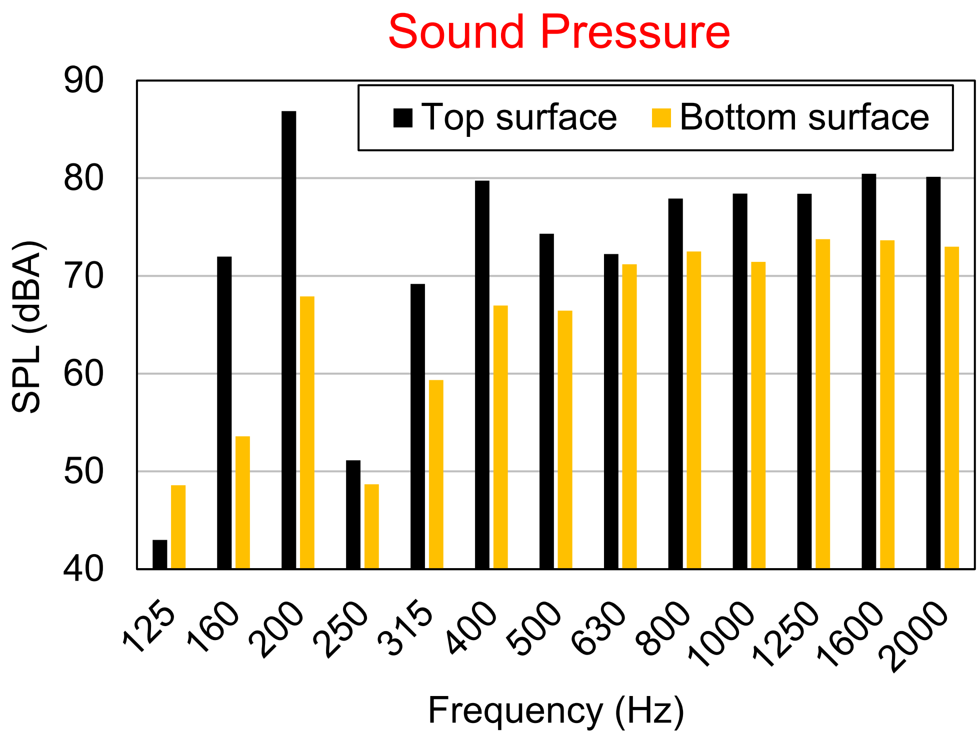
UAV on hovering: with blade ~5700 RPM

UAV Measured by P-U Probe

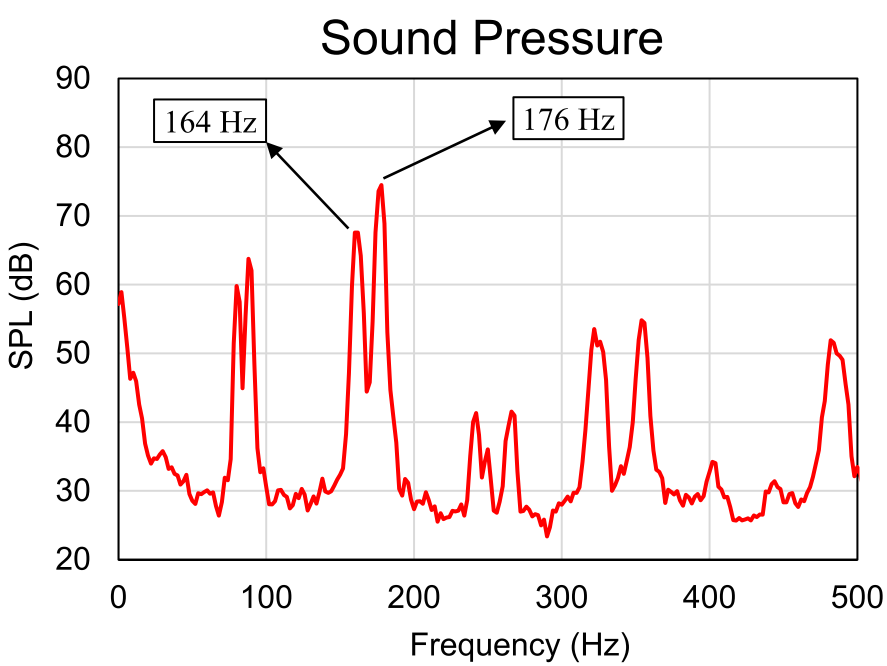


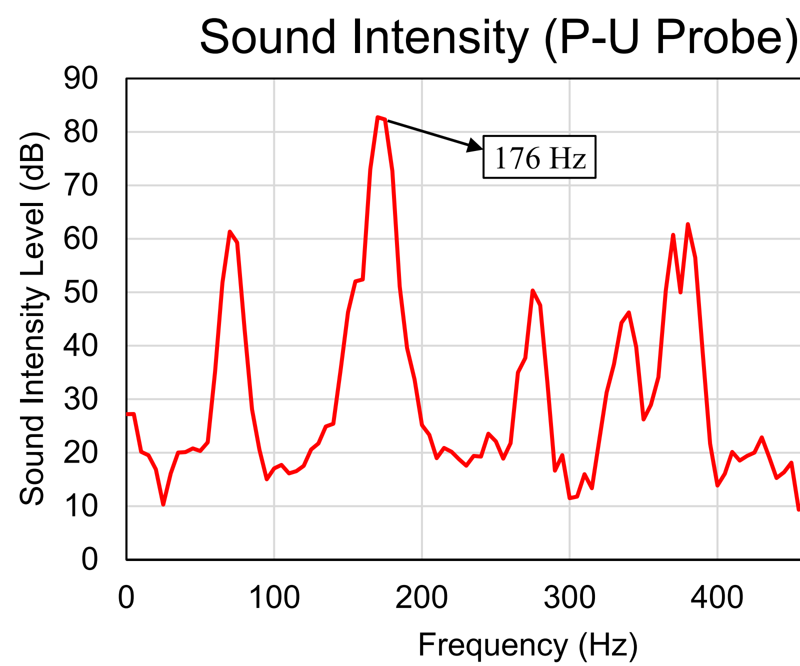
