Measurements using Smart Phone Apps and the PU Probe

Vibro-Acoustics Consortium Web Meeting
University of Kentucky

Vibro-Acoustics Consortium
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
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

![Diagram of MEMS Microphone Components]

- **Backplate Electrode**
- **Diaphragm**
- **Substrate**
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• PU Probe UAV Application
• PU Probe Radiation Efficiency
Smartphone Types

iPhone 6 Plus

iPhone 7 Plus

LG Tribute Dynasty
Microphones

PCB 378B11
Siemens DAQ

Internal Microphone

Mic-W
BSWA


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Smartphone Apps Used

Sound Meter X
Faber Acoustical

Signal Scope X
Faber Acoustical

NIOSH SLM

iNVH
Bosch

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Microphone Calibration

Calibrate the PCB microphone

Mount the sensors together

Measure in “free field”

Generate a 94 dB noise (measured by PCB microphone)

Calibrate the Apps

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Microphone Calibration

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- Future Directions

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**Vibro-Acoustics Consortium**
Test Setup

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.

<table>
<thead>
<tr>
<th>Sound Meter</th>
<th>PCB</th>
<th>NIOSH</th>
<th>PCB</th>
<th>iNVH</th>
<th>PCB</th>
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</thead>
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<td>78.1</td>
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<td>98.5</td>
<td>100.0</td>
<td>101.8</td>
</tr>
</tbody>
</table>
**iPhone 6 Plus with Internal Microphone**

White noise source with internal microphones calibrated.

<table>
<thead>
<tr>
<th>Sound Meter</th>
<th>PCB</th>
<th>NIOSH</th>
<th>PCB</th>
<th>iNVH</th>
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<td>98.5</td>
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</table>
## iPhone 6 Plus with Mic-W

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

<table>
<thead>
<tr>
<th>Sound Pressure Level (dB)</th>
<th>Sound Meter</th>
<th>PCB SCADAS</th>
<th>NIOSH</th>
<th>PCB SCADAS</th>
<th>iNVH</th>
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<td>70.0</td>
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<td>69.5</td>
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<td>75.1</td>
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<td>80.0</td>
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<tr>
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<td>100.0</td>
<td>99.9</td>
<td>100.0</td>
<td>99.5</td>
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</tr>
</tbody>
</table>
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- **PU Probe** Radiation Efficiency
- Future Directions

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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.

<table>
<thead>
<tr>
<th>Device</th>
<th>Sound Meter</th>
<th>NIOSH</th>
<th>iNVH</th>
<th>PCB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Microphone (iPhone 7 Plus)</td>
<td>85.2</td>
<td>83.6</td>
<td>85.2</td>
<td>86.7</td>
</tr>
<tr>
<td>Mic-W (iPhone 6 Plus)</td>
<td>85.1</td>
<td>83.4</td>
<td>84.8</td>
<td>86.7</td>
</tr>
</tbody>
</table>
The smartphone, Mic-W and PCB microphone are mounted directly above the compressor. Apps are calibrated using 94 dB @ 1 kHz. SPL in dBA.

<table>
<thead>
<tr>
<th>Device</th>
<th>Sound Meter</th>
<th>NIOSH</th>
<th>iNVH</th>
<th>PCB</th>
</tr>
</thead>
<tbody>
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<td>Internal Microphone</td>
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<td>82.8</td>
<td>83.0</td>
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<tr>
<td>(iPhone 7 Plus)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mic-W</td>
<td>82.4</td>
<td>82.6</td>
<td>82.0</td>
<td>83.8</td>
</tr>
<tr>
<td>(iPhone 6 Plus)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>
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

<table>
<thead>
<tr>
<th>PCB Mic Siemens DAQ Reference</th>
<th>Mic-W Signal Scope</th>
<th>LG Internal Mic Sound Meter</th>
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</thead>
<tbody>
<tr>
<td>84.5</td>
<td>85</td>
<td>81</td>
</tr>
<tr>
<td>89.7</td>
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<td>83</td>
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<tr>
<td>109.8</td>
<td>110</td>
<td>88</td>
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</table>
Motorcycle Engine SPL Comparison