Sound Pressure Levels





Near Field Measurement

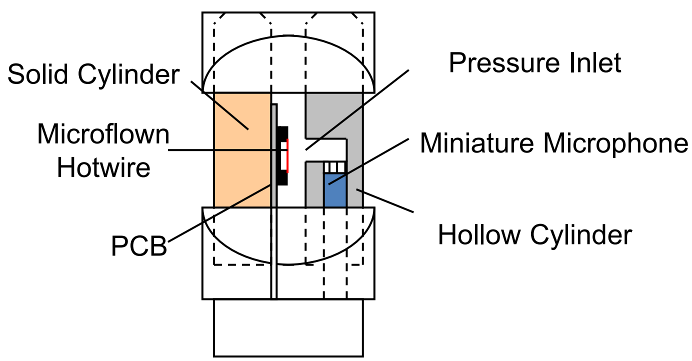




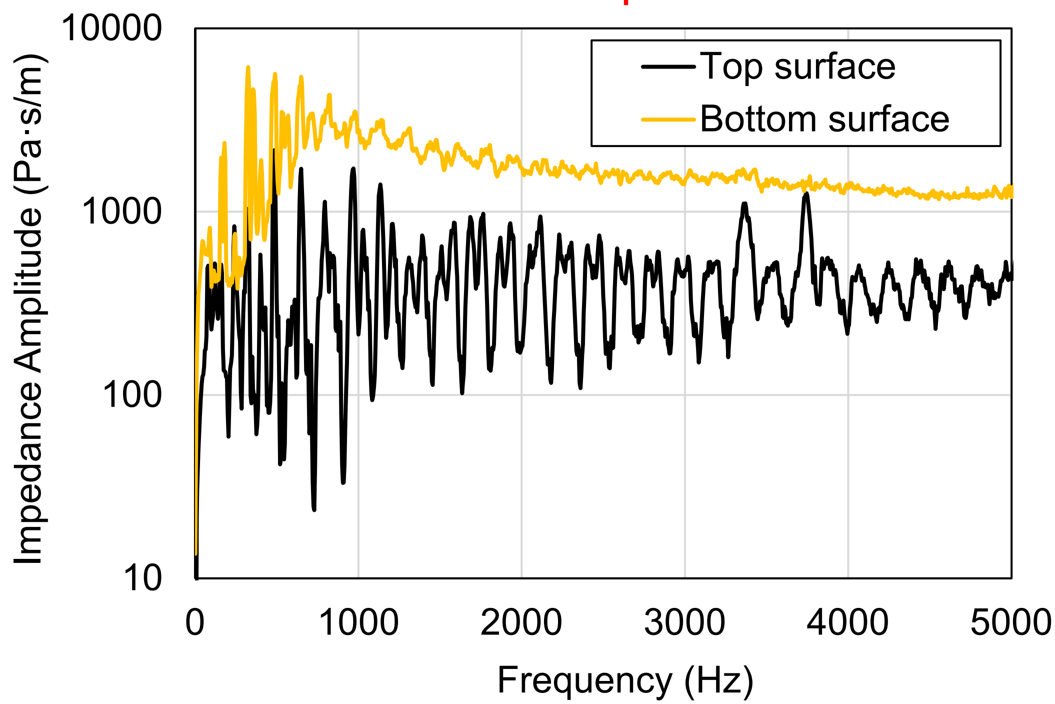
Unlike microphone, P-U probe is able to filter out nearby source components.

Top and Bottom Impedance

P-U Probe



Acoustic Impedance



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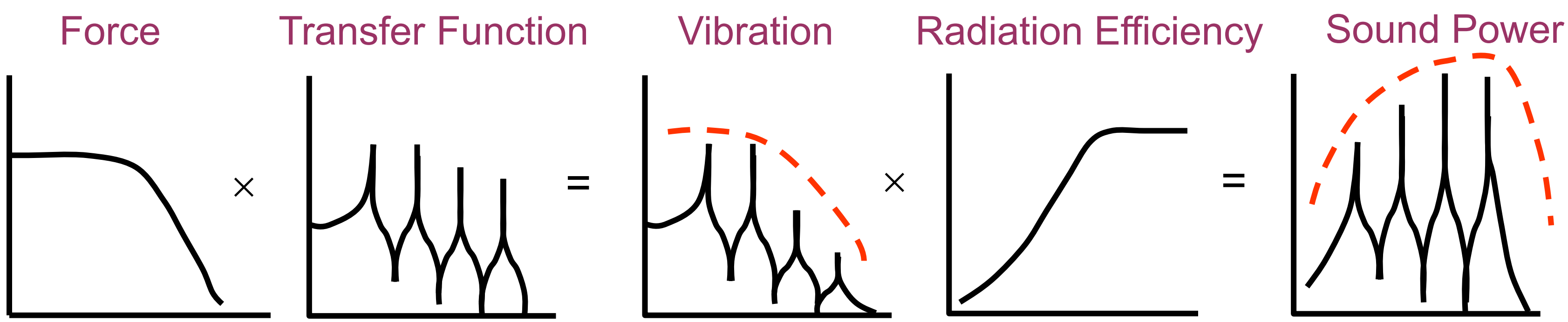
Radiation Efficiency