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

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Summary

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Portable</td>
<td>• Issues at low frequency and low sound pressure levels</td>
</tr>
<tr>
<td>• Easy to use</td>
<td></td>
</tr>
<tr>
<td>• Good accuracy below 10 kHz</td>
<td></td>
</tr>
<tr>
<td>• Inexpensive</td>
<td></td>
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</tbody>
</table>
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- PU Probe Radiation Efficiency
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Microflown PU Probe

Solid Cylinder
Microflown Hotwire
PCB
Pressure Inlet
Miniature Microphone
Hollow Cylinder

P-U Probe
P-U Probe with Wind Shield
Microflown PU Probe

2 Hot Wires

Hot Wire

Heat Transfer

Resistance Changes

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Microflown PU Probe Calibration

Impedance: \[ Z = \rho c \frac{ikr}{1 + ikr} \]

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

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Pressure</th>
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<tbody>
<tr>
<td>$S_p$</td>
<td>47</td>
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<tr>
<td>$f_{c1p}$</td>
<td>32</td>
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<tr>
<td>$f_{c2p}$</td>
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<tr>
<td>$f_{c3p}$</td>
<td>5848</td>
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<tr>
<td>$C_{1p}$</td>
<td>28</td>
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<tr>
<td>$C_{2p}$</td>
<td>37</td>
</tr>
<tr>
<td>$C_{3p}$</td>
<td>200000</td>
</tr>
</tbody>
</table>

Sensitivity

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

Phase

$$\varphi_p [\text{deg}] = \arctan \left( \frac{C_{1p}}{f} \right) + \arctan \left( \frac{C_{2p}}{f} \right) + \arctan \left( \frac{f}{C_{3p}} \right)$$
Particle Velocity Sensitivity and Phase

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Particle Velocity Calibration

<table>
<thead>
<tr>
<th>Parameters Velocity</th>
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<td>$f_{c4u}$</td>
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<td>$C_{2u}$</td>
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<td>$C_{3u}$</td>
<td>24000</td>
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<tr>
<td>$C_{4u}$</td>
<td>50</td>
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</tbody>
</table>

Sensitivity

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

Phase

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

![Graph comparing sound intensity for P-P and P-U probes]

- P-P Probe
- P-U Probe

Intensity (dB)

Frequency (Hz)

30 inches

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Motorcycle Engine Transmission

36 Grid Locations

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Averaged Sound Intensity Comparison

![Graph showing averaged sound intensity comparison between P-U Probe and P-P Probe. The graph includes peak sound intensities at 700 Hz and 1375 Hz, marked by blue and red lines respectively. There is a 10 dB difference between the two lines.](image-url)
Intensity and Velocity Mapping (700 Hz)
Intensity and Velocity Mapping (1375 Hz)

P-U Intensity

P-P Intensity

P-U Velocity

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UAV Measured by P-U Probe

UAV on hovering: with blade ~5700 RPM
UAV Measured by P-U Probe

Particle Velocity

Hz

dB

m/s(pv)

s

(Time)

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Sound Pressure Levels

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Near Field Measurement

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

Acoustic Impedance

![Diagram of P-U Probe]

- Solid Cylinder
- Pressure Inlet
- Microflown
- Hotwire
- PCB
- Hollow Cylinder
- Miniature Microphone

Frequency (Hz)

Impedance Amplitude (Pa·s/m)

- Top surface
- Bottom surface
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Radiation Efficiency

\[ \text{Force} \times \text{Transfer Function} \times \text{Vibration} \times \text{Radiation Efficiency} = \text{Sound Power} \]
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

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

Test 1

Intensity Scanning
Accelerometer Point

Source
ISO 7849 Measure 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.

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Surface Velocity Correction

Calibration Constant ($C_{cal}$)

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

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 m²
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

Radiation Efficiency

- 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

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Aluminum Panel Sound Power

Radiation Efficiency

![Graph showing the comparison between Original and Averaged Aluminum Panel Sound Power.](image-url)
Aluminum Panel Radiation Efficiency

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 m²
Oil Pan Radiation Efficiency

Single position correction
Reference: Position 5
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Radiation Efficiency

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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


PU Probe


Standard Measurement Procedure for Radiation Efficiency


Radiation Efficiency Research at UK