Radiation Efficiency



Radiation Efficiency

Radiation Efficiency

$$\sigma_{rad} = \frac{W(f)}{\rho c S \bar{u}^2(f)}$$

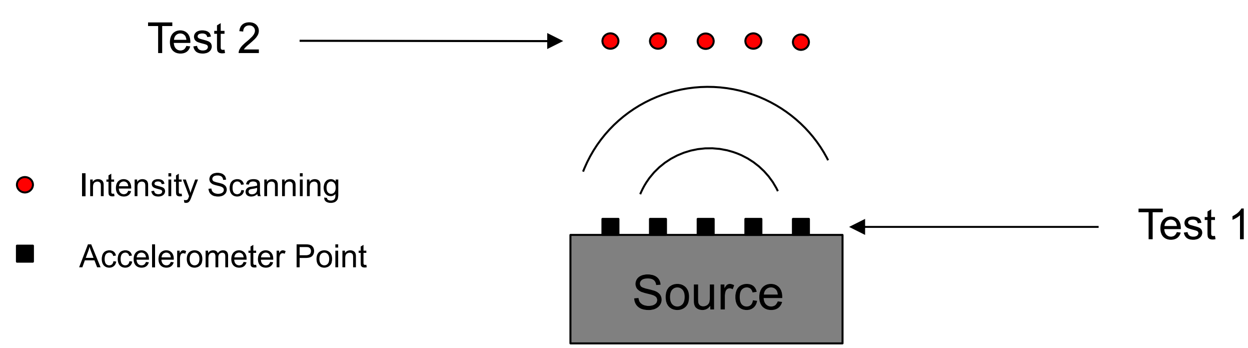
$W(f)$	sound power emitted by the vibrating surface
S	vibrating surface area
$\bar{u}^2(f)$	spatially averaged RMS value of velocity

ISO 7849 Measure Radiation Efficiency

Radiation Efficiency

ISO-7849 – Determination of airborne sound power levels emitted by machinery using vibration measurement -- Part 2: Engineering method including determination of the adequate radiation factor

- Test 1 – Accelerometer Array for Surface Velocity
- Test 2 – Intensity Scan for Radiated Sound Power

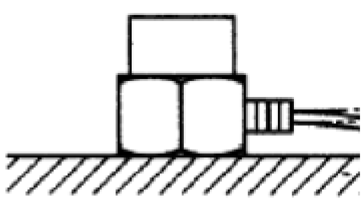


ISO 7849 Measure Radiation Efficiency

Radiation Efficiency

Disadvantages

- Accelerometers affect surface vibration.
- Requires two separate tests – longer setup time.
- Complicated structures may be difficult to instrument.

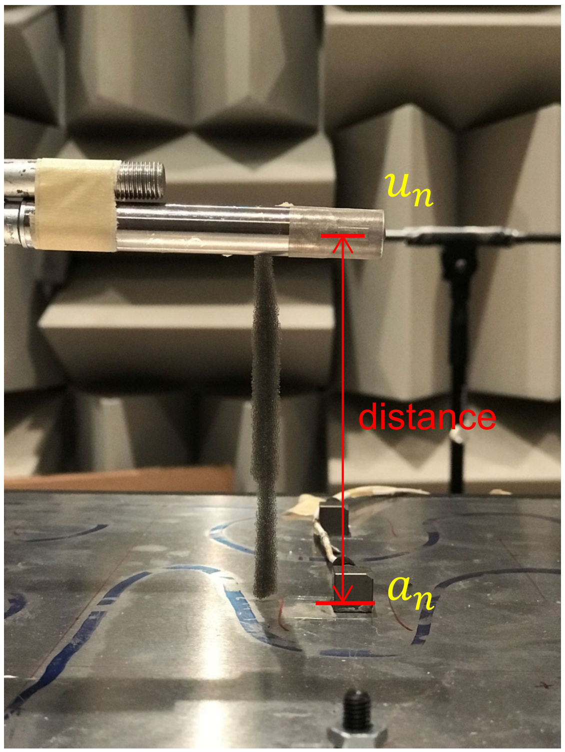


Alternative – PU Probe

- Both particle velocity and sound power can be measured with same sensor using scanning approaches.

Surface Velocity Correction

Radiation Efficiency



Calibration Constant (C_{cal})

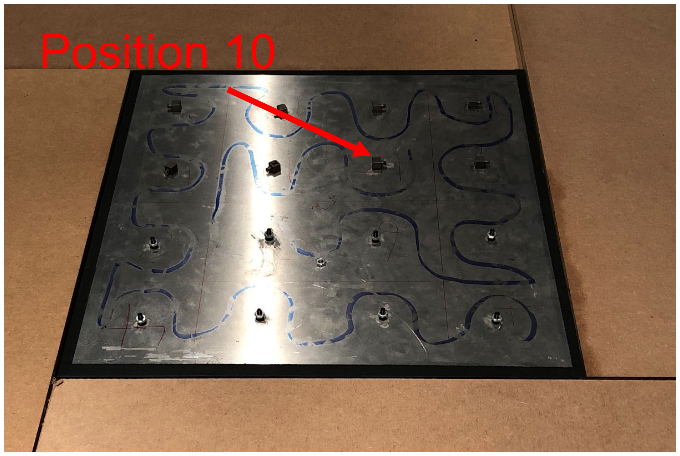
$$C_{cal} = \frac{u_n^2}{\left({a_n}/{j\omega}\right)^2}$$

Acceleration (a_n) is sampled at a single location. Particle velocity (u_n) may be sampled at a single location or multiple locations.

Aluminum Panel Test Setup

Radiation Efficiency

- The panel is divided into 16 patches and the standard method was used as a reference.
- Total sound power was measured by PU probe.
- Panel driven by shaker with white noise

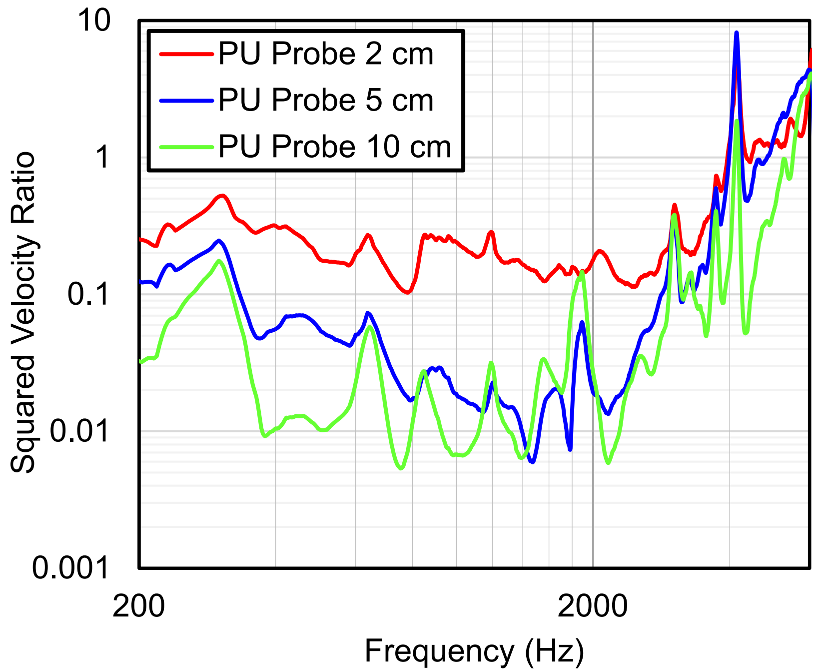


Size: 0.5×0.5 m^2

Thickness: 3 mm

Aluminum Panel Velocity Ratio

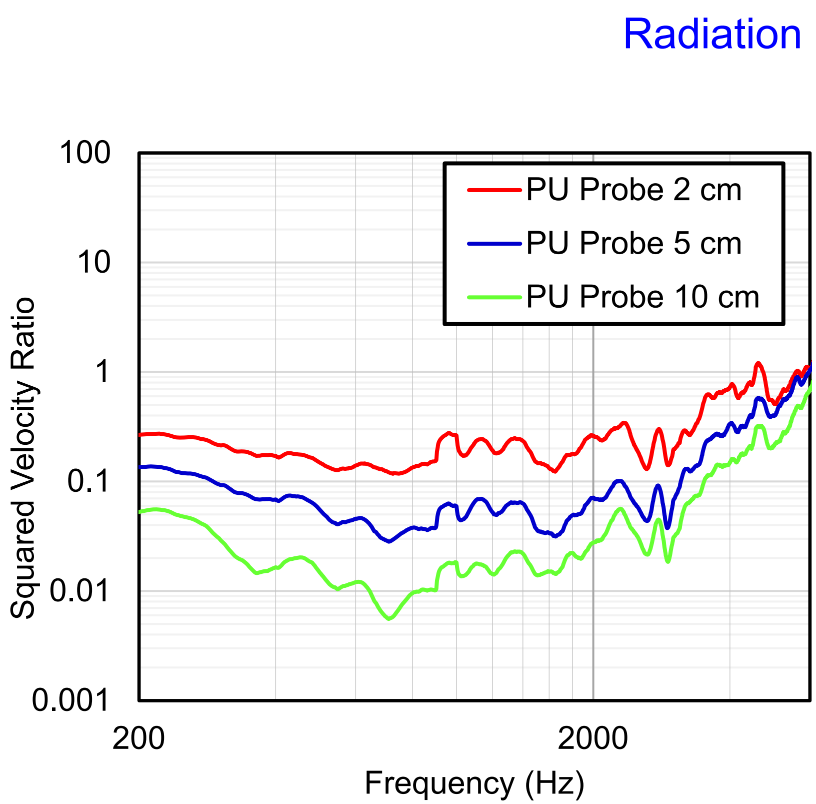
Radiation Efficiency



100 Hz running average applied to clean up data.

Single position correction
Reference: Position 10

Aluminum Panel Velocity Ratio

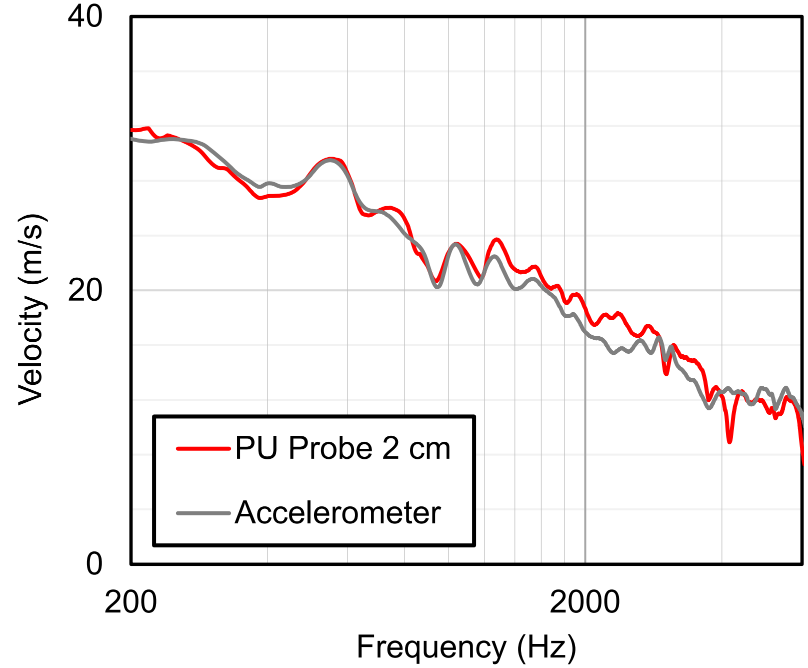


- 100 Hz running average applied to clean up data.
- Calibrated at 16 discrete positions.

Note: Data is shown for illustration purposes but not used for radiation efficiency calculation.

Aluminum Panel Velocity

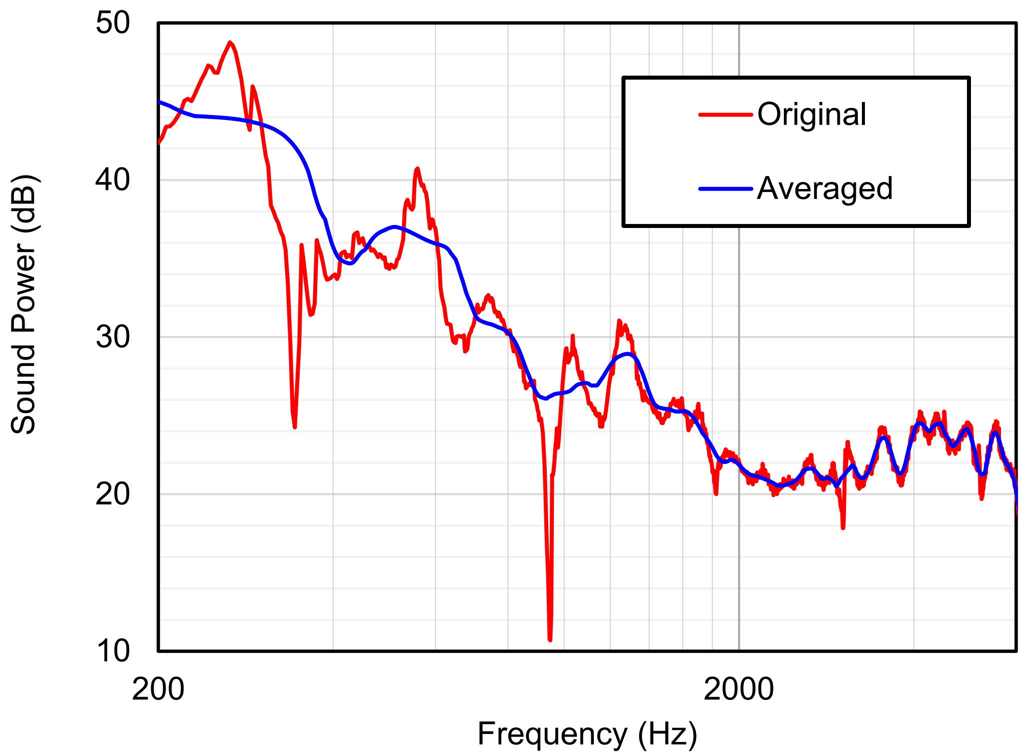
Radiation Efficiency



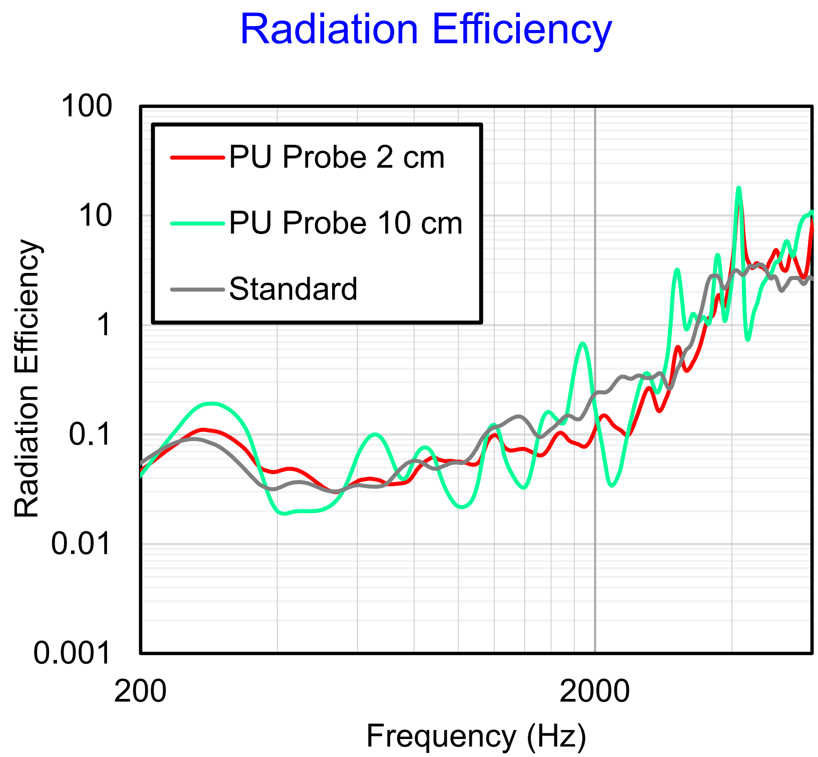
Single position correction
Reference: Position 10

Aluminum Panel Sound Power

Radiation Efficiency



Aluminum Panel Radiation Efficiency

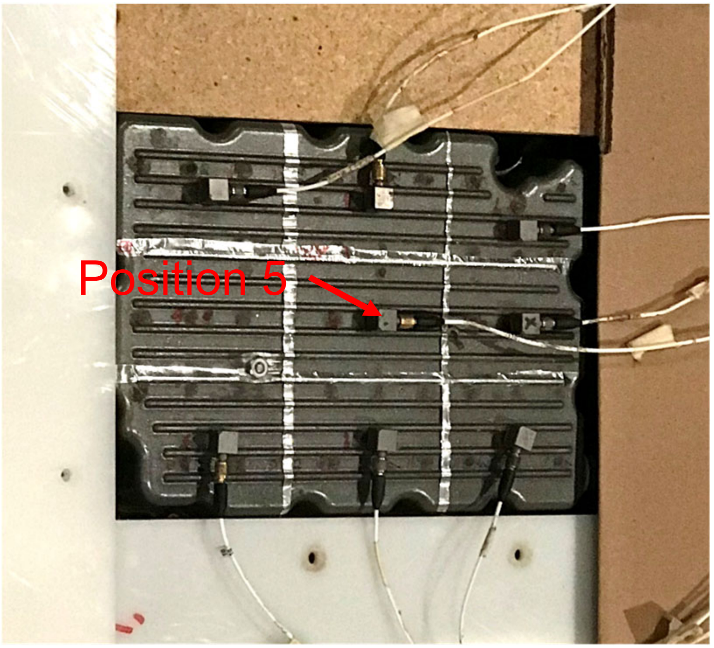


Single position correction
Reference: Position 10

Oil Pan Test Setup

Radiation Efficiency

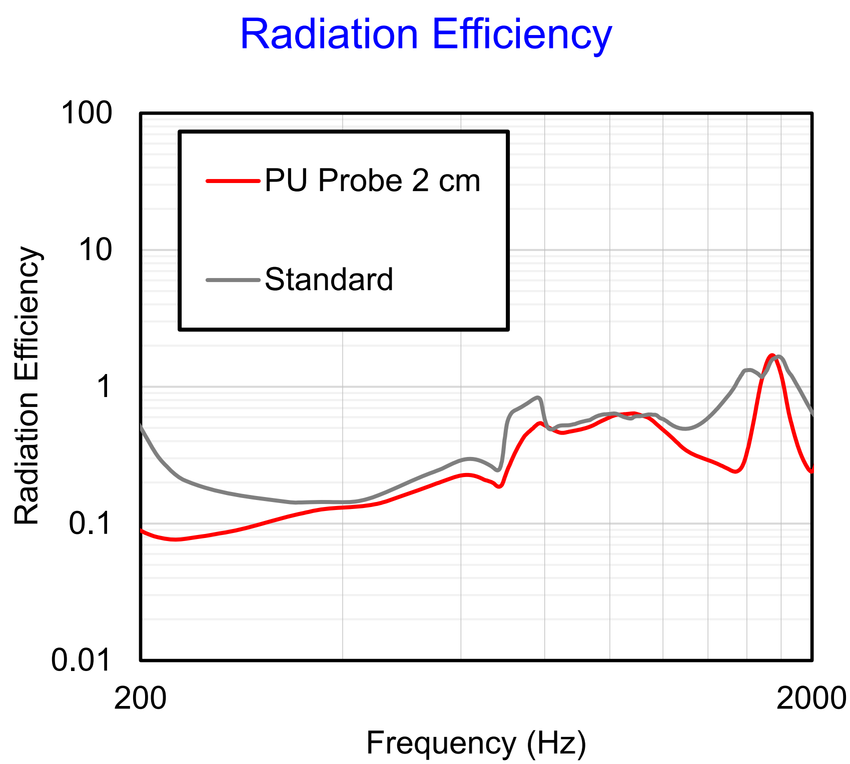
- The oil pan is divided into 9 patches and the standard method was used as a reference.
- Total sound power was measured by PU probe.
- Oil pan driven by shaker with white noise.



Material: Aluminum

Size: 0.24×0.17 m^2

Oil Pan Radiation Efficiency



Single position correction
Reference: Position 5

Overview

Radiation Efficiency

- Introduction
- Smart Phone Measurements Hardware and Software
- Smart Phone Measurements Level Tests
- Smart Phone Measurements Application Cases
- PU Probe Hardware
- PU Probe Engine Application
- PU Probe UAV Application
- PU Probe Radiation Efficiency
- Future Directions

Future Directions

Radiation Efficiency

- UK will continue to investigate new measurement tools using smartphones.
- The PU probe may also be used for sound quality. The particle velocity can be converted to a .wav file and listened to.
- The PU probe may also be used for transient particle velocity measurements. This should have application to pass-by noise.

References

Radiation Efficiency

Smart Phone Microphones

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